ECE321 Electronics I
Fall 2006

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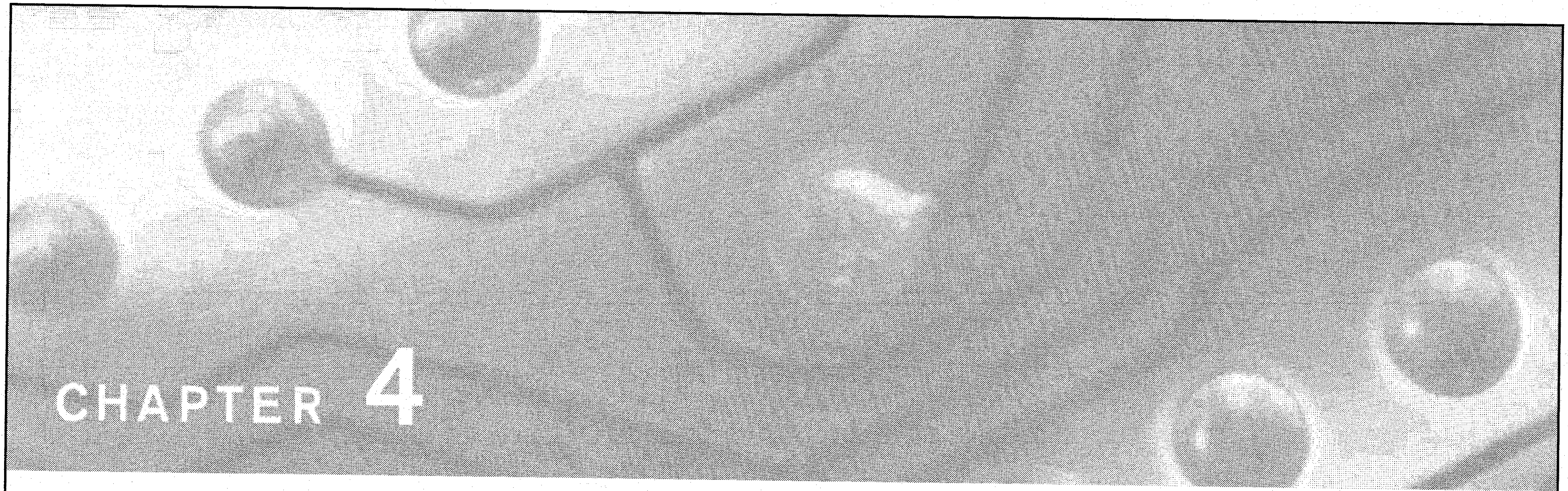
Lecture 10

26th October, 2006



MOS Field-Effect Transistors (MOSFETs)

~~4.5 Biasing~~

4.6 Small-Signal

4.7 Single Stage Amp's

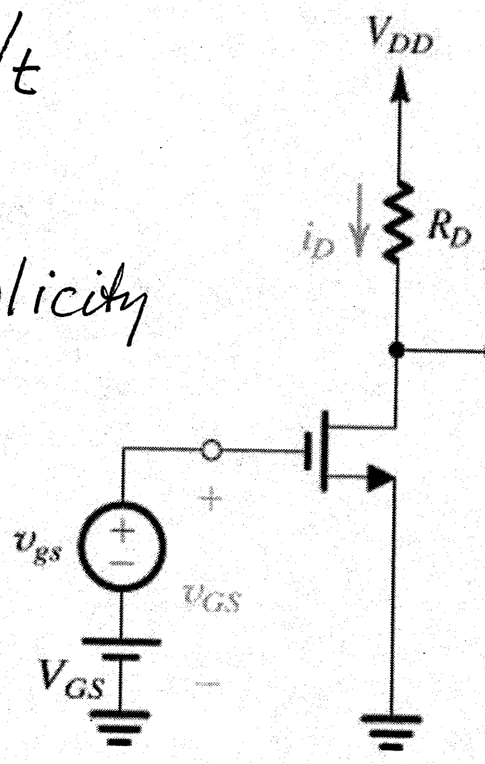
DC BIAS POINT

Assume saturation

i.e. $V_D > V_{GS} - V_t$

(then confirm)

Assume $\lambda = 0$ for simplicity



$$I_D = \frac{1}{2} k_n' \left(\frac{W}{L}\right)(V_{GS} - V_t)^2$$

$$= \frac{1}{2} k_n' \frac{W}{L} V_{ov}^2$$

$$V_D = V_{DD} - I_D R_D$$

Note: As amplifier, need $V_D > V_{GS} - V_t$ for all $v_{GS} = V_{GS} + v_{gs}$

i.e. $v_D)_{min} > v_{GS})_{max} - V_t$

Figure 4.34 Conceptual circuit utilized to study the operation of the MOSFET as a small-signal amplifier.

SMALL SIGNAL:

$$v_{GS} = V_{GS} + v_{gs} \longrightarrow i_D = \tfrac{1}{2} k_n' \frac{W}{L} (V_{GS} + v_{gs} - V_t)^2$$

$$= \tfrac{1}{2} k_n' \frac{W}{L} \left([V_{GS} - V_t]^2 + 2[V_{GS} - V_t] v_{gs} + v_{gs}^2 \right)$$

DC bias term → $[V_{GS} - V_t]^2$

Small signal; linear in v_{gs} → $2[V_{GS} - V_t] v_{gs}$

Non linear term → v_{gs}^2

Make $v_{gs} \ll 2(V_{GS} - V_t) \longrightarrow i_D = I_D + i_d$

where $i_d = k_n' \frac{W}{L} (V_{GS} - V_t) v_{gs}$

$$g_m = \frac{i_d}{v_{gs}} = k_n' \frac{W}{L} (V_{GS} - V_t) \xrightarrow{(V_{GS} - V_t)^2 = \frac{2 I_D}{k_n' W/L}} \sqrt{2 k_n' \frac{W}{L} I_D}$$

$$\xrightarrow{k_n' \frac{W}{L} = \frac{2 I_D}{(V_{GS} - V_t)^2}} \frac{2 I_D}{V_{GS} - V_t} = \frac{2 I_D}{V_{ov}}$$

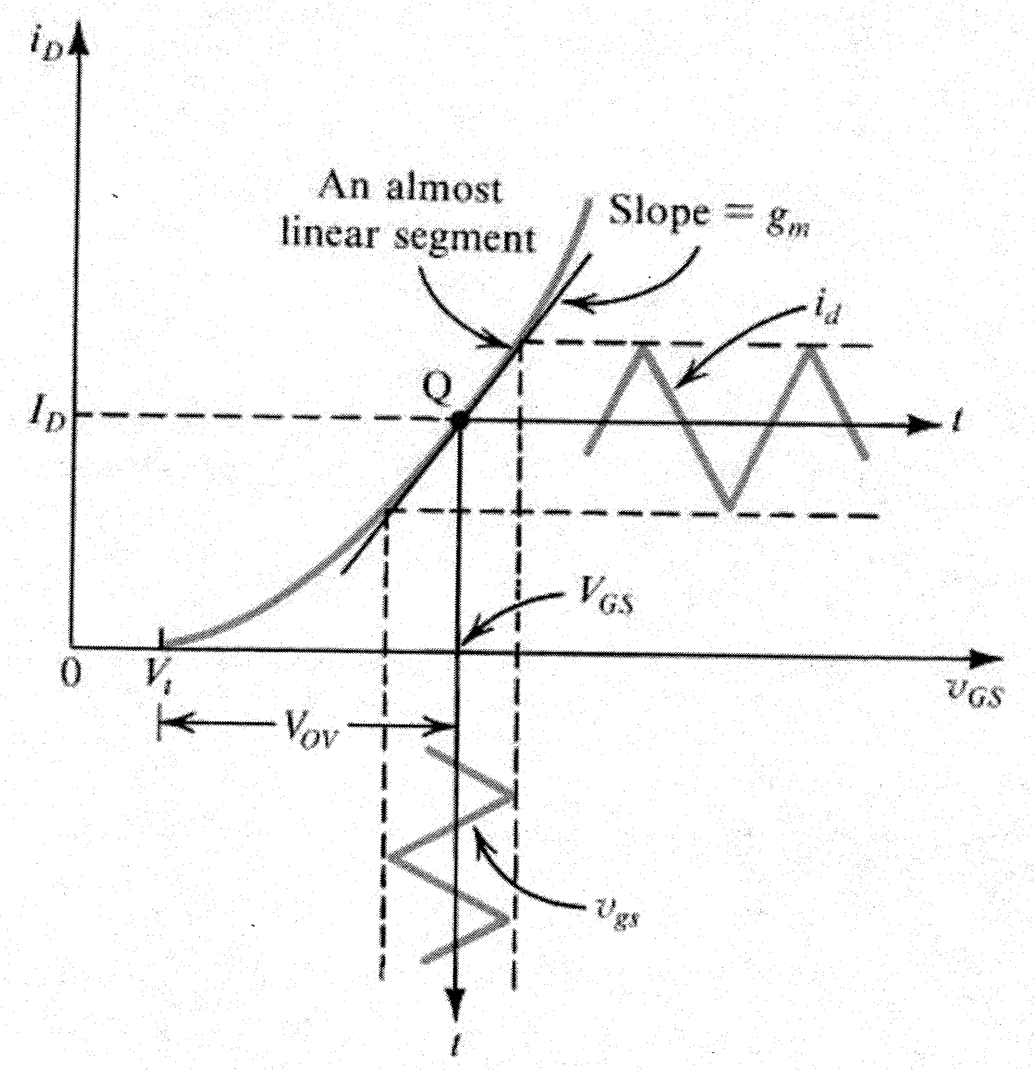


Figure 4.35 Small-signal operation of the enhancement MOSFET amplifier.

$$v_D = V_{DD} - i_D R_D = V_{DD} - R_D(I_D + i_d) = V_D + v_d$$

$$\therefore v_d = -i_d R_D$$

$$= -g_m v_{gs} R_D$$

$$\therefore A_V = \frac{v_d}{v_{gs}} = -g_m R_D$$

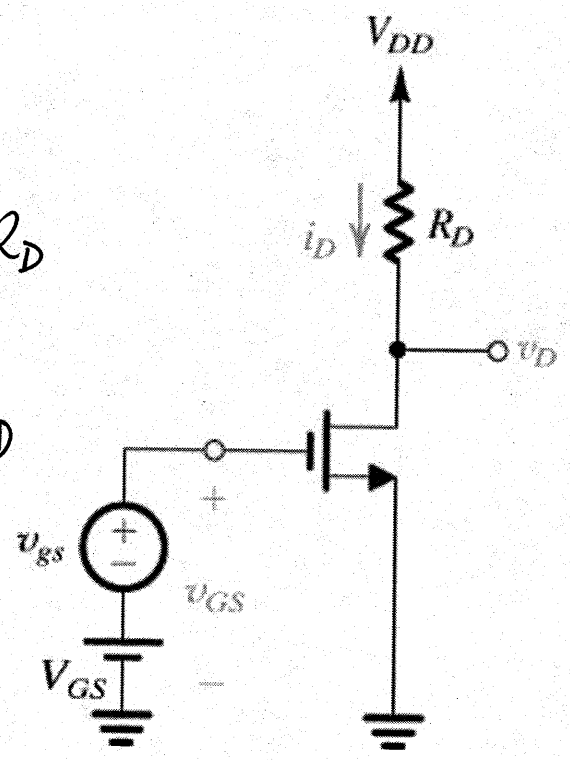
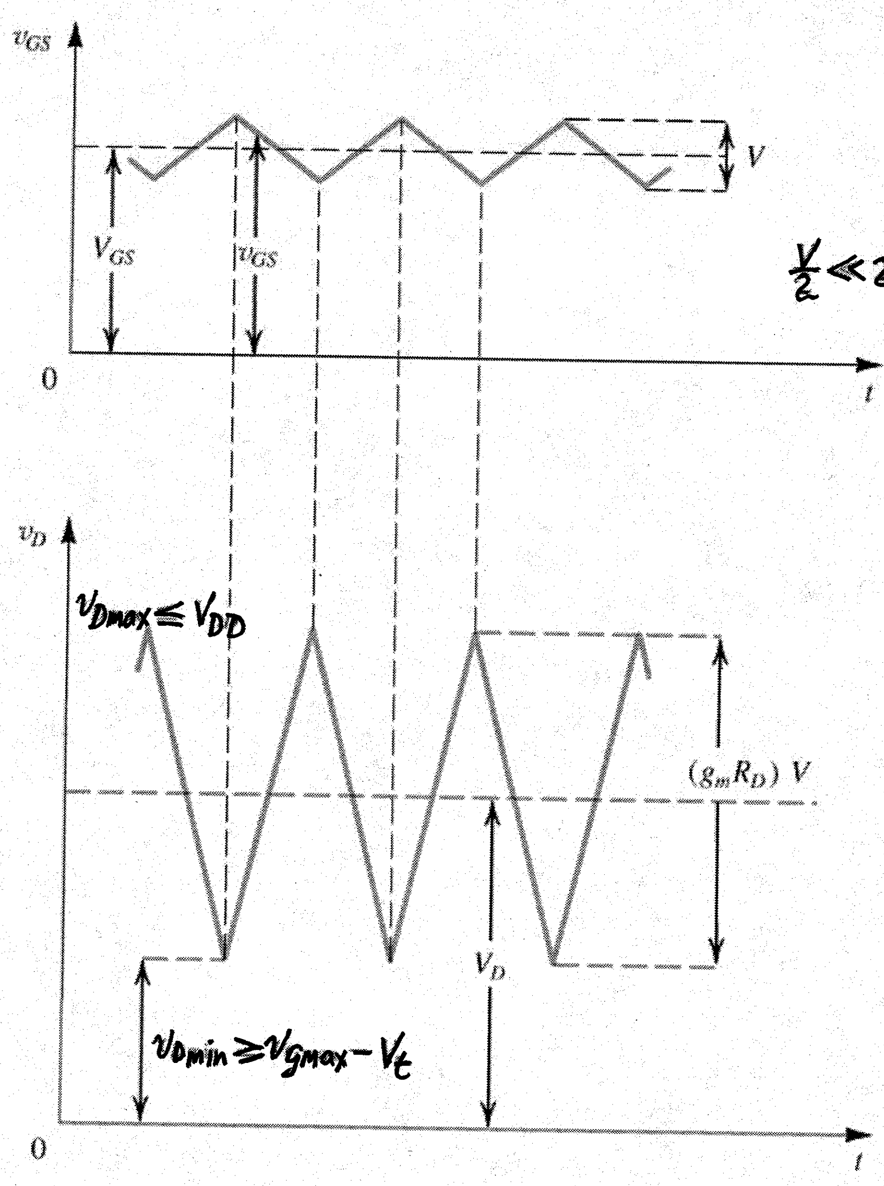


Figure 4.34 Conceptual circuit utilized to study the operation of the MOSFET as a small-signal amplifier.

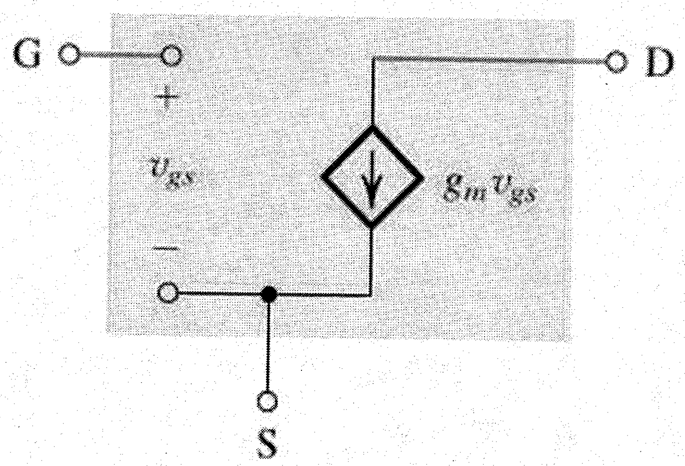


approx!

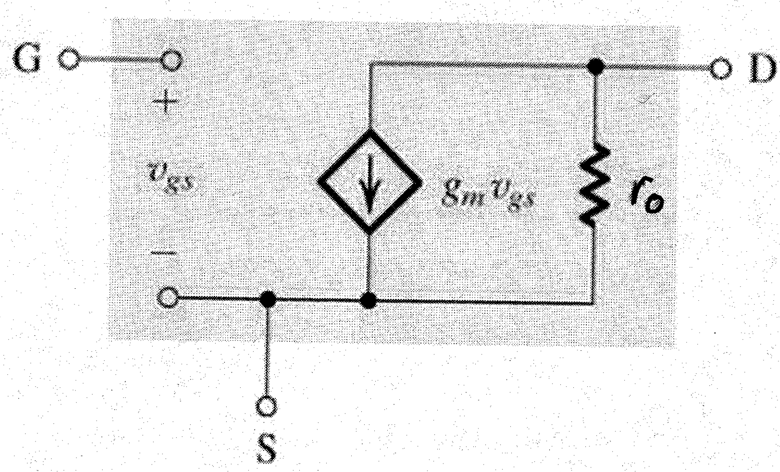
$\frac{V}{2} \ll 2(V_{GS} - V_t)$ for linearity

Figure 4.36 Total instantaneous voltages v_{GS} and v_D for the circuit in Fig. 4.34.

