모듈4 : MOSFET 증폭기 회로 해석 및 응용

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목 차

1. MOSFET의 I-V 특성, 동작모드 (포화, 활성, 차단)

⊙ Introduction

▶ History of FETs

- ▷ the basic concept is known in the 1930s
- ▷ the device became practical in the 1960s
- ▷ MOSFET has been popular since the late 1970s

▶ Types of FETs

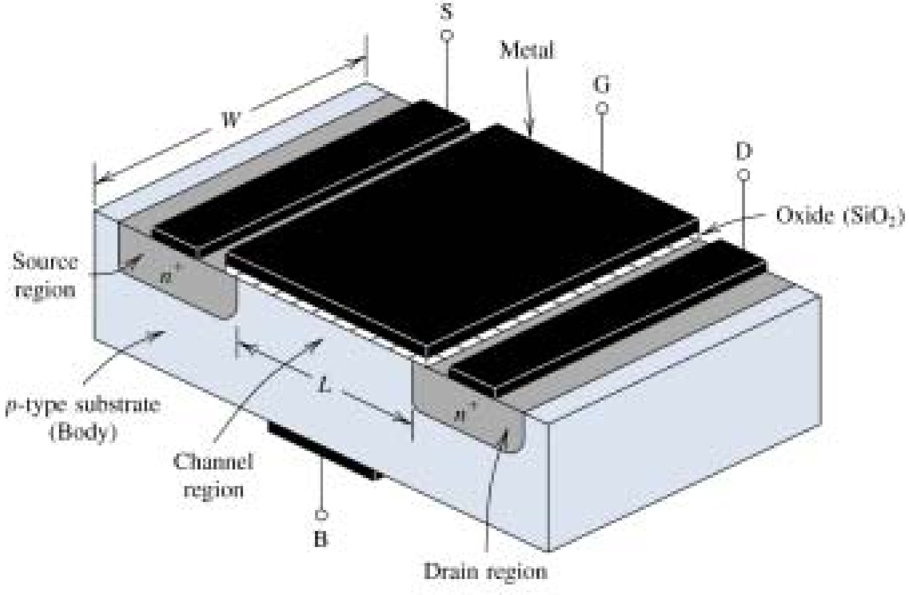
- ▷ **MOSFET** → **enhancement mode**
  → depletion mode
- ▷ JFET
- ▷ MESFET

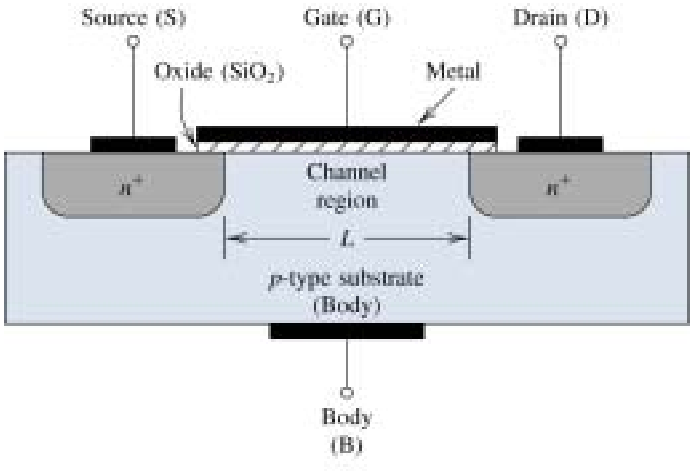
▶ Features of MOSFETs (compared to BJTs)

- ▷ small area
- ▷ simple process
- ▷ low power
- ▷ digital logic and memory functions using MOSFETs only
- ▷ most VLSI circuits are made using MOS technology

1. MOS FET의 I-V 특성, 동작모드 (포화, 활성, 차단)

⊙ Device Structure

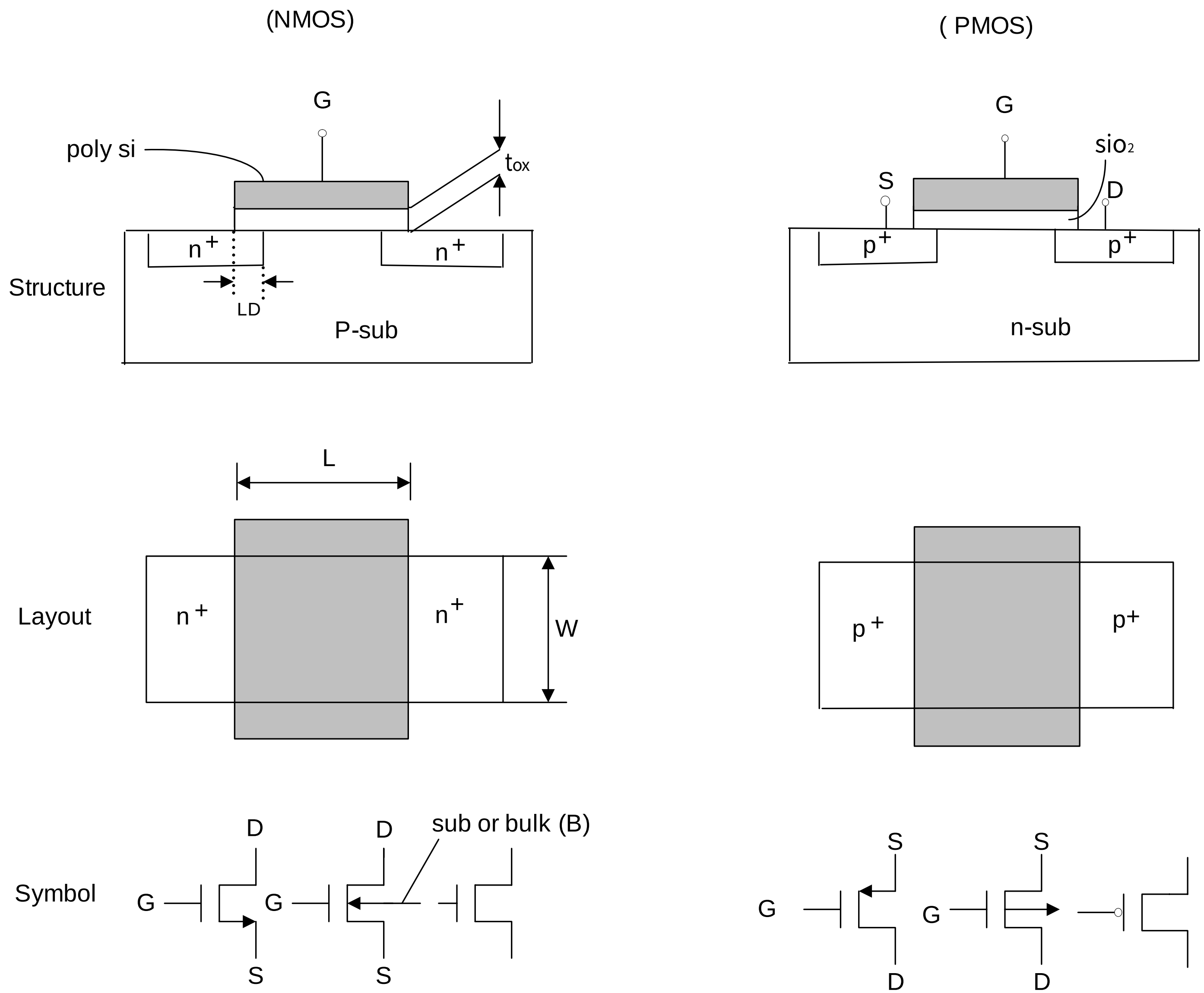




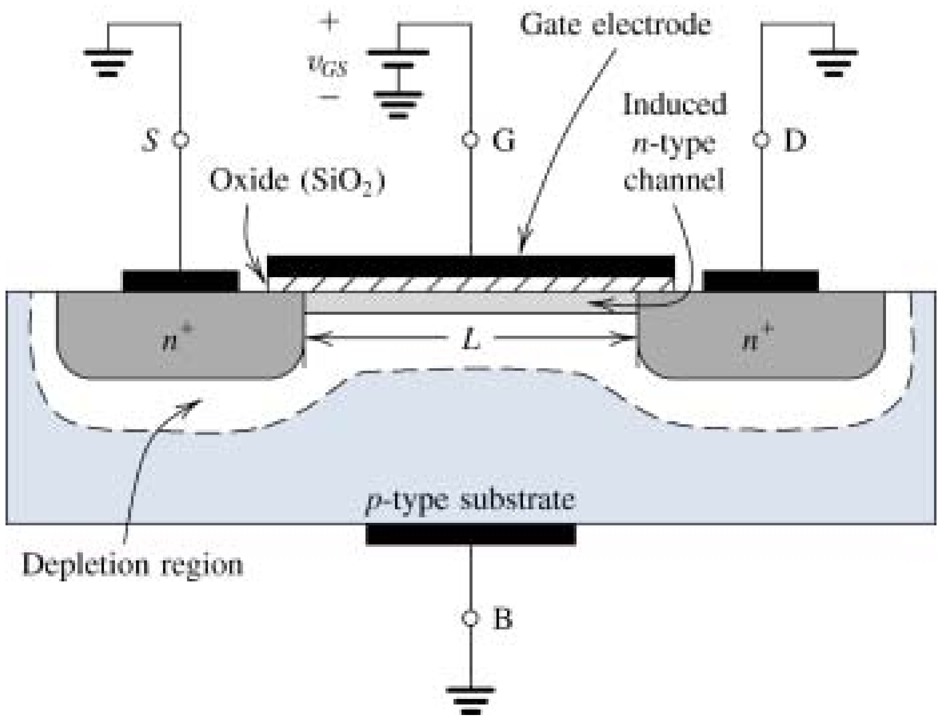
- ▶ 4 terminals : Drain(D), Gate(G), Source(S), Body(B)
- ▶ symmetrical (S & D can be interchanged)
- ▶ silicon gate (polysilicon)
- ▶ another name : IGFET(insulated-gate FET)

1. MOS FET의 I-V 특성, 동작모드 (포화, 활성, 차단)