SMALL SIGNAL EQUIVALENT CIRCUIT



(a)



(b)

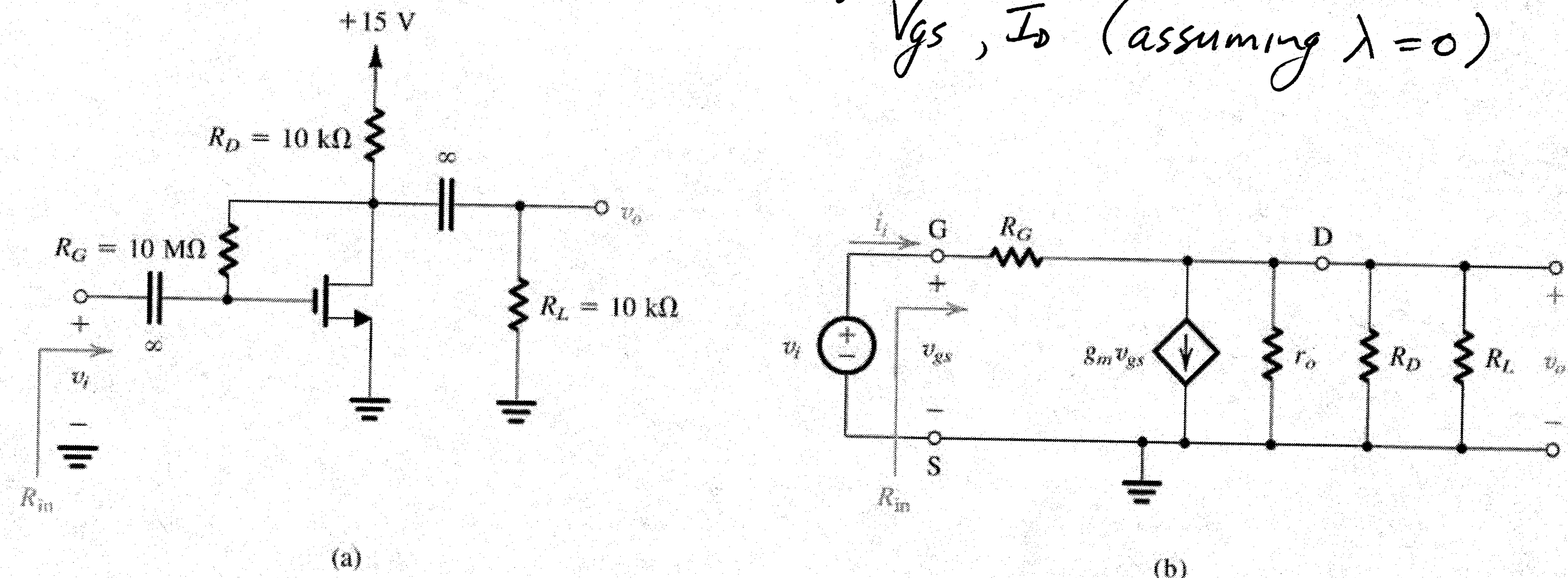
$$r_o = \frac{|V_A|}{I_D}$$

$$A_V \longrightarrow -g_m (r_o \| R_D)$$

Figure 4.37 Small-signal models for the MOSFET: **(a)** neglecting the dependence of i_D on v_{DS} in saturation (the channel-length modulation effect); and **(b)** including the effect of channel-length modulation, modeled by output resistance $r_o = |V_A| / I_D$.

Example 4.10 — Feedback R_G

① Find DC operating point to verify saturation and calculate V_{GS}, I_D (assuming $\lambda = 0$)



② Calculate g_m, r_o [Note: r_o calculation uses approximate DC bias]

Gain calculation neglects R_G (negligible current from D to G)

But R_{in} is due to R_G ∴ must include R_G in R_{in} calculation

Figure 4.38 Example 4.10: **(a)** amplifier circuit; **(b)** equivalent-circuit model.

Hybrid-Π to T-Model

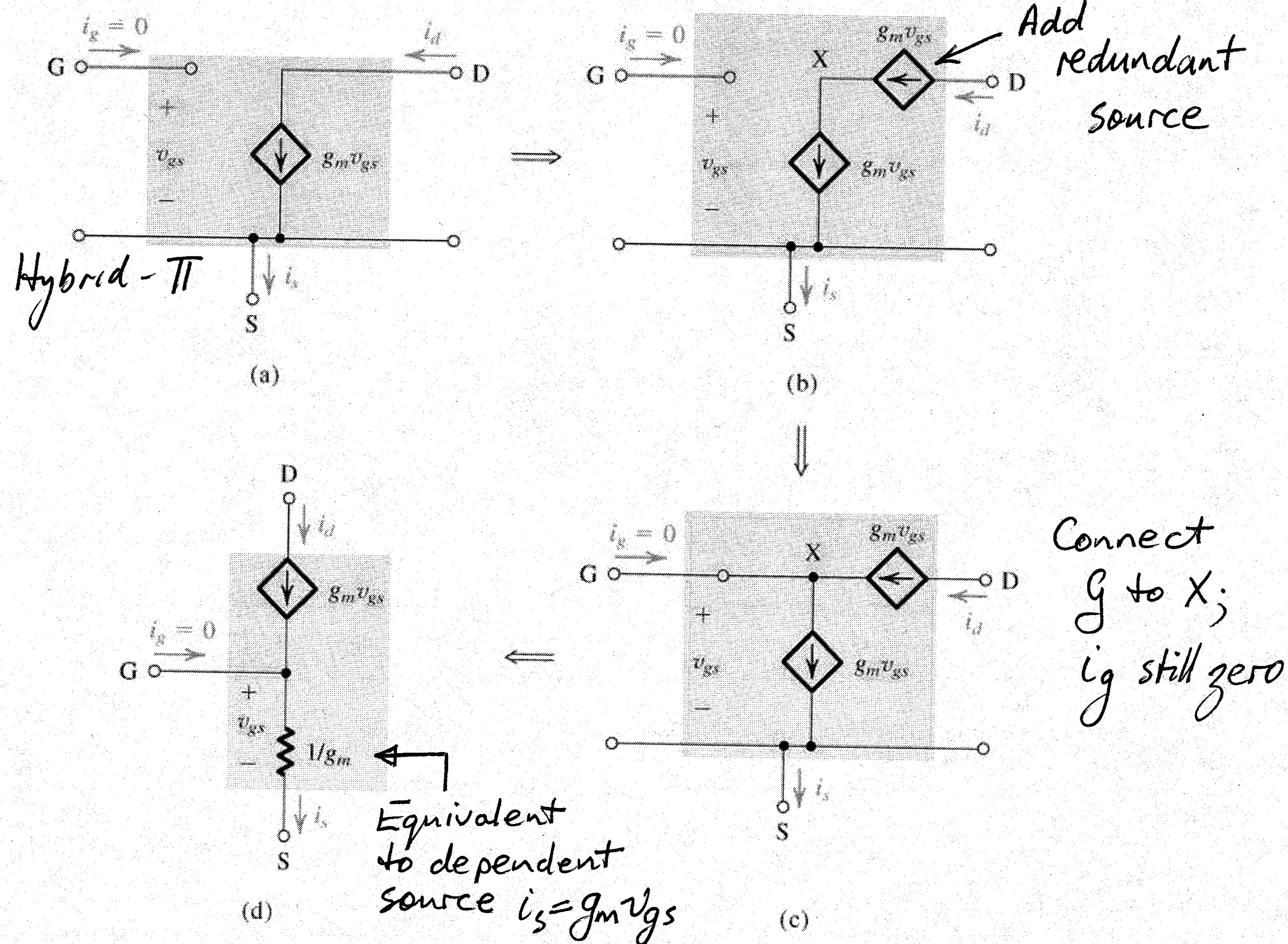


Figure 4.39 Development of the T equivalent-circuit model for the MOSFET. For simplicity, r_o has been omitted but can be added between D and S in the T model of **(d)**.

Channel-length Modulation → r_o

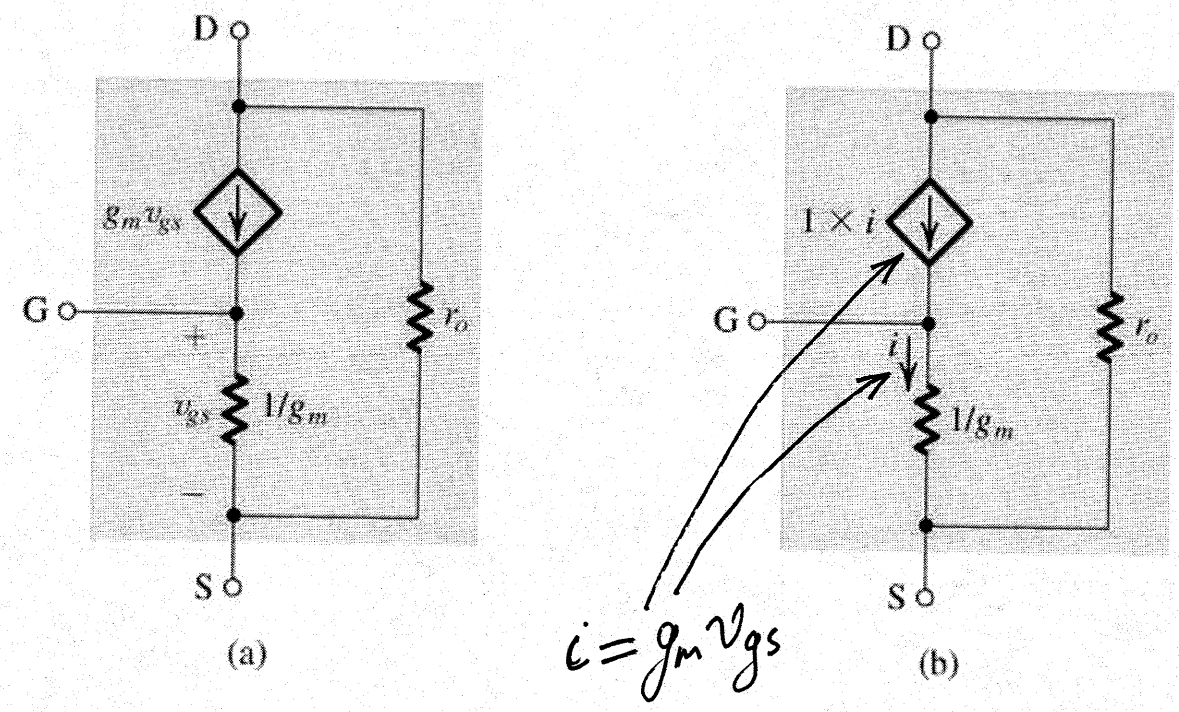


Figure 4.40 **(a)** The T model of the MOSFET augmented with the drain-to-source resistance r_o. **(b)** An alternative representation of the T model.

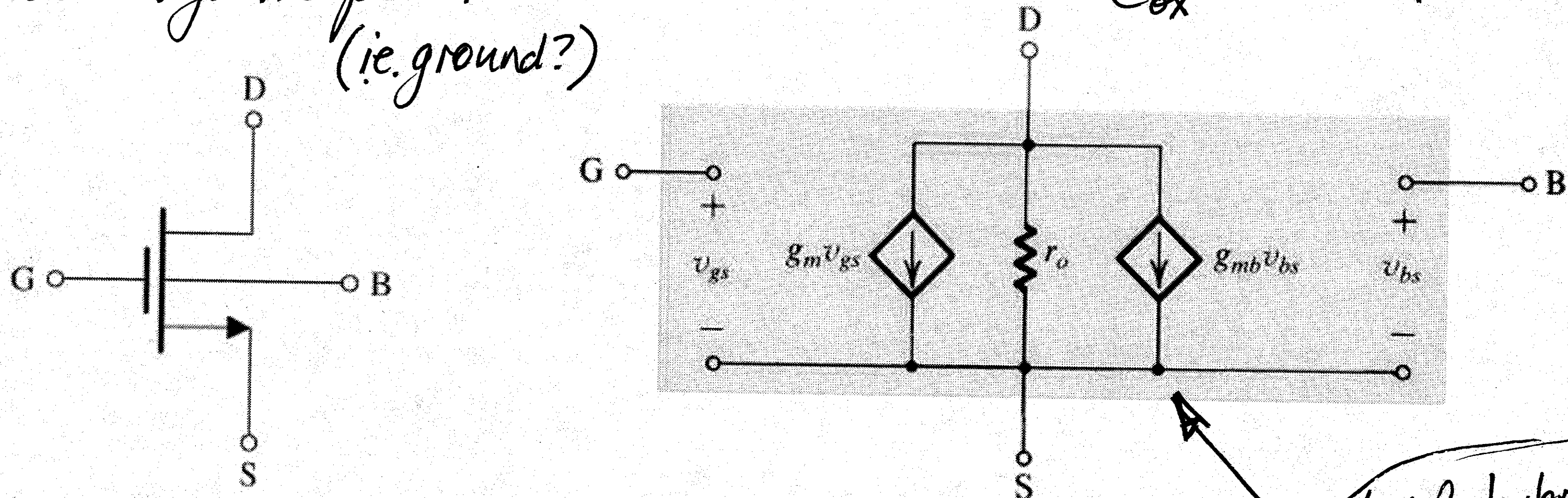
BODY EFFECT

See Section #4.2.5 Eqⁿ 4.33

$$V_t = V_{to} + \gamma\left[\sqrt{2\phi_f + V_{SB}} - \sqrt{2\phi_f}\right]$$

$$\gamma = \frac{\sqrt{2qN_A\varepsilon_s}}{C_{ox}}, \quad 2\phi_f \sim 0.6\text{v typ.}$$

For N-channel,
Connect B (substrate) to most negative point (ie. ground?)



Modify hybrid-π

Often, S connected to ground/most negative point

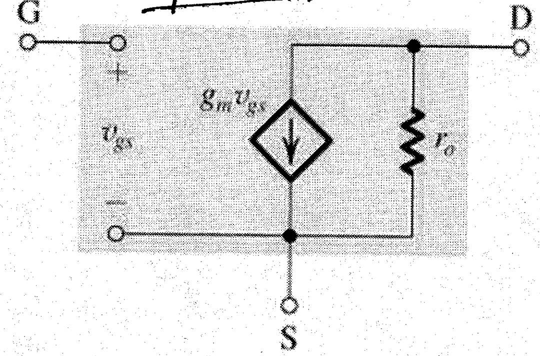
If not, get $v_{bs} \neq 0 \longrightarrow$ "back gate" $\longrightarrow i_{ds_2} = -g_{mb} v_{bs}$

$$g_{mb} = \left.\frac{\partial i_D}{\partial v_{BS}}\right|_{\substack{v_{GS}\ \text{constant} \\ v_{DS}\ \text{constant}}} = \chi g_m, \quad \text{where } \chi = \frac{\partial V_t}{\partial V_{SB}} = \frac{\gamma}{2\sqrt{2\phi_f + V_{SB}}}$$

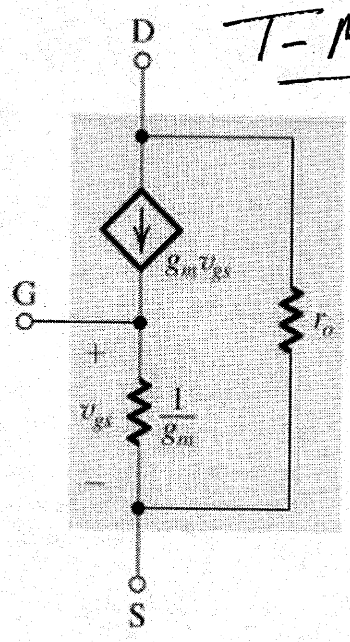
Figure 4.41 Small-signal equivalent-circuit model of a MOSFET in which the source is not connected to the body.

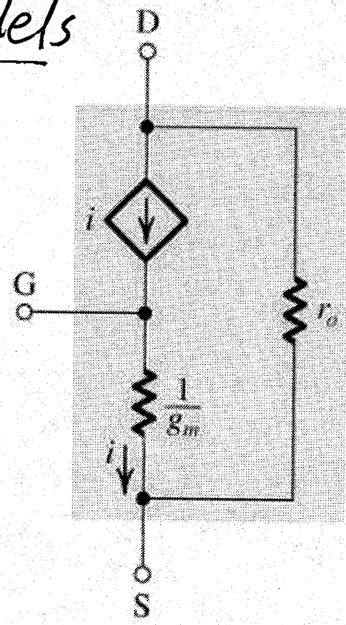
SUMMARY

Hybrid-π



T-Models





NMOS

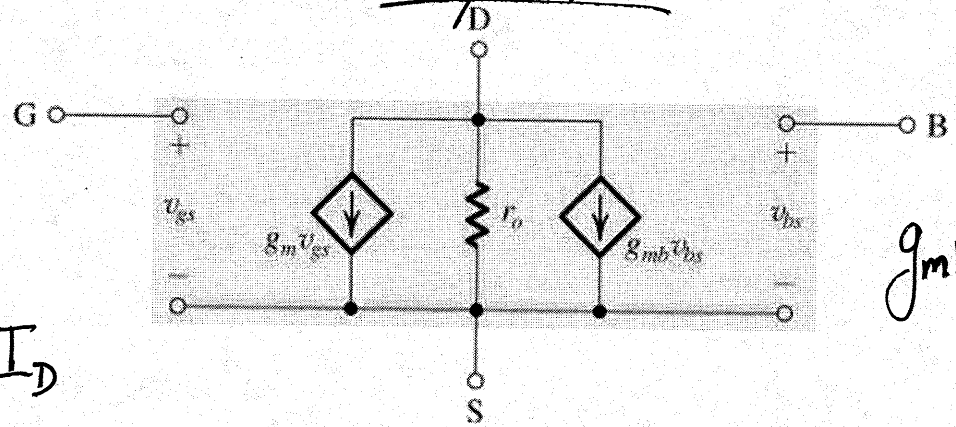
$$g_m = \mu_n C_{ox} \frac{W}{L} V_{OV}$$

$$= \sqrt{2 \mu_n C_{ox} \frac{W}{L} I_D}$$

$$= 2 I_D / V_{OV}$$

$$r_o = V_A / I_D = 1 / \lambda I_D$$

Body Effect



$$g_{mb} = \chi g_m$$

$$= \frac{\gamma}{2\sqrt{2\phi_f + V_{SB}}} g_m$$

Table 4.2

Exercises:

4.23. For the amplifier of Fig 4.34 : $V_{DD} = 5V$, $R_D = 10K\Omega$, $V_t = 1v$, $k_n' = 20\mu A/V^2$, $\frac{W}{L} = 20$, $V_{GS} = 2v$, $\lambda = 0$
(a) Find I_D, V_D (b) Find g_m (c) Find voltage gain (d) For $v_{gs} = 0.2 \sin\omega t$ volts, find v_d assuming the small signal approximation; what are min/max values of v_D? (e) Use eqn 4.57 to determine components of i_D. Using $\sin^2\omega t = \frac{1}{2} - \frac{1}{2}\cos 2\omega t$, show there is a slight shift in I_D. (How much?) and a second harmonic.

4.24 An NMOS transistor has $\mu_n C_{ox} = 60\mu A/V^2$, $W/L = 40$, $V_t = 1V$, $V_A = 15v$. Find g_m, r_o when (a) $V_{GS} = 1.5v$, and (b) $I_D = 0.5mA$

4.25 MOSFET operates at $I_D = 0.1mA$ and needs $g_m = 1mA/V$. If $k_n' = 50\mu A/V^2$ find W/L and V_{ov}.

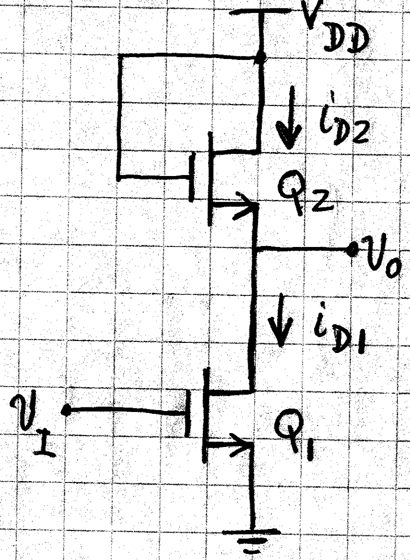
4.26 For process giving $\mu_p \approx 0.4\mu_n$, find W_p/W_n for equal g_m at equal bias. ($L_1 = L_2$)

4.27 NMOS transistor. $2\phi_f = 0.6v$, $\gamma = 0.5V^{1/2}$, $V_{SB} = 4v$. Find $\chi = g_{mb}/g_m$

4.28 PMOS transistor $V_t = -1V$, $k_p' = 60\mu A/V^2$, $W/L = 16\mu m/0.8\mu m$. Find I_D, g_m for $V_{GS} = -1.6v$. Also r_o if λ (at $L = 1\mu m$) $= -0.04 V^{-1}$

4.29 Derive an expression for $g_m r_o$ in terms of V_A, V_{ov}. Evaluate $g_m r_o$ for 0.8µm CMOS process, $V_A' = 12.5v/\mu m$ channel length, with min. channel length and $V_{ov} = 0.2v$

PROBLEM P4.54



CS amplifier with load resistor R_D replaced by Q_2

"Saturated load" or "enhancement load" NMOS

Q_2 in saturation, since $v_{DG} = 0$

$$i_{D1} = i_{D2}$$

For Q_1 in saturation i.e. $V_{DS_1} > V_{GS_1} - V_{t_1}$ & $V_{GS_1} > V_{t_1}$

for $v_o + V_{t_1} > v_I > V_{t_1}$

$$\tfrac{1}{2} k_n' \left(\tfrac{W}{L}\right)_1 (V_{GS_1} - V_{t_1})^2 = \tfrac{1}{2} k_n' \left(\tfrac{W}{L}\right)_2 (V_{GS_2} - V_{t_2})^2 \qquad V_{GS_1} = v_I \ \& \ V_{GS_2} = V_{DD} - v_o$$

$$\therefore (W/L)_1 (v_I - V_{t_1})^2 = (W/L)_2 (V_{DD} - v_o - V_{t_2})^2$$

$$[(W/L)_1/(W/L)_2]^{1/2} (v_I - V_{t_1}) = (V_{DD} - v_o - V_{t_2})$$

$$v_o = V_{DD} - \left[\frac{(W/L)_1}{(W/L)_2}\right]^{1/2} v_I + \left[\frac{(W/L)_1}{(W/L)_2}\right]^{1/2} V_{t_1} - V_{t_2}$$

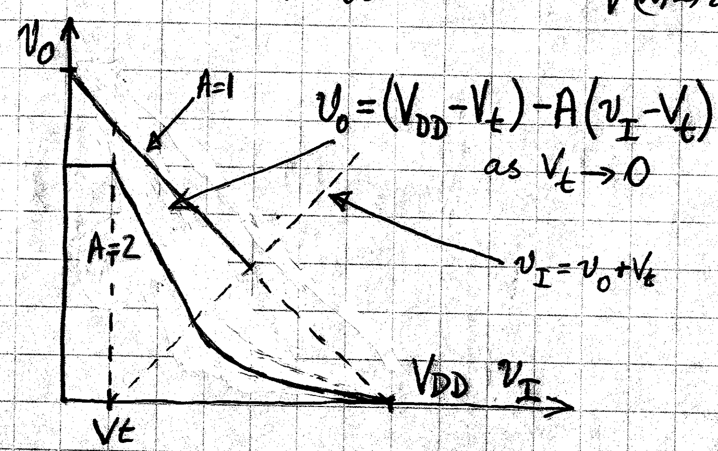
$$= V_{DD} - A v_I + (A-1) V_t \qquad \text{for } V_{t_1} = V_{t_2} = V_t \ \& \ A = \sqrt{\frac{(W/L)_1}{(W/L)_2}}$$

For $v_I < V_t$, $i_{D_{1,2}} = 0$ & $v_o \leq V_{DD}$ (V_{DS2} undefined)

For $v_I > v_o + V_t$, Q in triode $\Rightarrow$

$$2\left(\tfrac{W}{L}\right)_1 \left[(v_I - V_t) v_o - v_o^2/2\right] = \left(\tfrac{W}{L}\right)_2 (V_{DD} - v_o - V_t)^2$$

until $v_I > \dfrac{V_{DD} + AV_t}{1+A}$



Single-Stage MOS Amplifiers (Assume $\lambda = 0$ for simplicity)

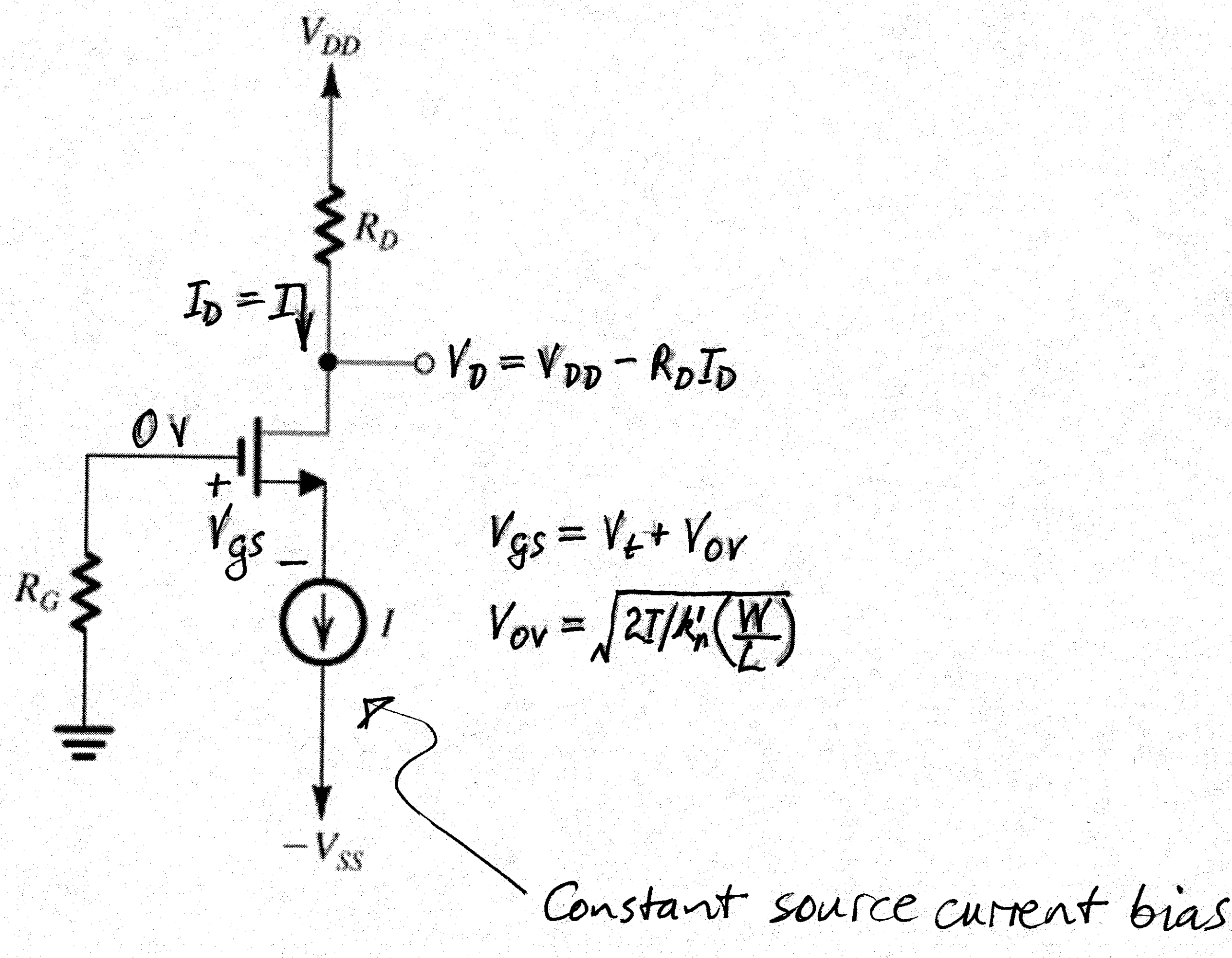


Figure 4.42 Basic structure of the circuit used to realize single-stage discrete-circuit MOS amplifier configurations.

Exercise 4.30

CS Amplifier

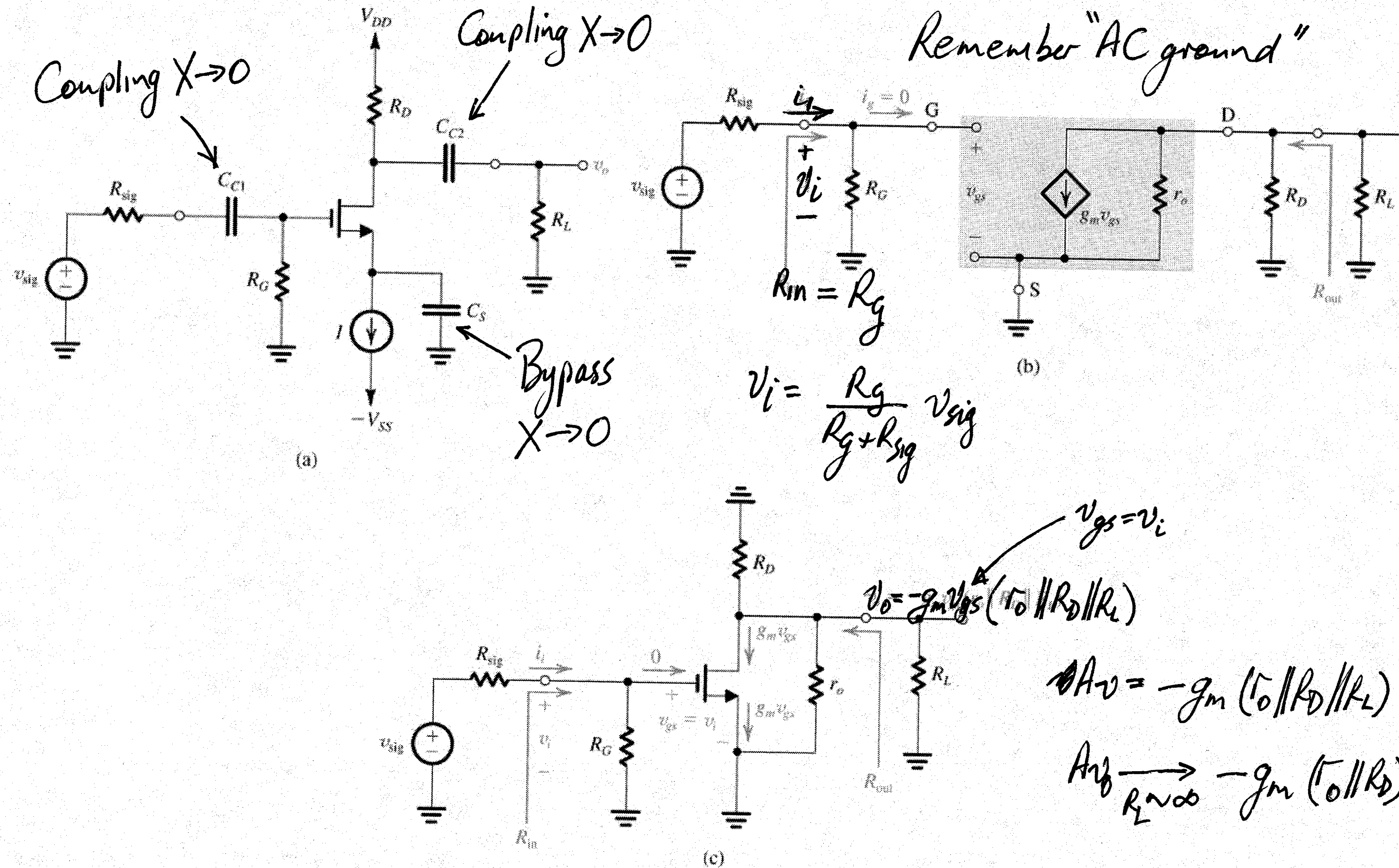
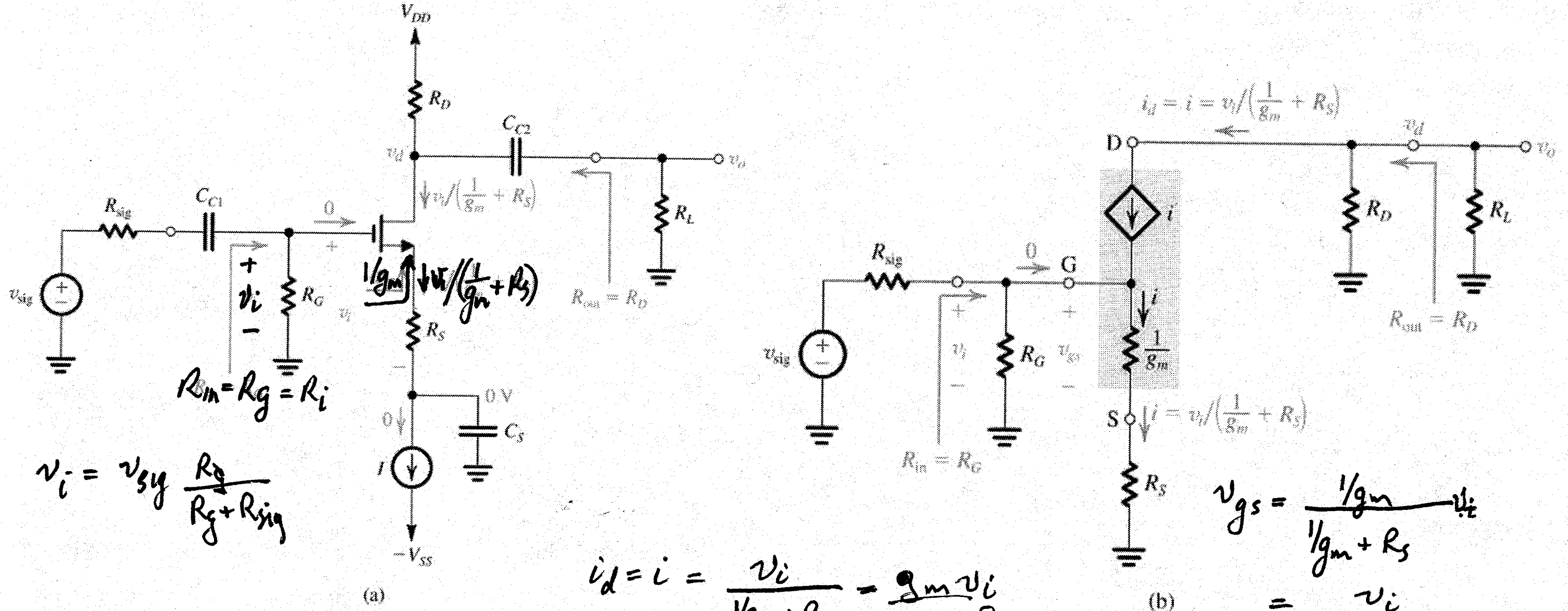


Figure 4.43 **(a)** Common-source amplifier based on the circuit of Fig. 4.42. **(b)** Equivalent circuit of the amplifier for small-signal analysis. **(c)** Small-signal analysis performed directly on the amplifier circuit with the MOSFET model implicitly utilized.