⊙ Layout & Symbol



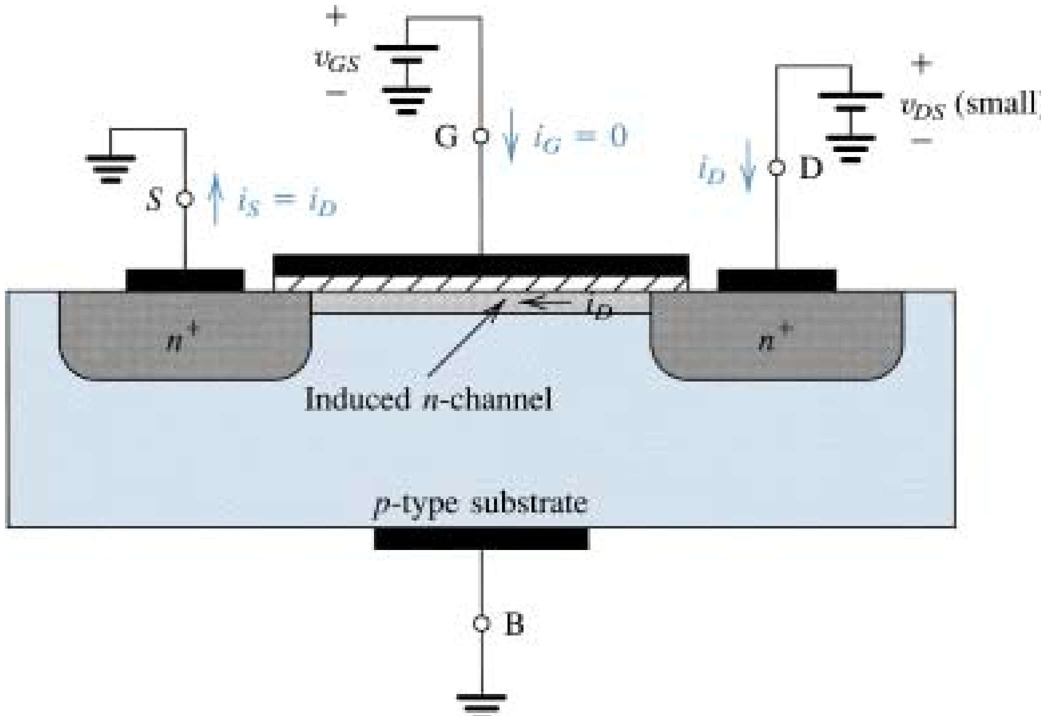
⊙ Creating a channel



- ▶ positive v_{GS}
  - ▷ repel the free holes → a carrier depletion region
  - ▷ attract electrons from the S & D in the channel region
- ▶ induced n region → n-channel → inversion layer
- ▶ threshold voltage V_t
  - ▷ v_{GS} at which a sufficient electrons accumulate in the channel