CS Amplifier with Source Resistor R_S
(Neglect r_o → major complication)



$R_{in} = R_G = R_i$

$v_i = v_{sig} \dfrac{R_G}{R_G + R_{sig}}$

$v_{gs} = \dfrac{1/g_m}{1/g_m + R_S} v_i = \dfrac{v_i}{1 + g_m R_S}$

$i_d = i = \dfrac{v_i}{1/g_m + R_S} = \dfrac{g_m v_i}{1 + g_m R_S}$

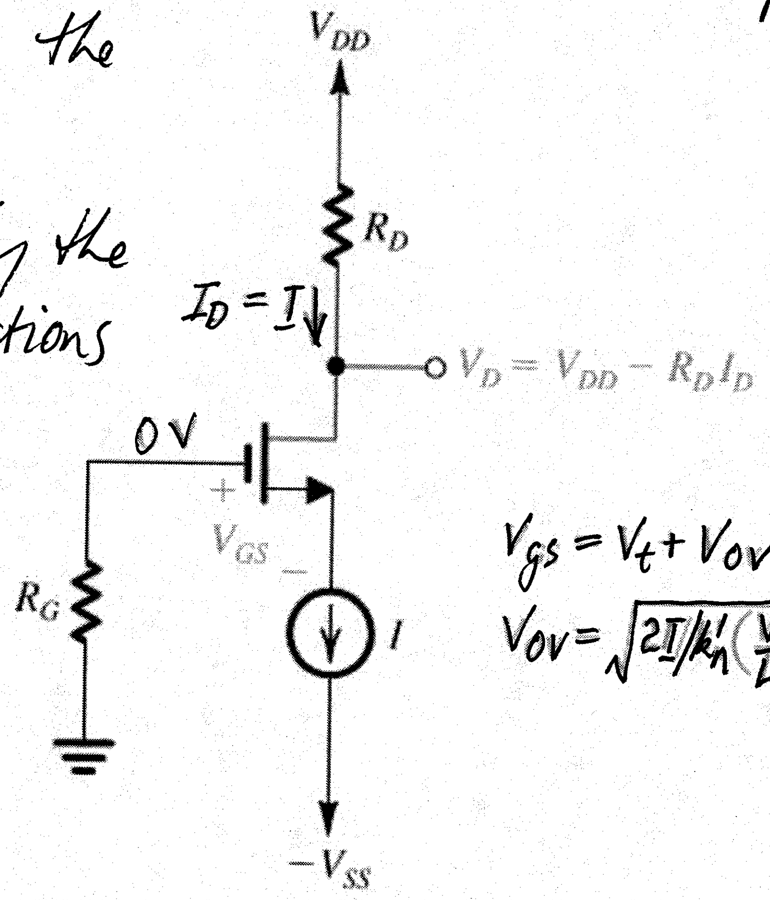
$v_o = -i_d (R_L \| R_D) = -\dfrac{g_m}{1 + g_m R_S} (R_L \| R_D) v_i$

$\therefore A_v = -\dfrac{g_m}{1 + g_m R_S} (R_D \| R_L) \longrightarrow A_{vo} \xrightarrow{R_L = \infty} \dfrac{-g_m R_D}{1 + g_m R_S}$

Figure 4.44 **(a)** Common-source amplifier with a resistance R_S in the source lead. **(b)** Small-signal equivalent circuit with r_o neglected.

$G_v = -\dfrac{R_G}{R_G + R_{sig}} \cdot \dfrac{g_m}{1 + g_m R_S} (R_D \| R_L)$

The Common Gate & Common Drain amplifiers use the same bias circuit as the Common Source amplifier. Only the AC signal connections change.



Assume saturation

$V_{gs} = V_t + V_{ov}$

$V_{ov} = \sqrt{2I / k_n' \left(\frac{W}{L}\right)}$

Figure 4.42 Basic structure of the circuit used to realize single-stage discrete-circuit MOS amplifier configurations.

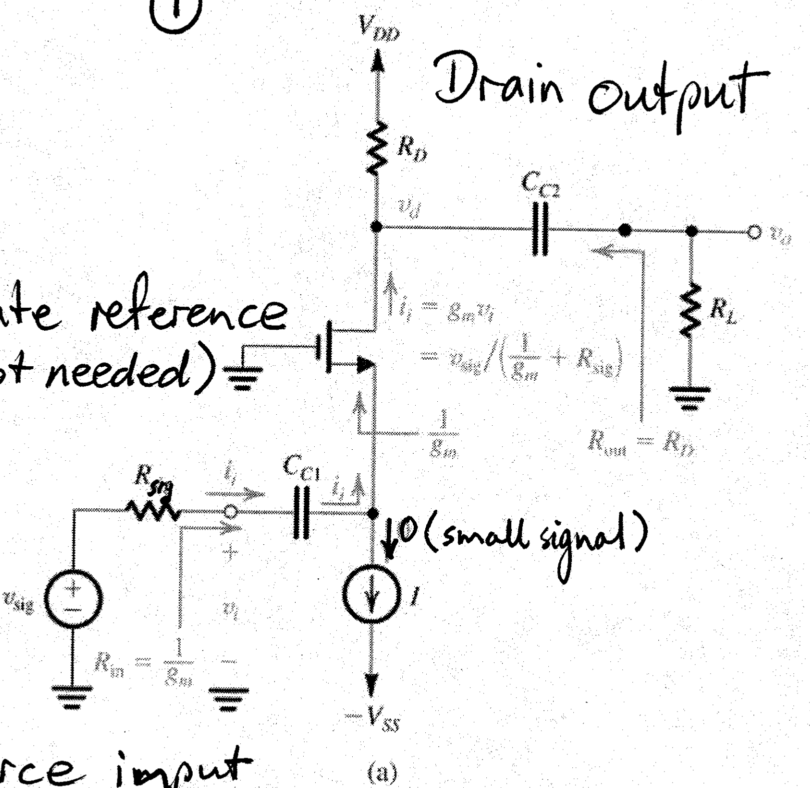
Fig 4.42 from last lecture

Common Gate (CG) Amplifier

① Drain output

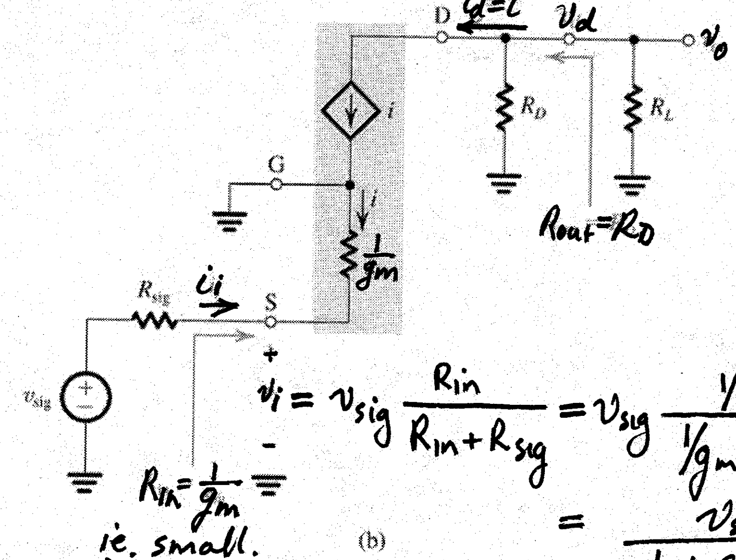
Gate reference (R_g not needed)

Source input



Note: r_o excluded; would connect input to output — complications!

② T-model circuit



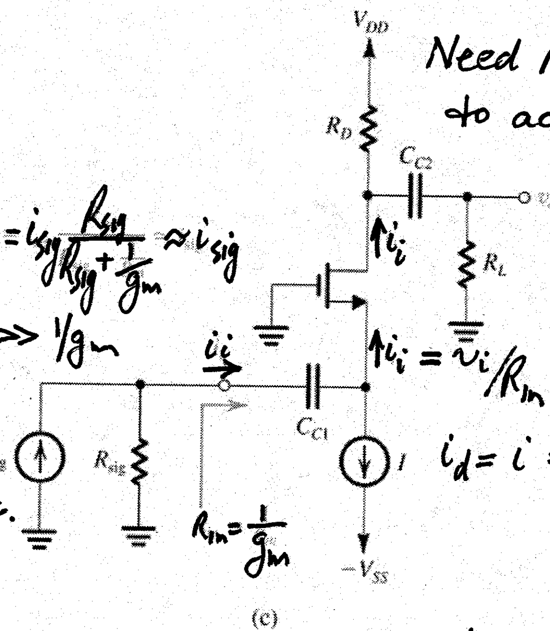
$$v_i = v_{sig}\frac{R_{in}}{R_{in}+R_{sig}} = v_{sig}\frac{1/g_m}{1/g_m + R_{sig}} = \frac{v_{sig}}{1+g_m R_{sig}}$$

Need $R_{sig} \ll 1/g_m$ (small) to act as voltage source.

②

$$i_i = i_{sig}\frac{R_{sig}}{R_{sig}+\frac{1}{g_m}} \approx i_{sig}$$

if $R_{sig} \gg 1/g_m$ i.e. current source.



$i_i = v_i/R_{in} = g_m v_i$

$i_d = i = -i_i = -g_m v_i$

Figure 4.45 **(a)** A common-gate amplifier based on the circuit of Fig. 4.42. **(b)** A small-signal equivalent circuit of the amplifier in (a). **(c)** The common-gate amplifier fed with a current-signal input.

$$A_V = \frac{v_o}{v_i} = -i_d(R_L \| R_D)/v_i = +g_m\frac{v_i}{v_i}(R_L \| R_D)$$

$\therefore A_{vo} = +g_m R_D$.

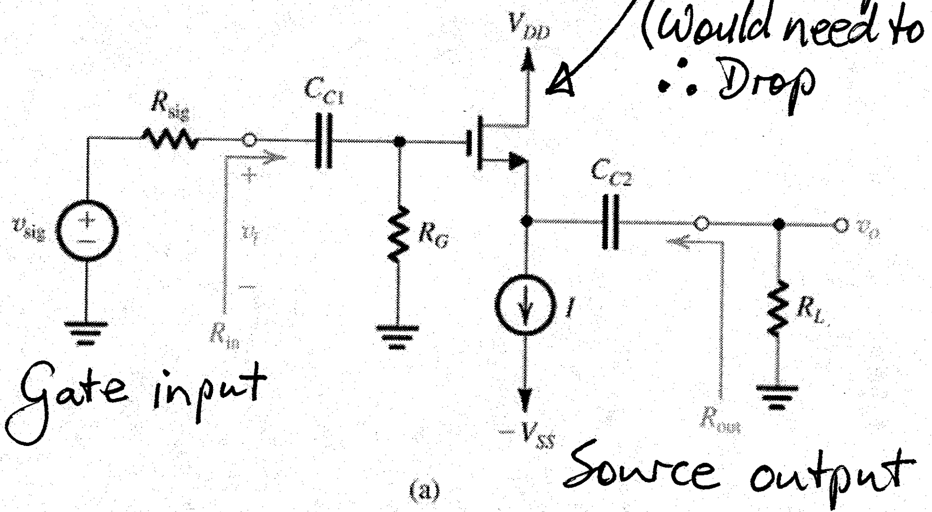
$$G_v = \frac{v_o}{v_i}\frac{v_i}{v_{sig}} = \frac{R_{in}}{R_{in}+R_{sig}}\cdot g_m(R_D \| R_L) = \frac{g_m}{1+g_m R_{sig}}(R_D \| R_L)$$

$R_{in} = 1/g_m$ relatively small $\therefore$ current input → "unity gain current amp."

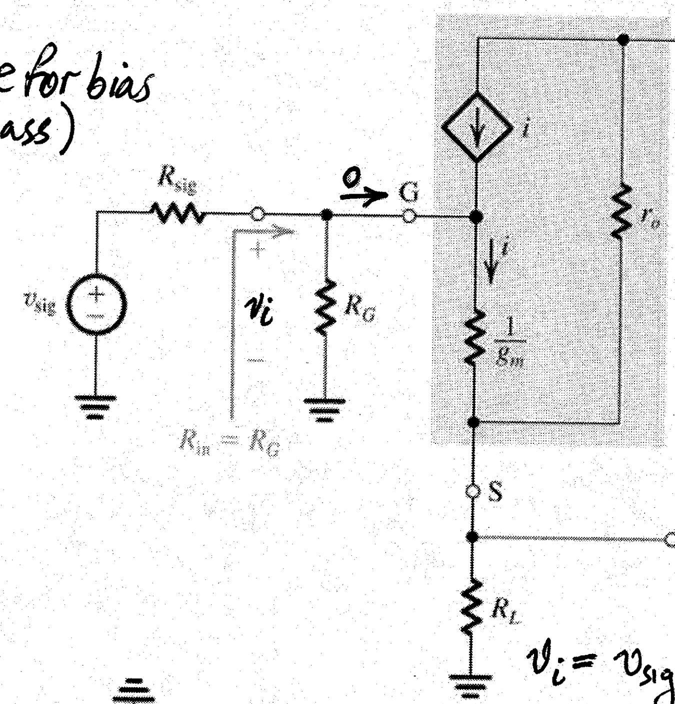
Common Drain (CD) Amplifier

Drain is reference

R_D has no purpose for bias (Would need to bypass) ∴ Drop



T- model circuit



Can include r_o — note: r_o from output terminal to ac ground.

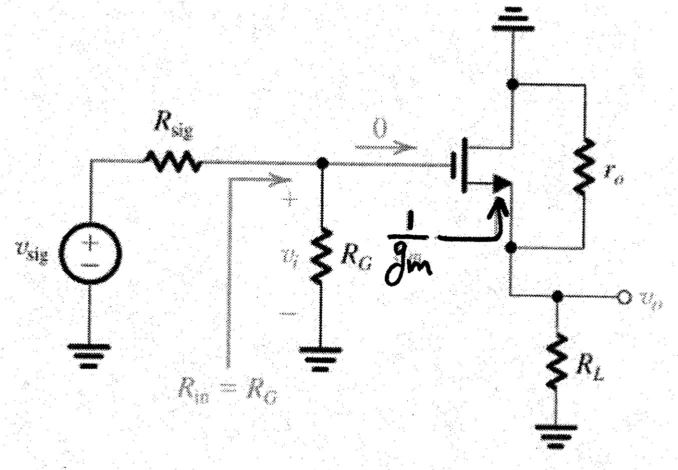
$$v_i = v_{sig} \frac{R_G}{R_G + R_{sig}}$$

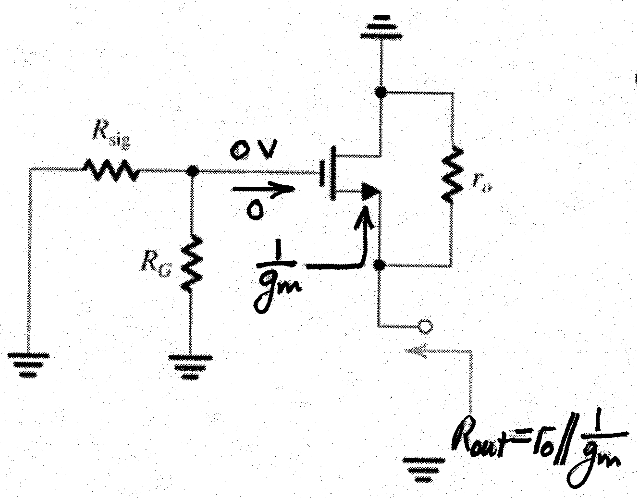
$$\approx v_{sig} \text{ if } R_G \gg R_{sig}$$

$$\frac{v_o}{v_i} = \frac{(R_L \| r_o)}{1/g_m + (R_L \| r_o)}$$

$$A_v = \frac{g_m (R_L \| r_o)}{1 + g_m (R_L \| r_o)}$$

$$\approx 1$$





$$A_{vo} = \frac{g_m r_o}{1 + g_m r_o} \approx 1$$

Figure 4.46 **(a)** A common-drain or source-follower amplifier. **(b)** Small-signal equivalent-circuit model. **(c)** Small-signal analysis performed directly on the circuit. **(d)** Circuit for determining the output resistance R_{out} of the source follower.

$$G_v = \frac{R_G}{R_G + R_{sig}} \cdot \frac{g_m (R_L \| r_o)}{1 + g_m (R_L \| r_o)} \approx 1$$

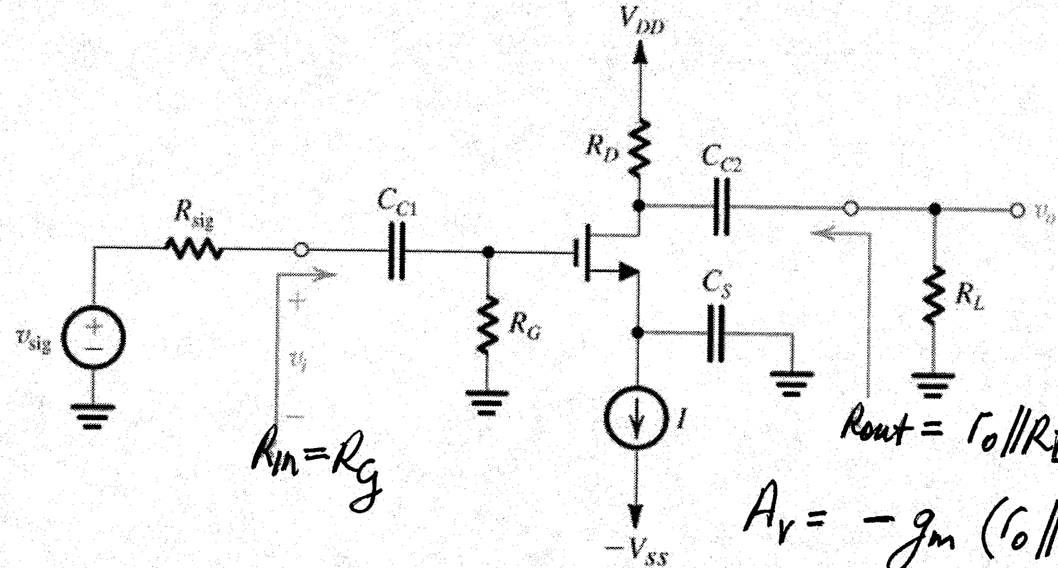
$$R_{out} = r_o \| 1/g_m \approx 1/g_m$$

Unity gain voltage amplifier ⟶ Source follower

SUMMARY

CS

Voltage amplifier



$R_{in} = R_g$

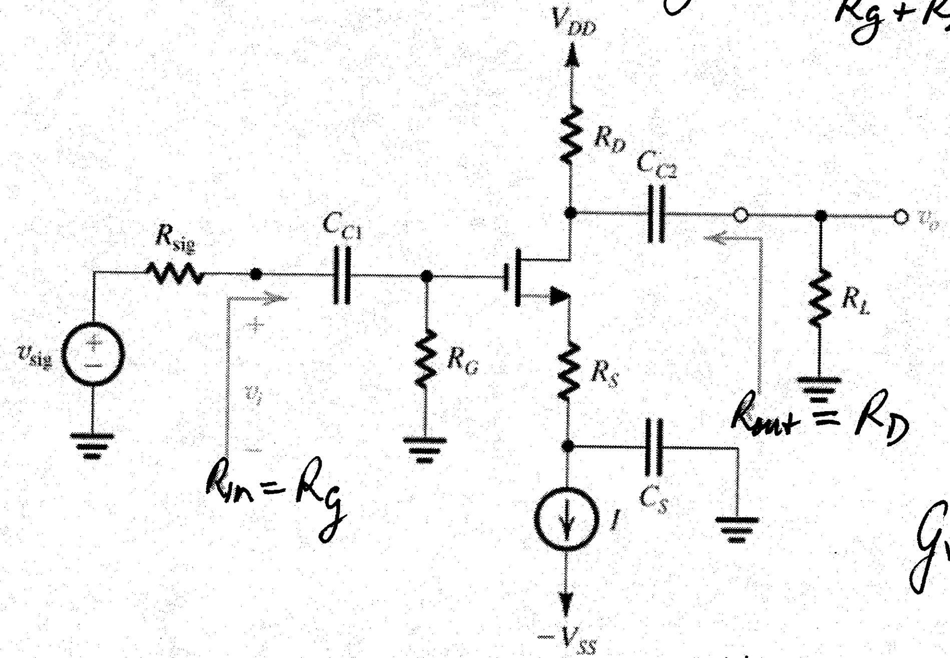
$R_{out} = r_o \| R_D$

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

$G_v = -\frac{R_g}{R_g + R_{sig}} g_m (r_o \| R_D \| R_L)$

CS with R_S

Reduced gain voltage amplifier



$R_{in} = R_g$

$R_{out} \cong R_D$

Note: r_o neglected here.

$A_v = \frac{-g_m (R_L \| R_D)}{1 + g_m R_S}$

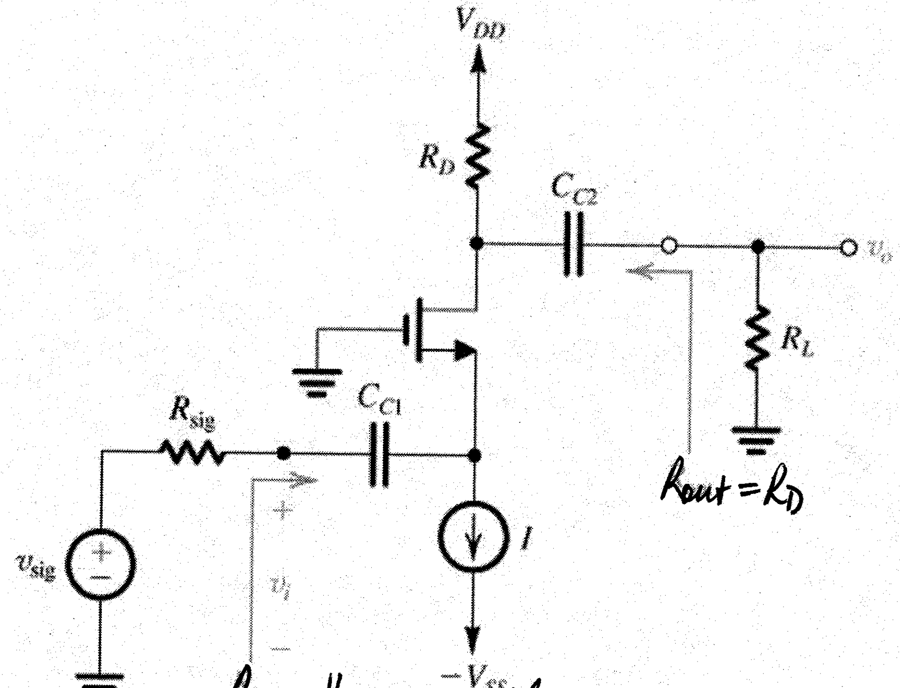
$G_v = \frac{R_g}{R_g + R_{sig}} \frac{g_m (R_D \| R_L)}{1 + g_m R_S}$

Note: $v_{gs} = \frac{v_i}{1 + g_m R_S}$

Table 4.4

CG

Note: Neglecting r_o



$R_{out} = R_D$

$R_{in} = 1/g_m$ small

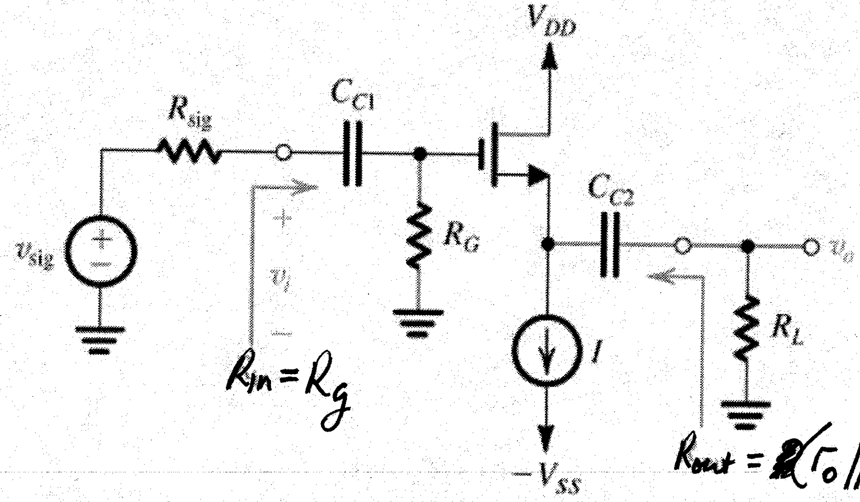
$$A_v = g_m (R_D \| R_L)$$

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

Table 4.4 *(Continued)*

Current follower → Cascode circuit

CD



$R_{in} = R_G$

$R_{out} = (r_o \| 1/g_m)$

$$A_v = \frac{g_m (r_o \| R_L)}{1 + g_m (r_o \| R_L)}$$

$$G_v = \frac{R_G}{R_G + R_{sig}} \frac{r_o \| R_L}{(r_o \| R_L) + 1/g_m}$$

Voltage follower

Assignment #5

Problems:

D4.36

D4.37

D4.56

4.74

4.75

Generalized Amplifiers

① Basic amplifier: R_i R_o A_{vo} A_{is} G_m

② Generalized → R_{in} R_{out} A_v A_i G_{vo} G_v

May depend on R_{sig}, R_L $R_i = R_{in}\Big]_{R_L=\infty}$ $R_o = R_{out}\Big]_{R_{sig}=0}$

③ Unilateral amplifiers (no internal feedback) $R_i = R_{in}$ $R_o = R_{out}$

Non-unilateral amplifiers (with feedback) $R_{in} \neq R_i$ $R_{out} \neq R_o$ in general

④ $G_v = v_o/v_{sig}$ $G_{vo} = \frac{v_o}{v_{sig}}\Big]_{R_L=\infty} = G_v\Big]_{R_L=\infty}$

Overall voltage gain Open circuit overall voltage gain

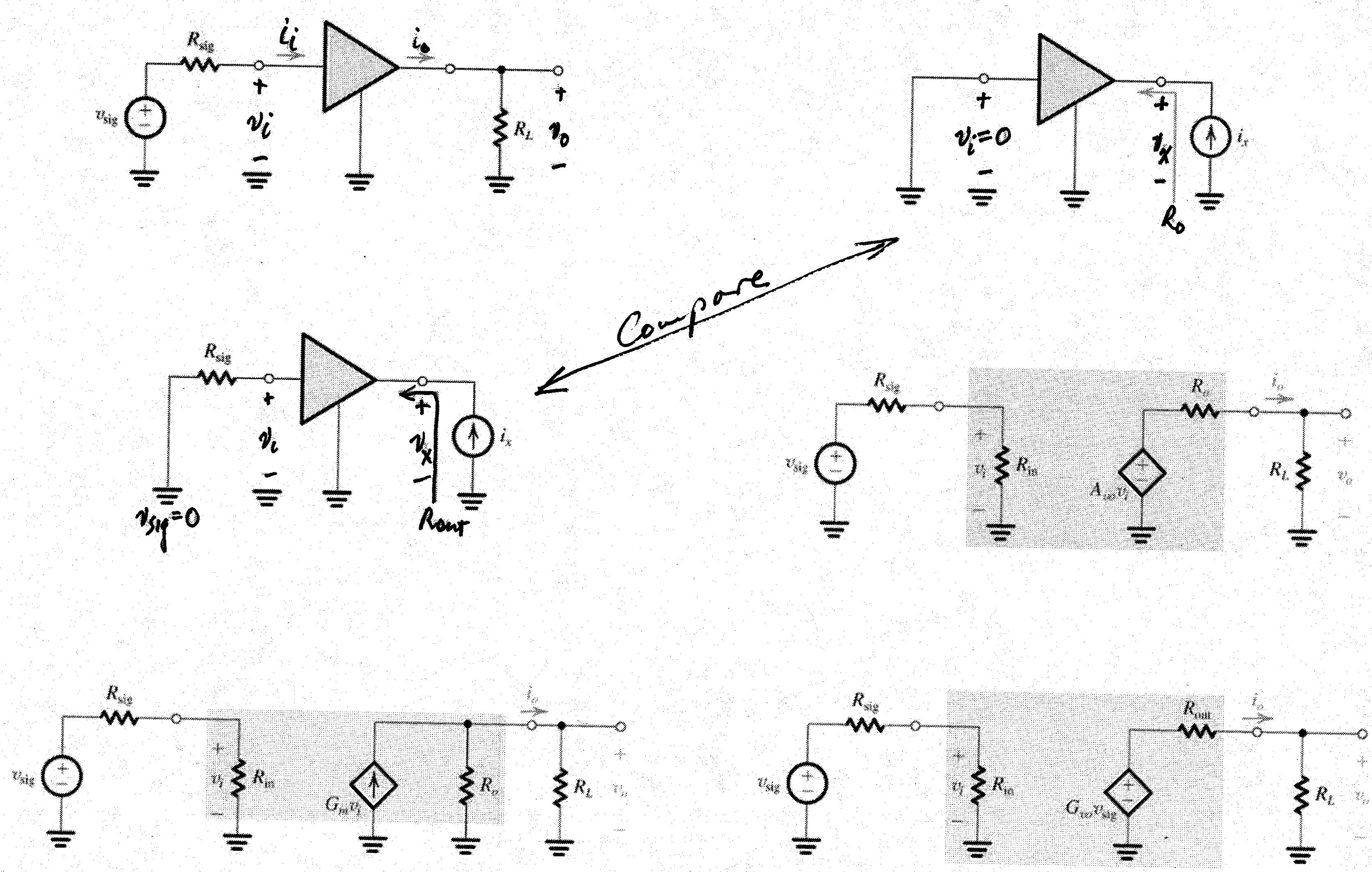
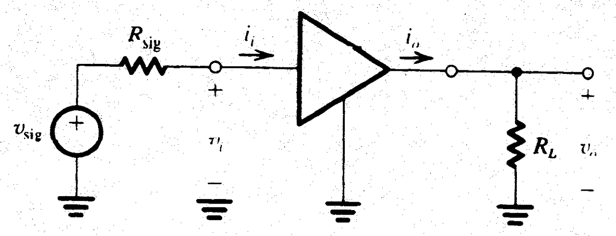


Table 4.3 Amplifier characteristics

Circuit



Definitions

- Input resistance with no load:

$$R_i \equiv \left.\frac{v_i}{i_i}\right|_{R_L=\infty}$$

- Input resistance:

$$R_{in} \equiv \frac{v_i}{i_i}$$

- Open-circuit voltage gain:

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

- Voltage gain:

$$A_v \equiv \frac{v_o}{v_i}$$

- Short-circuit current gain:

$$A_{is} \equiv \left.\frac{i_o}{i_i}\right|_{R_L=0}$$

- Current gain:

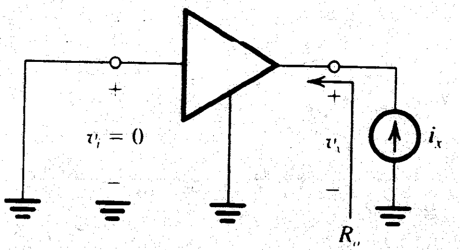
$$A_i \equiv \frac{i_o}{i_i}$$

- Short-circuit transconductance:

$$G_m \equiv \left.\frac{i_o}{v_i}\right|_{R_L=0}$$

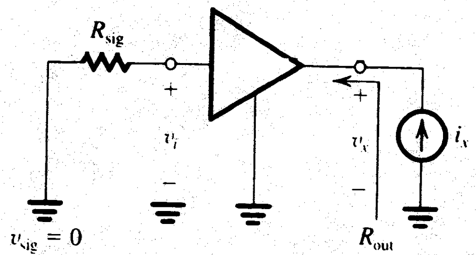
- Output resistance of amplifier proper:

$$R_o \equiv \left.\frac{v_x}{i_x}\right|_{v_i=0}$$



- Output resistance:

$$R_{out} \equiv \left.\frac{v_x}{i_x}\right|_{v_{sig}=0}$$



- Open-circuit overall voltage gain:

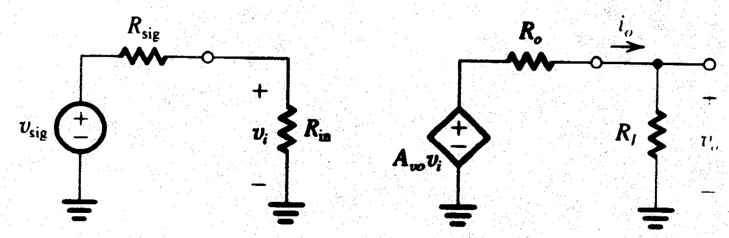
$$G_{vo} \equiv \left.\frac{v_o}{v_{sig}}\right|_{R_L=\infty}$$

- Overall voltage gain:

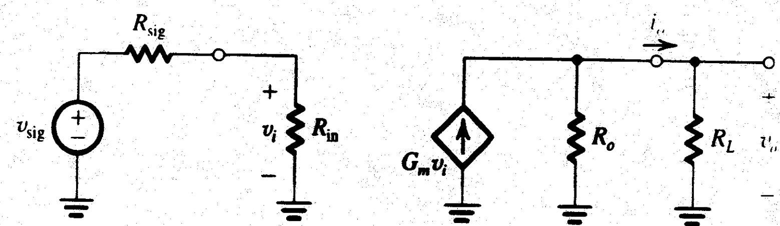
$$G_v \equiv \frac{v_o}{v_{sig}}$$

Equivalent Circuits

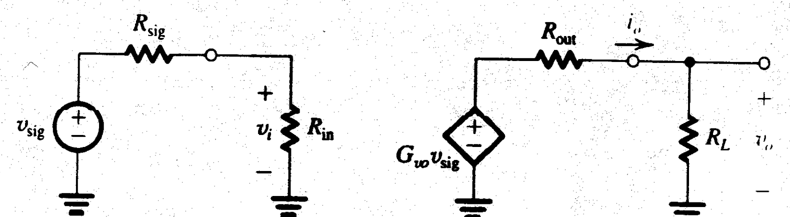
- A:



- B:



- C:



Relationships

- $\frac{v_i}{v_{sig}} = \frac{R_{in}}{R_{in} + R_{sig}}$
- $A_v = A_{vo}\frac{R_L}{R_L + R_o}$
- $A_{vo} = G_m R_o$
- $G_v = \frac{R_{in}}{R_{in} + R_{sig}} A_{vo}\,\overline{R}$
- $G_{vo} = \frac{R_i}{R_i + R_{sig}} A_{vo}$
- $G_v = G_{vo}\frac{R_L}{R_L + R_{out}}$

Exercise 4.31 (include Example 4.11)

Exercise 4.32

Exercise 4.33

Ex 4.30 See Fig 4.42. $V_{DD} = V_{SS} = 10v$, $I = 0.5mA$, $R_G = 4.7M\Omega$, $R_D = 15K\Omega$, $V_t = 1.5v$
$k_n' W/L = 1mA/V^2$, Find V_{ov}, V_{GS}, V_G, V_S, V_D, & g_m, r_o for $V_A = 75v$
Max signal swing at drain to remain saturated?

4.31 (a) For Example 4.11, if R_{sig} is doubled, Find R_{in}, G_v, R_{out}
(b) Repeat for R_{sig} same, R_L doubled
(c) " " both R_L & R_{sig} doubled

4.32 CS amplifier, based on Fig E4.30: Find R_{in}, A_{vo}, R_{out} with & without r_o.
Calculate G_v (incl r_o) for $R_{sig} = 100K\Omega$, $R_L = 15K\Omega$. Output for $v_{sig} = 0.4v$ p-p.

4.33 Ex 4.32 (cont'd) $.4v \xrightarrow{p-p} 2.8v$ Incr input → 1.2v p-p. Find R_s
for same ~~at~~ output.

Example 4.11 → Ex. 4.31

Example 4.11

	v_i	v_o
$R_L = \infty$	9mV	90mV
$R_L = 10K$	8mV	70mV

No R_L : $A_{vo} = 90/9 = 10$

$G_{vo} = 90/10 = 9 = \frac{R_i}{R_i + R_{sig}} A_{vo} \rightarrow 9 = 10 \frac{R_i}{R_i + 100K}$

$\therefore R_i = 900K$

$R_L = 10K$: $A_v = 70/8 = 8.75$

$G_v = 70/10 = 7$

$A_v = \frac{R_L}{R_L + R_o} A_{vo} \rightarrow \frac{70}{8} = \frac{10}{10 + R_o} 10$

$\therefore R_o = \frac{800 - 700}{70} K$

$= 1.43K$

Similarly $G_v = G_{vo} \frac{R_L}{R_L + R_{out}} \rightarrow 7 = 9 \frac{10}{10 + R_{out}}$ $\therefore R_{out} = \frac{90 - 70}{7} = 2.86K$

$\frac{v_i}{v_{sig}} = \frac{R_{in}}{R_{in} + R_{sig}} \rightarrow \frac{8}{10} = \frac{R_{in}}{R_{in} + 100}$ $\therefore R_{in} = \frac{800}{2} = 400K$

$G_m = A_{vo}/R_o = 10/1.43K = 7mA/V$

$A_i = \frac{v_o/R_L}{v_i/R_{in}} = \frac{v_o}{v_i} \frac{R_{in}}{R_L} = A_v \frac{R_{in}}{R_L} = \frac{70}{8} \frac{400}{10} = \frac{28}{8} 100 = 350$

$A_{is} =$

Ex 4.31 Want R_{in}, G_v, R_{out} for

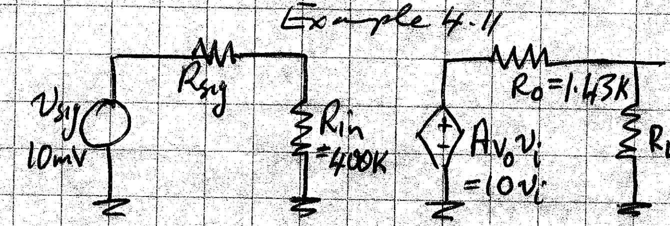
	R_L	R_{sig}	
	10K	100K	← Example 4.11
(a)	10K	200K	
(b)	20K	100K	
(c)	20K	200K.	

$R_{in} \Rightarrow \frac{v_i}{v_{sig}} = \frac{R_{in}}{R_{in}+R_{sig}}$

$G_v \Rightarrow \left.\frac{v_o}{v_i}\right)_{R_L}$

$R_{out} \Rightarrow G_v = G_{vo}\frac{R_L}{R_L+R_{out}}$

Example 4.11



(a) R_{in} indep of R_{sig} → 400K.

$G_v = \frac{R_{in}}{R_{in}+R_{sig}} A_v = \frac{400}{400+200} 8.75 = 5.83$ (8.75: E4.11 unchanged, indep of R_{sig})

$G_{vo} = \frac{R_i}{R_i+R_{sig}} A_{vo} = \frac{900}{900+200} 10 = 8.18$

$G_v = G_{vo}\frac{R_L}{R_L+R_{out}} \longrightarrow 5.83 = 8.18\frac{10}{10+R_{out}} \rightarrow R_{out} = \frac{81.8-58.3}{5.83} = 4.03K$

(b) R_{sig} same → R_o, R_{out} as for E4.11 $R_{out} = 2.86K$

G_{vo} is for $R_L=\infty$ ∴ Same → $G_{vo} = 9$

∴ $G_v = G_{vo}\frac{R_L}{R_L+R_{out}} = 9\frac{20}{20+2.86} = 7.87$

& $G_v = \frac{R_{in}}{R_{in}+R_{sig}} A_{vo}\frac{R_L}{R_L+R_o} \rightarrow 7.87 = \frac{R_{in}}{R_{in}+100}\cdot 10\cdot\frac{20}{20+1.43} \Rightarrow R_{in} = 538K$

(c) R_{in} as for (b) → 538K

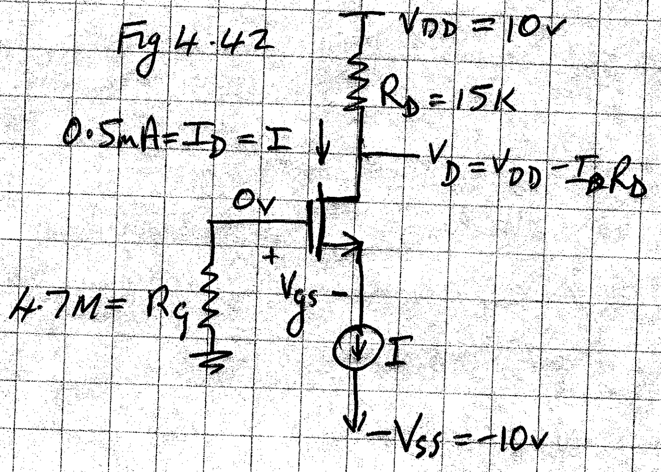
R_{out} indep of R_L ∴ Same as (a) $R_{out} = 4.03K\Omega$

$G_v = \frac{R_{in}}{R_{in}+R_{sig}} A_{vo}\frac{R_L}{R_L+R_o} = \frac{538}{538+100} 10 \frac{20}{20+1.43} = 6.8$ (1.43: fm E4.11)

Ex 4.30

$V_t = 1.5v$

$k_n' \frac{W}{L} = 1mA/V^2$



$V_{ov} = V_{gs} - V_t$

$I_D = \frac{1}{2} k_n' \frac{W}{L} (V_{ov})^2$

$\therefore V_{ov} = \left(\frac{2 \times 0.5mA}{1mA} \right)^{1/2} = 1v$

$\therefore V_{gs} = V_{ov} + V_t$
$= 2.5v$

$V_g = 0v$

$\therefore V_s = -2.5v$

$V_D = 10 - 15\times10^3 \times 0.5\times10^{-3} = 2.5v$

$g_m = 2I_D/V_{ov} = 1mA/1v = 1mA/V$

$r_o = V_A/I_D = 75v/0.5mA = 150K$

Ex 4.31 (incl Example 4.11)

Ex 4.32 For Ex 4.30 figure & values. $g_m = 1mA/V$ $r_o = 150K$

$R_{in} = R_g = 4.7M\Omega$ (with or without r_o)

$A_{vo}\big|_{r_o=\infty} = -g_m R_D = -10^{-3} \times 15\times10^3 = -15$

$A_{vo}\big|_{r_o=150K} = -g_m (R_D \| r_o) = -10^{-3} \frac{15\times150}{165} 10^3 = -13.64$

$R_{OUT})_{r_o=\infty} = R_D = 15K$

$R_{OUT})_{r_o=150K} = R_D \| r_o = \frac{15\times150}{165} K = 13.64K\Omega$

$G_v = \frac{R_{in}}{R_{in}+R_{sig}} \cdot A_{vo} \cdot \frac{R_L}{R_L+R_{out}} \xrightarrow{\text{incl } r_o} \frac{4.7}{4.7+0.1} \; -13.64 \; \frac{15}{15+13.64}$

(R_{sig} ↑ 0.1M)

$= -6.995$

$\therefore$ for $v_{sig} = 0.4v$ p-p $\therefore v_o \approx 2.8v$ p-p

Bias $V_D = 2.5v$ $\therefore$ $v_D \rightarrow 1.1 \text{ to } 3.9v$

$v_D)_{min} = 1.1v > V_g - V_t = -1.5v.$

$v_D)_{max} < V_{DD}$

4.33 Incr v_i 3x R_s for same output?

$1 + g_m R_s = 3$ $\therefore R_s = 2/g_m = 2K$. (2.15K in text incorrect)

Exercise 4.34

Exercise 4.35

Ex 4.34/35 Amplifiers designed with circuit of Fig 4.42 (bias) analyzed in Fig E4.30. Note $g_m = 1mA/volt$.

4.34 CG Amplifier: $R_D = 15K\Omega$. $R_L = 15K\Omega$ ($R_{sig} = 50\Omega$)

Find R_{in}, R_{out}, A_{vo}, A_v, G_v & overall voltage gain for $R_{sig} \Rightarrow 1K\Omega, 10K\Omega, 100K\Omega$

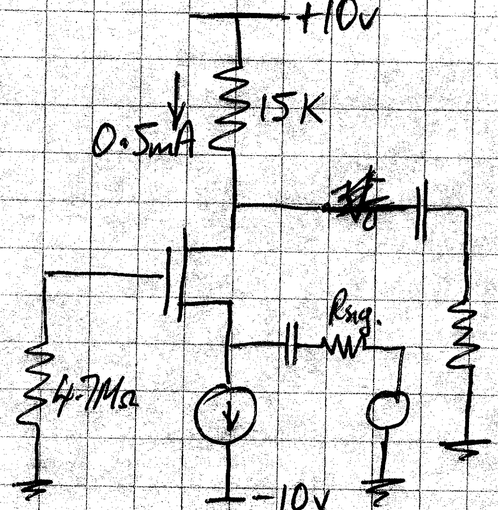
4.35 CD (source follower) Amplifier: $r_o = 150K\Omega$ ($R_{sig} = 1M\Omega$) $R_L = 15K\Omega$

Find R_{in}, A_{vo}, A_v, R_{out} with and without r_o

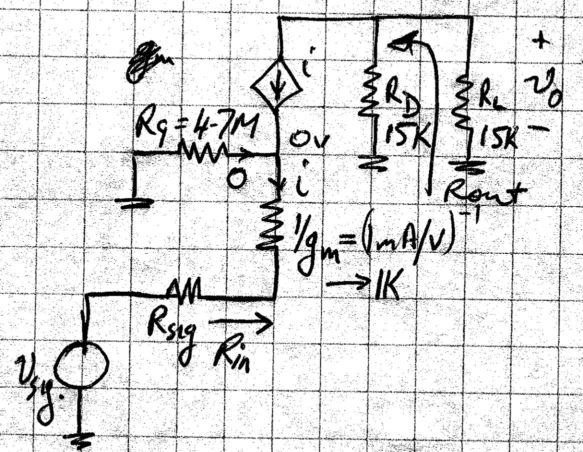
Find G_v with r_o

Ex 4.34

Could drop →



⟹



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

$R_{OUT} = R_D = 15K$

$A_{vo} = g_m R_D = 10^{-3} \times 15 \times 10^3 = 15$

$A_v = g_m R_D \| R_L = 10^{-3} \times 7.5 \times 10^3 = 7.5$

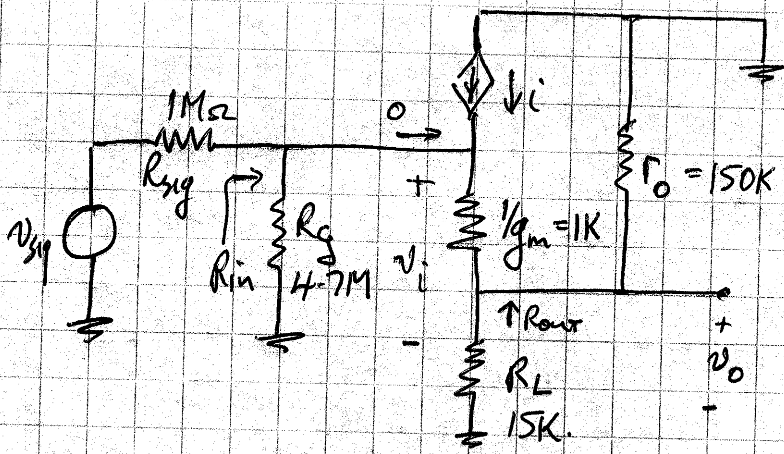
$G_v = \dfrac{R_{in}}{R_{in} + R_{sig}} A_v = \dfrac{1K}{1K + .05K} 7.5 = \dfrac{1}{1.05} 7.5 = 7.14$

$R_{sig} = 1K \qquad G_v = \dfrac{1}{1+1} 7.5 = 3.75$

$10K \qquad \dfrac{1}{11} 7.5 = .68$

$100K \qquad \dfrac{1}{101} 7.5 = .07$

Ex 4.35



$R_{in} = R_g = 4.7M\Omega$ indep of r_o.