1. MOS FET의 I-V 특성, 동작모드 (포화, 활성, 차단)

⊙ Applying a small v_{DS}



▶ magnitude of i_D

▷ depends on the density of electrons in the channel & v_{GS}

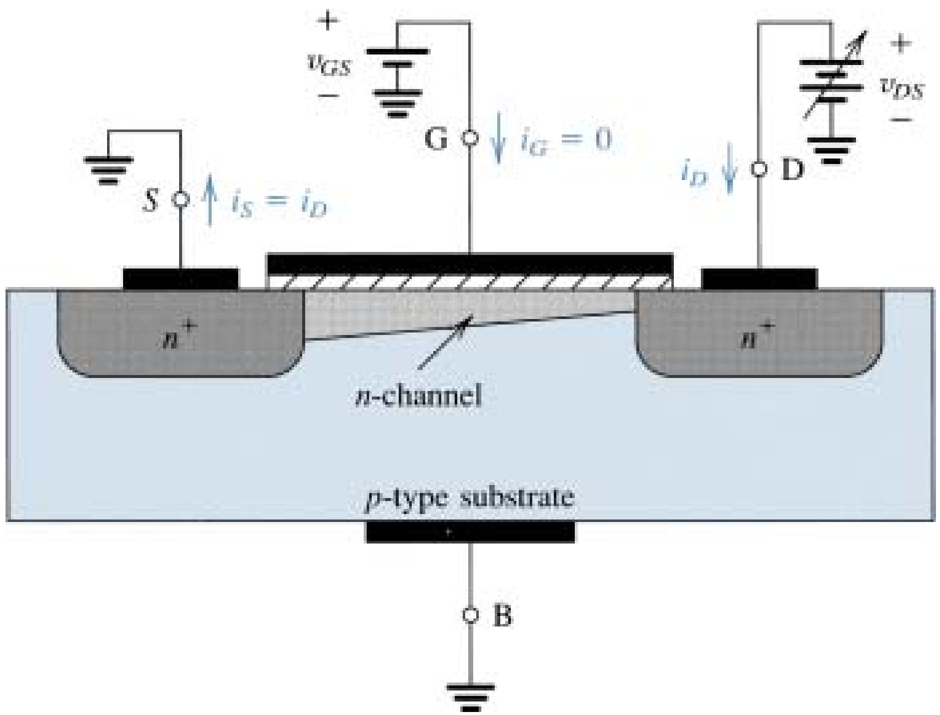
▶ $v_{GS} = V_t$ → the channel is just induced → i_D is negligibly small

▶ v_{GS} ↑ → channel electrons↑ → channel depth↑ → channel resistance↓

▶ channel conductance & $i_D \propto v_{GS} - V_t$: excess gate voltage

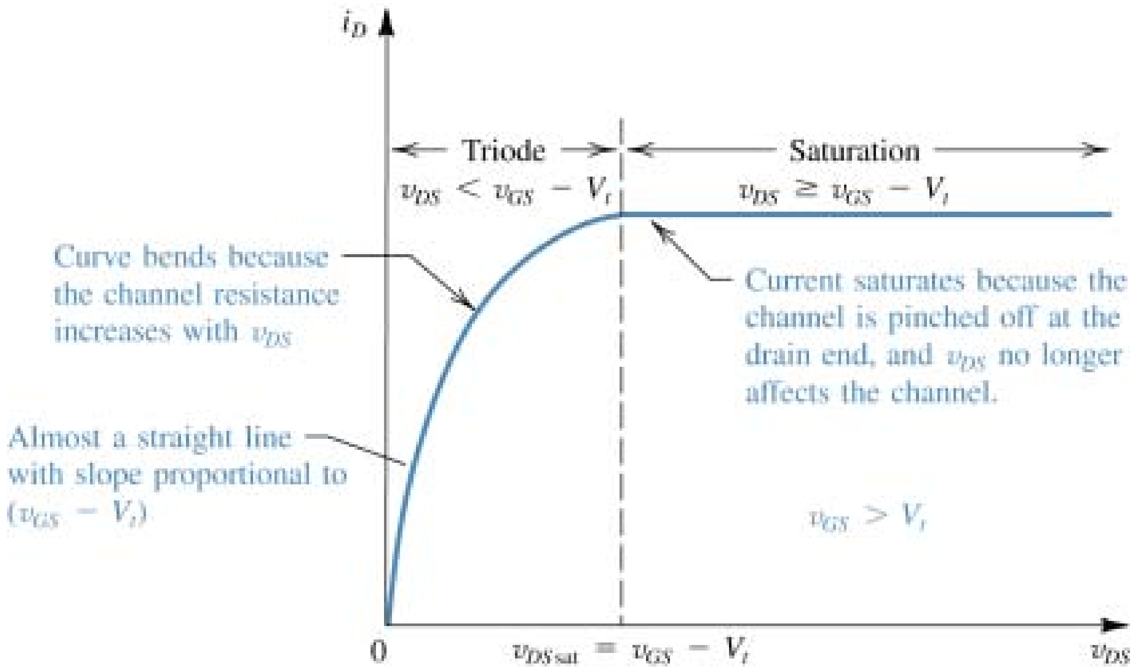
1. MOS FET의 I-V 특성, 동작모드 (포화, 활성, 차단)

⊙ Operation as v_{DS} is increased



- ▶ Gate-to-channel voltage
  - ▷ v_{GS} at the source end → deep channel
  - ▷ $v_{GS} - v_{DS}$ at the drain end → shallow channel
- ▶ v_{DS} ↑ → channel becomes more tapered → resistance ↑

1. MOS FET의 I-V 특성, 동작모드 (포화, 활성, 차단)



▶ $v_{GD} = V_t$ or $v_{DS} = v_{GS} - V_t$

▷ the channel depth at the drain end becomes zero → pinched off

▶ $v_{DS} > v_{GS} - V_t$

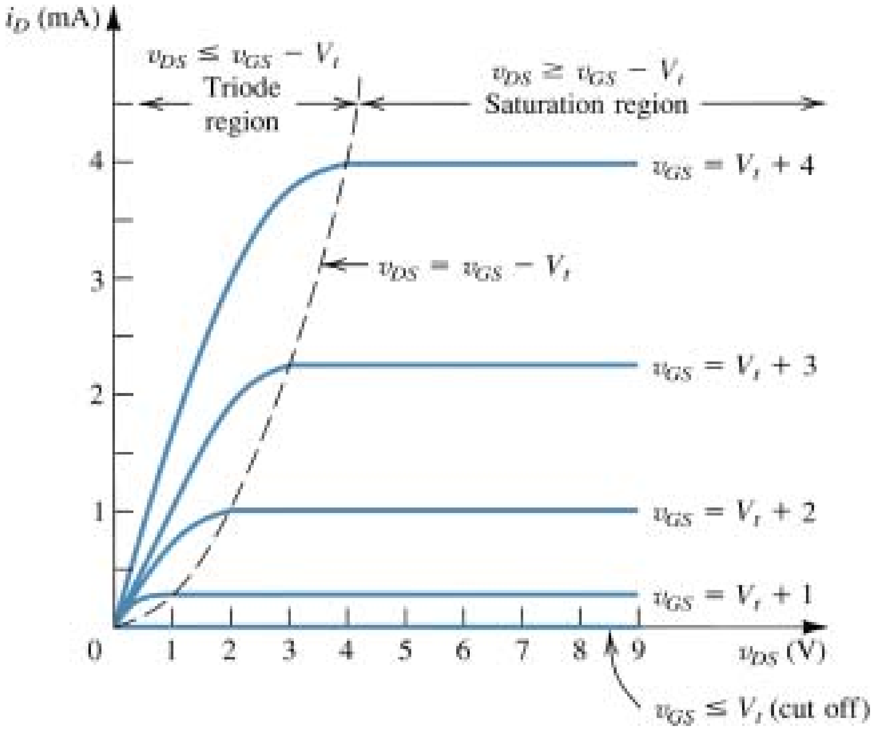
▷ has little effect on the channel shape