No R_L → $A_{vo} = \frac{r_o}{r_o + 1/g_m} = \frac{150}{151} = .993 \longrightarrow 1$ for $r_o \to \infty$

(A_{vo} ← v_o/v_i)

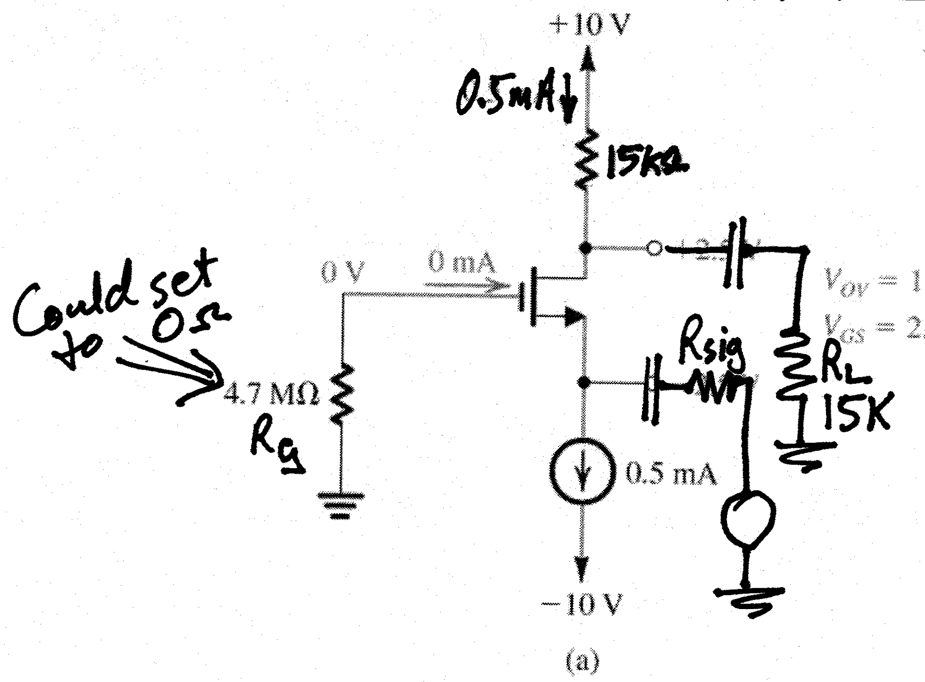
$A_v = \frac{R_L \| r_o}{R_L \| r_o + 1/g_m} = \frac{15\|150}{15\|150 + 1} = .932 \longrightarrow .938$ for $r_o \to \infty$

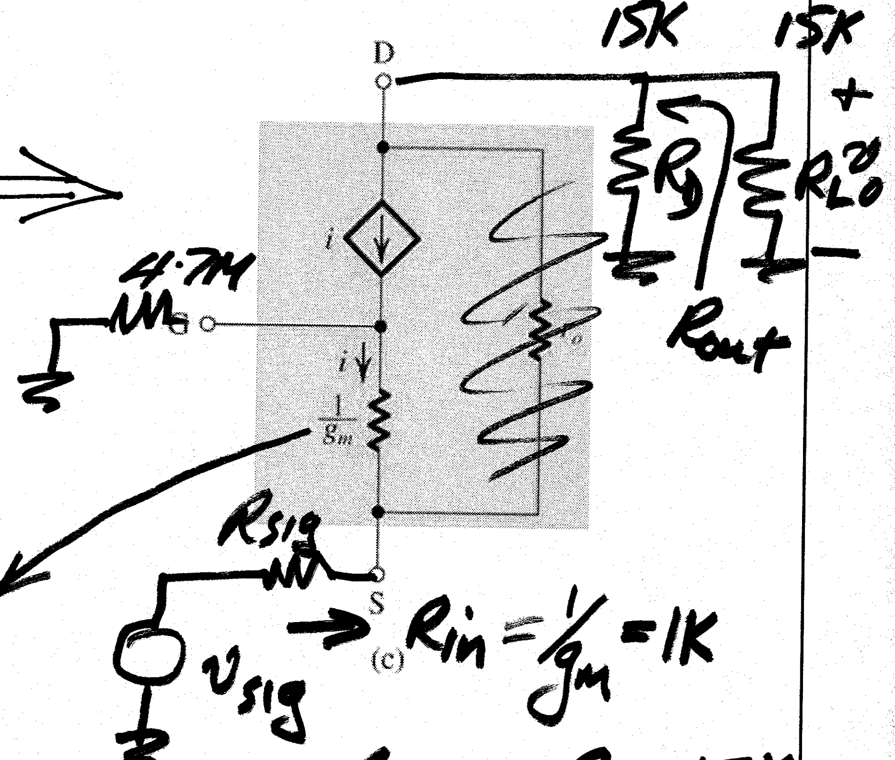
$R_{out} = 1/g_m \| r_o = \frac{1 \cdot 150}{151} = .993\,k\Omega \longrightarrow 1K$ for $r_o \to \infty$

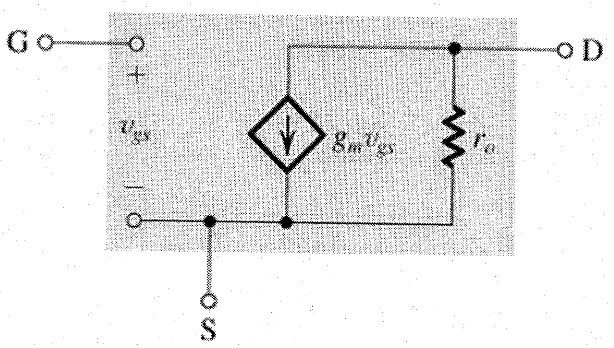
$g_v = \frac{R_g}{R_g + R_{sig}} \cdot \frac{R_L \| r_o}{R_L \| r_o + 1/g_m} = \frac{4.7}{5.7} \cdot \frac{15\|150}{15\|150+1} = .768$

Ex 4.34 uses Ex 4.30

$R_{sig} = 50\Omega$







$g_m = 1$ mA/V

$r_o = 150$ kΩ

$1/g_m = 1$ kΩ

$R_{in} = \frac{1}{g_m} = 1K$

$R_{out} = R_D = 15K$

$A_{vo} = g_m R_D = 10^{-3} \times 15 \times 10^3 = 15$

$A_v = g_m (R_D \| R_L) = 7.5$

$G_v = \frac{R_{in}}{R_{in} + R_{sig}} A_v = \frac{1K}{1K + .05K} 7.5 = 7.14$

Figure E4.30

R_{sig}	G_v	
$R_{sig} = 1K$	$G_v = \frac{1}{1+1} 7.5 = 3.75$	
10K	$\frac{1}{11} 7.5$	.68
100K	$\frac{1}{101} 7.5$	.07

Ex 4.35 uses Ex. 4.30

$$R_{out} = 1/g_m \,||\, r_o = \frac{1\times 150}{151}K = .993K \rightarrow 1K \text{ if } r_o \rightarrow \infty$$

$$G_v = \frac{R_g}{R_g+R_{sig}} \cdot \frac{R_L||r_o}{R_L||r_o + 1/g_m} = \frac{4.7}{5.7} \cdot \frac{15||150}{15||150+1} = .768$$

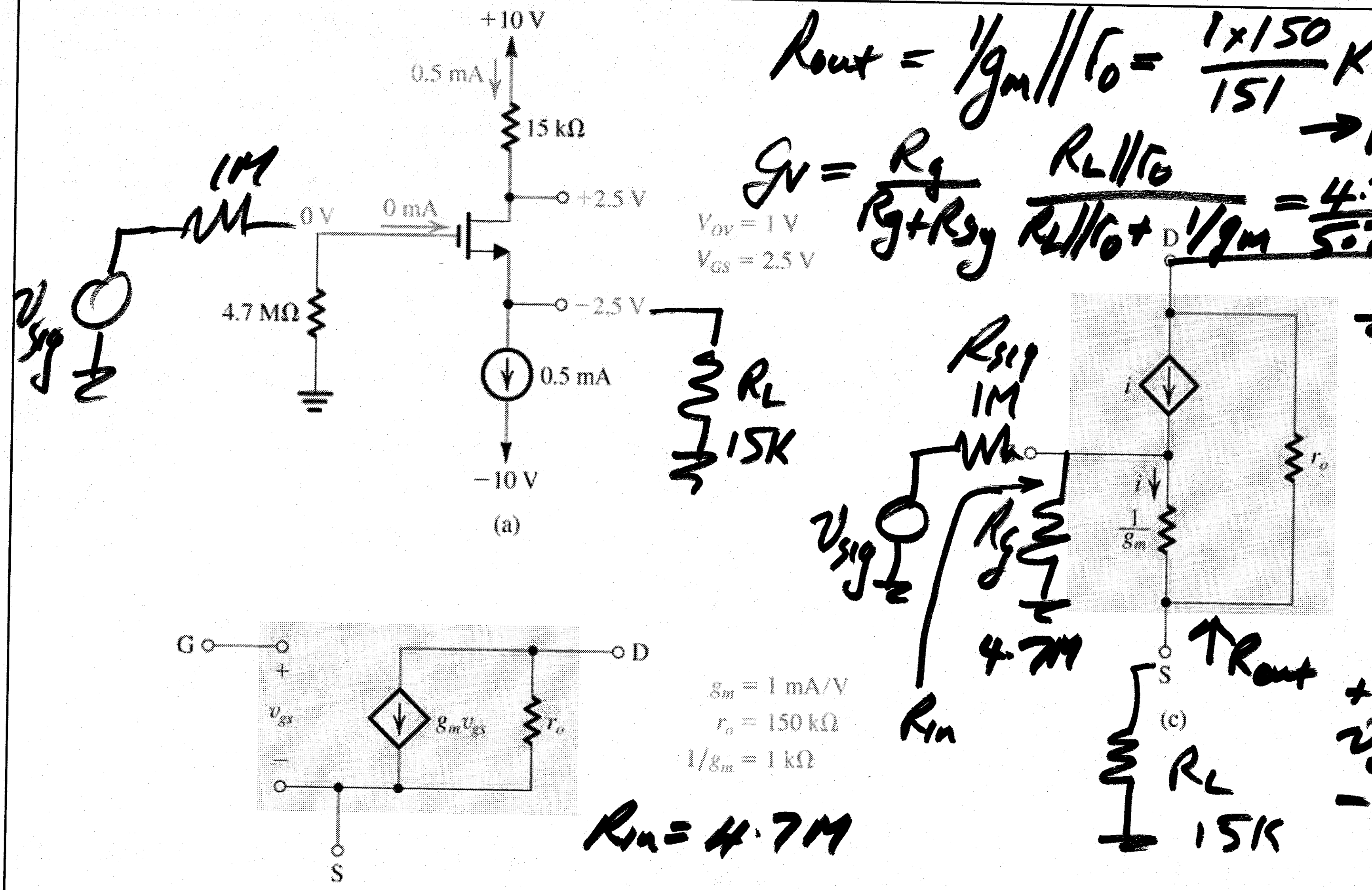


Figure E4.30

$R_{in} = 4.7M$

$$A_{vo} = v_o/v_i \big|_{R_L=\infty} = \frac{r_o}{r_o + 1/g_m} = \frac{150}{151} = .993 \rightarrow 1 \text{ if } r_o \rightarrow \infty$$

$$A_v = \frac{R_L||r_o}{R_L||r_o + 1/g_m} = \frac{15||150}{15||150+1} = .932 \longrightarrow .938 \text{ if } r_o \rightarrow \infty$$

Ex 4.32 follows from Ex 4.30

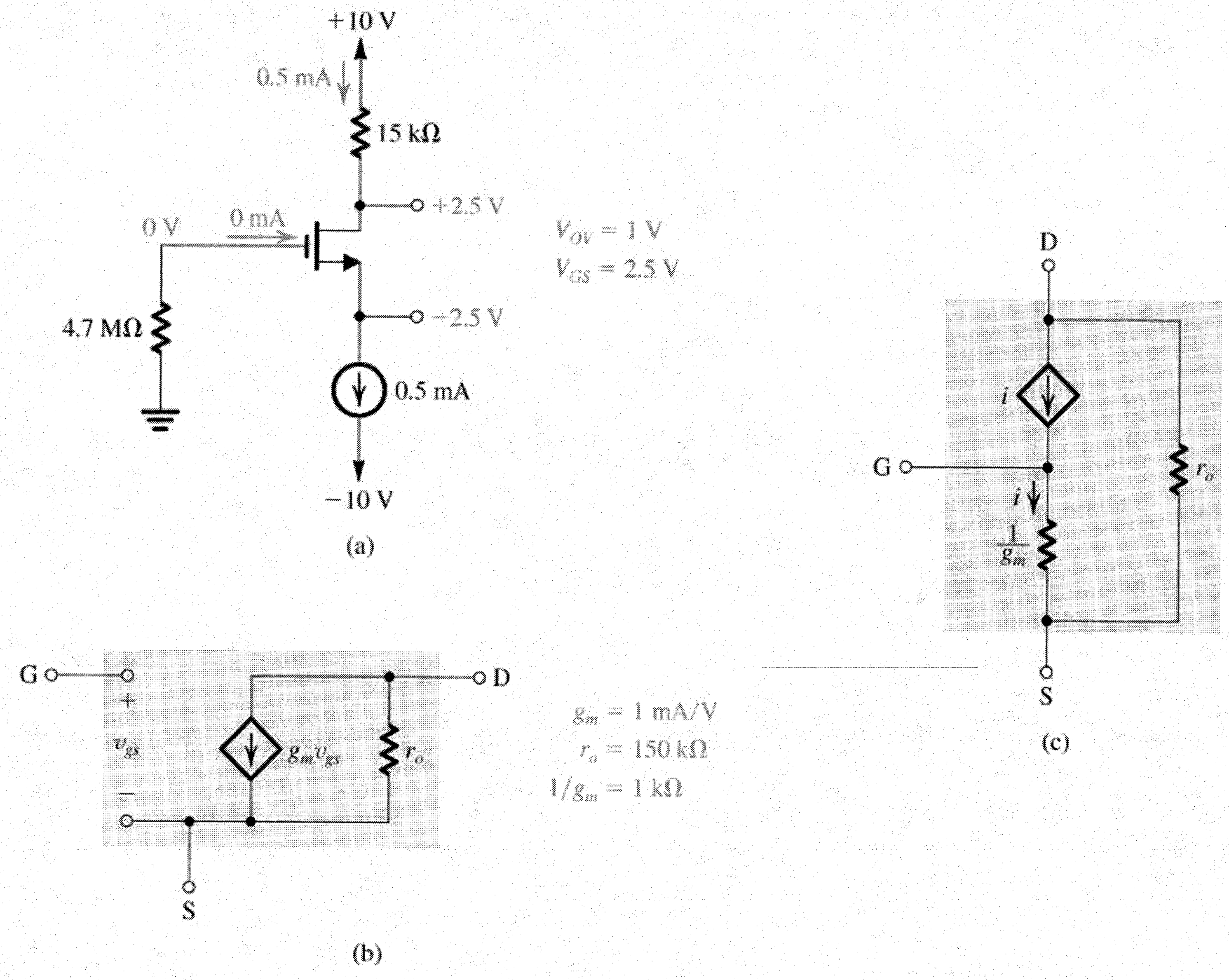
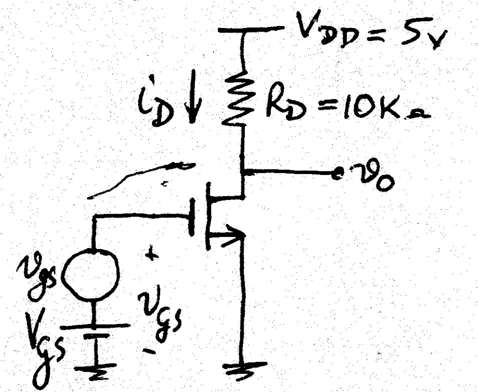


Figure E4.30

Ex 4.23 ① Draw diagram — Fig 4.34



$V_t = 1V \quad k_n' = 20\mu A/V^2 \quad W/L = 20 \quad V_{GS} = 2V \quad \lambda = 0$

② $I_D = \frac{1}{2} k_n' \frac{W}{L} (V_{GS} - V_t)^2$ if sat^d

$= \frac{1}{2}\, 20 \times 10^{-6} \times 20\, (1)^2 = 0.2\,mA$

$V_D = V_{DD} - I_D R_D = 5 - 0.2 \times 10^{-3} \times 10 \times 10^3 = 3V$

③ $g_m = k_n' \frac{W}{L} (V_{GS} - V_t) = 20 \times 10^{-6} \times 20 \times 1 = 0.4\,mA/V$

OR $\frac{2 I_D}{V_{GS} - V_T} \longrightarrow \frac{0.4 \times 10^{-3}}{1}$

④ Voltage gain $\frac{v_o}{v_{gs}} = -g_m R_D = -.4 \times 10^{3} \times 10 \times 10^{-3} = -4$