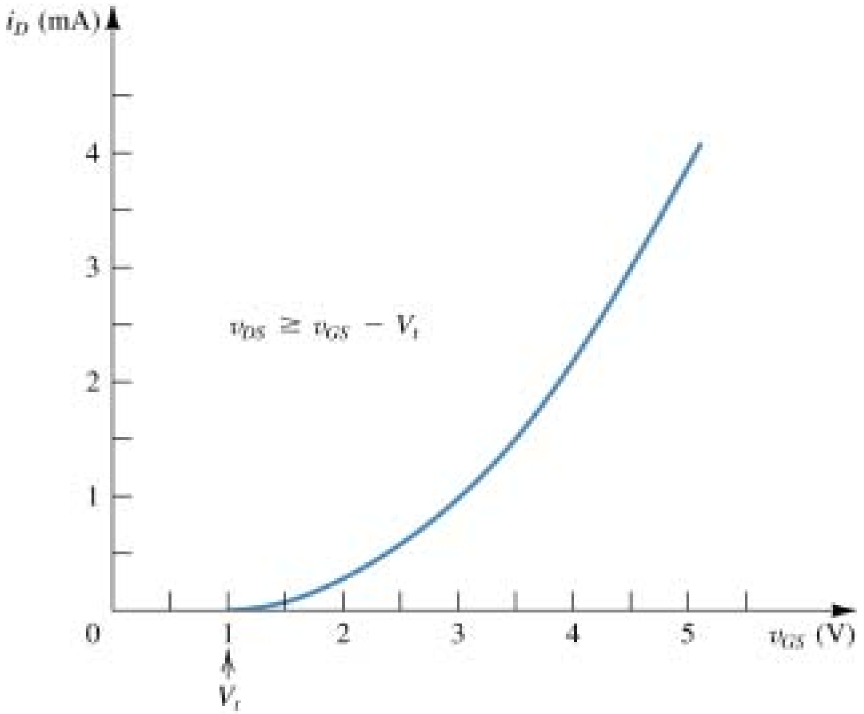
▷ i_D remains constant at the value reached for $v_{DS} = v_{GS} - V_t$

▷ i_D saturates at this value → saturation region

1. MOS FET의 I-V 특성, 동작모드 (포화, 활성, 차단)

⊙ I-V characteristics





1. MOS FET의 I-V 특성, 동작모드 (포화, 활성, 차단)

⊙ Operation mode (NMOS)

<cutoff region>

▶ condition : $v_{GS} < V_{tn}$

▶ no current flows ideally

<triode region>

▶ condition : $v_{GS} > V_{tn}$ & $v_{GD} > V_{tn}$ $\rightarrow$ $v_{DS} < v_{GS} - V_{tn}$

▶ $i_{DS} = \beta_n \left[(v_{GS} - V_{tn}) v_{DS} - \frac{1}{2} v_{DS}^2 \right]$ $\beta_n = k_n' \frac{W}{L}$ $k_n' = \mu_n C_{ox}$

▶ act as a linear resistor : $r_{DS} \approx 1 / \beta_n (v_{GS} - V_{tn})$

<saturation region>

▶ condition : $v_{GS} > V_{tn}$ & $v_{GD} < V_{tn}$ $\rightarrow$ $v_{DS} > v_{GS} - V_{tn}$

▶ $i_{DS} = \frac{\beta_n}{2} (v_{GS} - V_{tn})^2$

▶ act as an ideal current source

▷ its value is controlled by v_{GS}

1. MOS FET의 I-V 특성, 동작모드 (포화, 활성, 차단)

⊙ Operation mode (PMOS)

<cutoff region>

- ▶ condition : $v_{SG} < |V_{tp}|$
- ▶ no current flows ideally

<triode region>

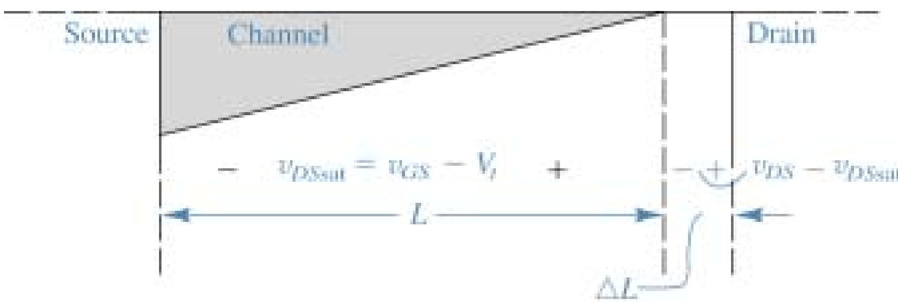
- ▶ condition : $v_{SG} > |V_{tp}|$ & $v_{DG} > |V_{tp}| \rightarrow v_{SD} < v_{SG} - |V_{tp}|$
- ▶ $i_{SD} = \beta_p \left[(v_{SG} - |V_{tp}|) v_{SD} - \frac{1}{2} v_{SD}^2 \right] \qquad \beta_p = k_p' \frac{W}{L} \qquad k_p' = \mu_p C_{ox}$
- ▶ act as a linear resistor : $r_{SD} \approx 1 / \beta_p (v_{SG} - |V_{tp}|)$

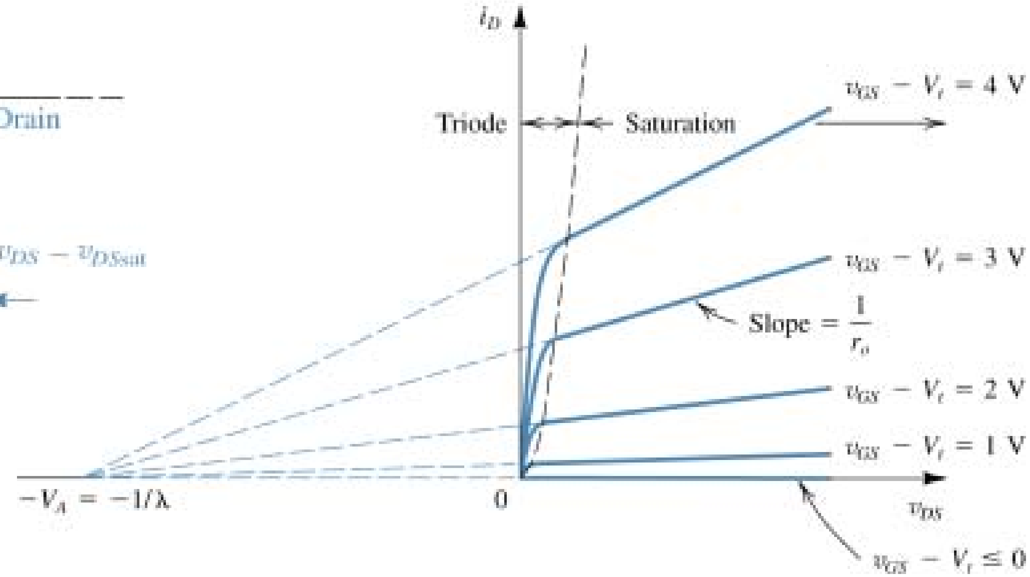
<saturation region>

- ▶ condition : $v_{SG} > |V_{tp}|$ & $v_{DG} < |V_{tp}| \rightarrow v_{SD} > v_{SG} - |V_{tp}|$
- ▶ $i_{SD} = \frac{\beta_p}{2} \left(v_{SG} - |V_{tp}| \right)^2$
- ▶ act as a ideal current source
  - ▷ its value is controlled by v_{SG}

1. MOS FET의 I-V 특성, 동작모드 (포화, 활성, 차단)

⊙ Channel-length modulation effect





▶ $v_{DS} \uparrow \rightarrow L \downarrow \rightarrow i_{DS} \uparrow$

$$i_{DS} = \frac{\beta_n}{2}(v_{GS} - V_{tn})^2(1 + \lambda v_{DS})$$

▶ channel-length modulation factor: $\lambda = \frac{1}{V_A} \propto \frac{1}{L}$

▶ output resistance

$$r_o = \left[\frac{\partial i_{DS}}{\partial v_{DS}}\right]_{v_{GS}}^{-1} \approx \frac{1}{\lambda I_{DS}} = \frac{V_A}{I_{DS}}$$