⑤ $v_{gs} = 0.2 \sin \omega t \xrightarrow{\text{small sig}} v_d = -0.8 \sin \omega t$

Min $v_D \longrightarrow V_D - |v_d| = 2.2V$

Max $v_D \longrightarrow \;\; + \;\; = 3.8V$

] Check $> V_{GS} - V_t = 1V$ ∴ Sat^d

⑥ Eq^n 4.57 $i_D = \frac{1}{2} k_n' \frac{W}{L} \left[(V_{GS} - V_t)^2 + 2(V_{GS} - V_t) v_{gs} + v_{gs}^2 \right]$

$= - - - - \left[(V_{GS} - V_t)^2 + 2(V_{GS} - V_t) \cdot 2 \sin \omega t + .04 \sin^2 \omega t \right]$

$= 200 \times 10^{-6} \left[1 + .4 \sin \omega t + .04 - \frac{.04}{2} \cos 2\omega t \right]$

$= 204 + 80 \sin \omega t - 4 \cos 2\omega t \;\; \mu A$

∴ I_D incr $\frac{4}{200} 100\% = 2\%$

2nd harmonic $\frac{4}{200} 100\% = 5\%$

Ex 4.24 $\mu_n C_{ox} = 60\mu A/V^2$ $\frac{W}{L} = 40$ $V_t = 1V$ $V_A = 15V$

$$g_m = \frac{2I_D}{V_{OV}} \quad \& \quad r_o = \frac{V_A}{I_D}$$

(a) $V_{GS} = 1.5V$ $\therefore$ $I_D = \frac{1}{2}\, 60\times10^{-6}\, 40\, (1.5-1)^2 = 300\mu A$

$$\therefore g_m = \frac{2\times300\times10^{-6}}{0.5} = 1.2 mA/V$$

$$r_o = 15/300\times10^{-6} = 50K\Omega$$

(b) $I_D = 0.5mA$ $g_m = \sqrt{2\mu_n C_{ox}\frac{W}{L}I_D} = \sqrt{2\times60\times10^{-6}\times40\ \cdot5\times10^{-3}}$

$$= \sqrt{2.4}\ mA/V = 1.55mA/V$$

$$r_o = V_A/I_D = 15V/.5\times10^{-3} = 30K\Omega.$$

Ex 4.25 $g_m = \frac{2I_D}{V_{OV}} = \frac{2\times0.1mA}{V_{OV}} = 1mA/V$ $\therefore V_{OV} = \frac{0.2mA}{1mA}V = 0.2V$

$$\therefore I_D = \frac{1}{2}k_n'\frac{W}{L}(V_{OV})^2 = 0.1mA = \frac{1}{2}\,50\mu A/V^2\,\frac{W}{L}\,(.2)^2$$

$$\therefore W/L = \frac{10^{-4}\times2}{50\times10^{-6}\ 4\times10^{-2}} = \frac{10^4}{100} = 100$$

• **4.26** $\mu_p = 0.4\mu_n$ Equal $g_m = \frac{2I_D}{V_{ov}}$ ← same ← same.

$\mu_p W_p = \mu_n W_n$ $\quad .4 W_p = W_n$ $\quad W_p = 2.5 W_n$

• **4.27** $\chi = \frac{g_{mb}}{g_m} = \frac{\gamma}{2\sqrt{2\phi_f + V_{SB}}} = \frac{0.5}{2\sqrt{.6+4}} = 0.1166$

• **4.28** PMOS $V_t = -1v$ $\quad k_p' = 60\mu A/V^2$ $\quad W/L = 16\mu m/0.8\mu m$ $\quad V_{GS} = -1.6v$

$I_D = 1/2 \; 60\mu A \; 20(.6)^2 = 216\mu A$ $\quad \therefore g_m = \frac{2I_D}{V_{ov}} = \frac{432\mu A}{.6}$

$= .720 \; mA/V$

$V_A \propto L \longrightarrow r_o = \frac{V_A \times L}{I_D} = \frac{(1/\lambda)L}{I_D} = \frac{25\times(.8)}{216\times10^{-6}} = 92.6\,K\Omega$

• **4.29** $g_m r_o = \frac{2I_D}{V_{OV}} \cdot \frac{V_A}{I_D} = 2\frac{V_A}{V_{OV}} = A_o$ intrinsic gain

$L = .8\mu m \; \therefore V_A = .8 \times 12.5v = 10v \quad \therefore g_m r_o = 2\frac{10}{.2} = 100$

Ex 4.30 Find V_{ov}, V_{gs}, V_g, V_s, V_D & g_m, r_o for $V_A = 75v$; max v_D swing for Q to remain sat^n

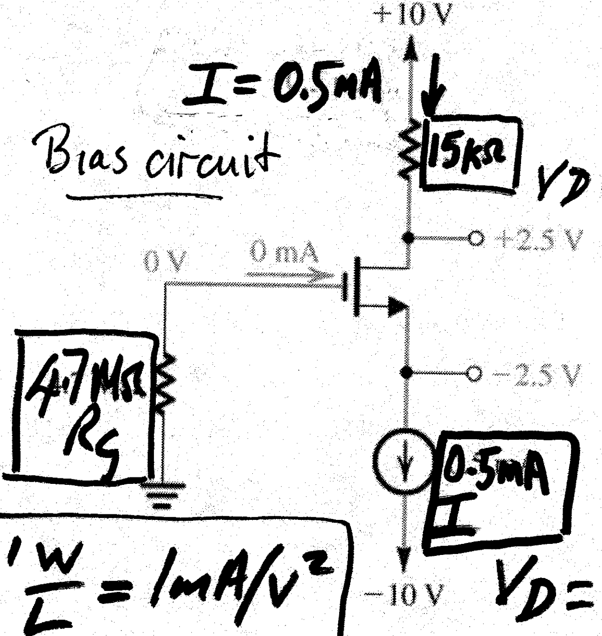
$V_{ov} = V_{gs} - V_t$

$I_D = \frac{1}{2} k_n' W/L (V_{ov})^2$

$\therefore V_{ov} = \left(\frac{2 \times 0.5mA}{1mA}\right)^{1/2} = 1V$

$\therefore V_{gs} = V_{ov} + V_t = 2.5V$

$\therefore V_s = -2.5V$

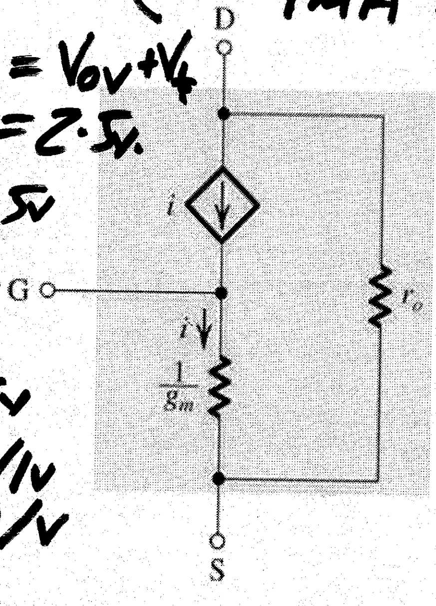


(a)

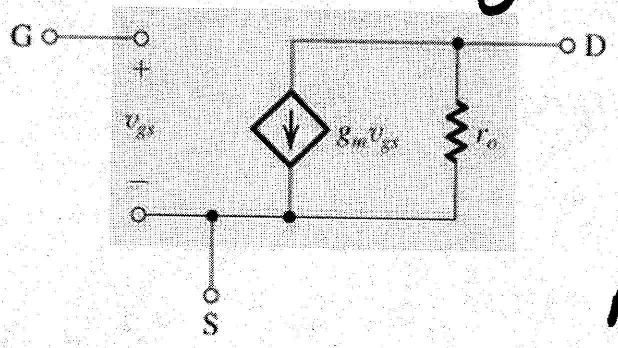
$k_n' \frac{W}{L} = 1mA/V^2$
$V_t = 1.5v$

$V_D = 10 - 15\times10^3 \times .5\times10^{-3}$
$= 10 - 7.5 = +2.5v$

$g_m = 2I_D/V_{ov} = 1mA/1v$
$= 1mA/V$



(c)



(b)

$g_m = 1mA/V$
$r_o = 150 k\Omega$
$1/g_m = 1 k\Omega$

$r_o = V_A/I_D = 75v/.5mA$
$= 150K$

Figure E4.30

Max swing: Onset of saturation when $V_{gs} - V_t \le V_{DS}$

i.e. $V_g - V_s - V_t \le V_D - V_s \Rightarrow V_{gD} \le V_t$ i.e. $0 - v_D \le 1.5v$

when $v_D \ge -1.5v$ i.e. max swing $+2.5$ (Bias) $\rightarrow -1.5v$ = 4v peak

Ex. 4.30

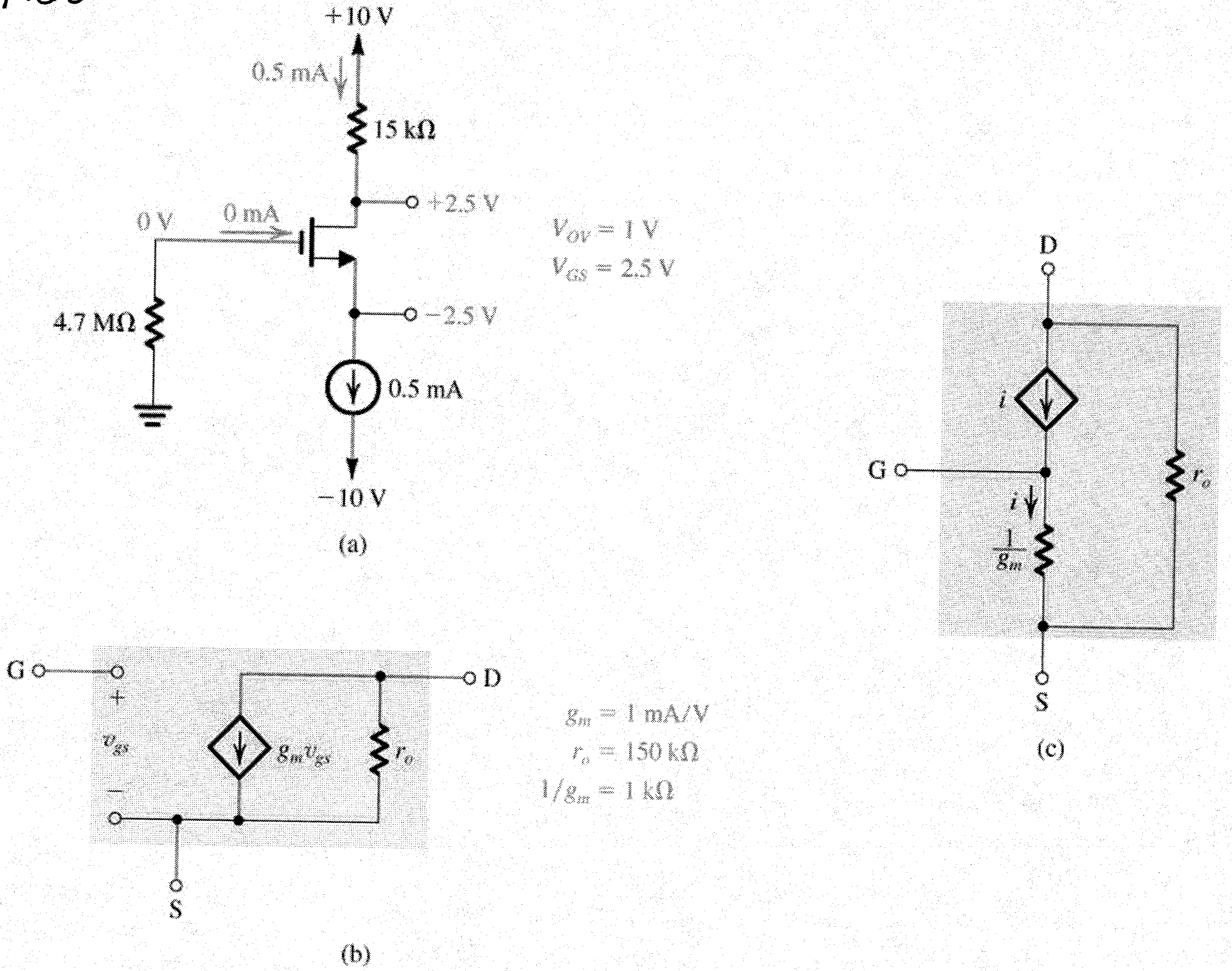
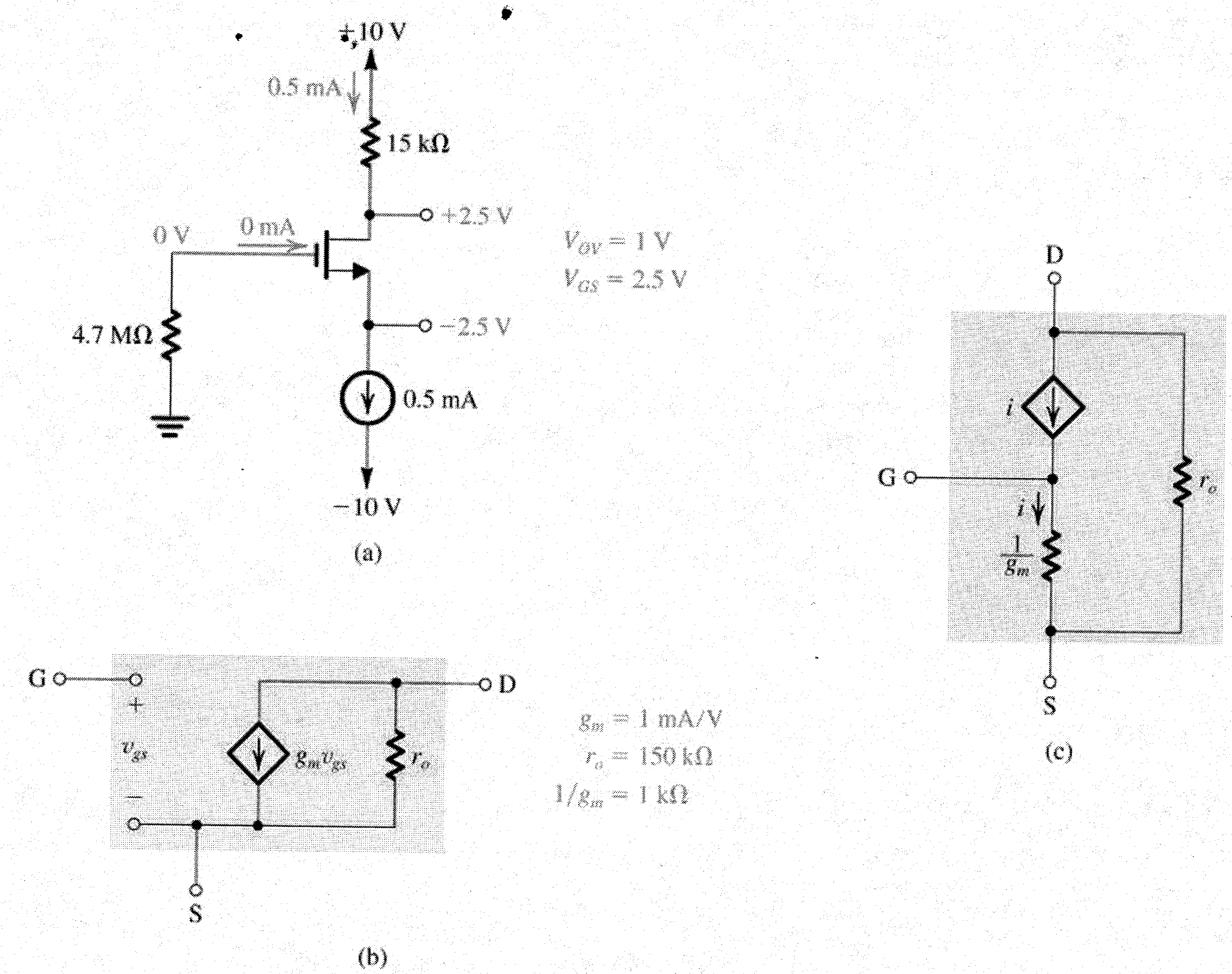


Figure E4.30



+10 V
0.5 mA
15 kΩ
+2.5 V
0 V
0 mA
V_{OV} = 1 V
V_{GS} = 2.5 V
4.7 MΩ
−2.5 V
0.5 mA
−10 V
(a)
G
+
v_{gs}
−
$g_m v_{gs}$
r_o
D
S
g_m = 1 mA/V
r_o = 150 kΩ
$1/g_m$ = 1 kΩ
(b)
D
i
G
i
$\frac{1}{g_m}$
r_o
S
(c)

Figure E4.30