1. MOS FET의 I-V 특성, 동작모드 (포화, 활성, 차단)

⊙ Body effect

▶ $V_{SB} \neq 0$ → depletion region ↑ → channel depth ↓
→ bulk charge ↑ → V_t ↑

$$V_t = V_{t0} + \gamma\left(\sqrt{2\phi_f + V_{SB}} - \sqrt{2\phi_f}\right)$$

▷ V_{t0} : threshold voltage for V_SB =0
▷ ϕ_f : Fermi potential
▷ γ : body-effect parameter (process parameter)

$$\gamma = \frac{\sqrt{2qN_A\varepsilon_s}}{C_{ox}}$$

▶ for PMOS

$$|V_t| = |V_{t0}| + \gamma\left(\sqrt{2\phi_f + V_{BS}} - \sqrt{2\phi_f}\right)$$

⊙ Temperature effects

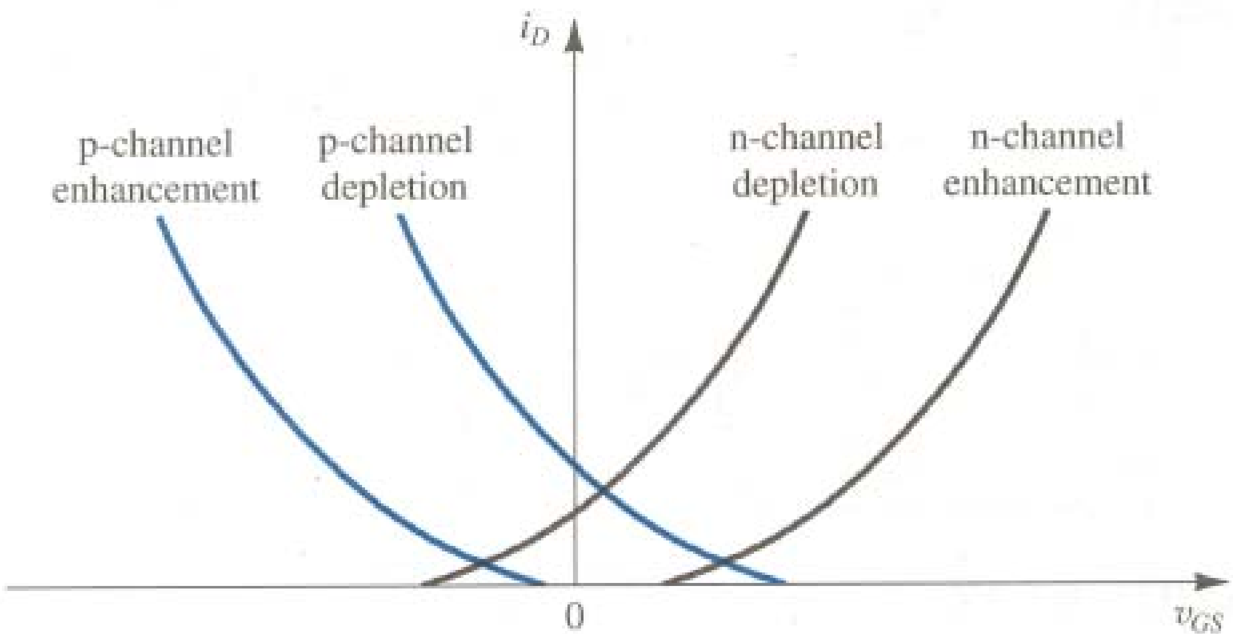
- ▶ V_t : -2mV/°C & $\mu \propto T^{-1.5}$
- ▶ $T\uparrow \rightarrow V_t\downarrow$ & $k'\downarrow\downarrow \rightarrow i_{DS}\downarrow$

⊙ Breakdown

- ▶ junction breakdown
  - ▷ 50 100V
  - ▷ occurs in the pn-junction bet. D & B
- ▶ punch-through : 20V
  - ▷ occurs in short-channel devices
  - ▷ the depletion region(D) extends to the S
  - ▷ does not result in permanent damage
- ▶ gate-oxide breakdown : 50V
  - ▷ occurs in gate oxide
  - ▷ results in permanent damage
  - ▷ small static charge can cause ∵ very high input impedance
  - ▷ gate protection devices are required

⊙ Depletion-type MOSFET

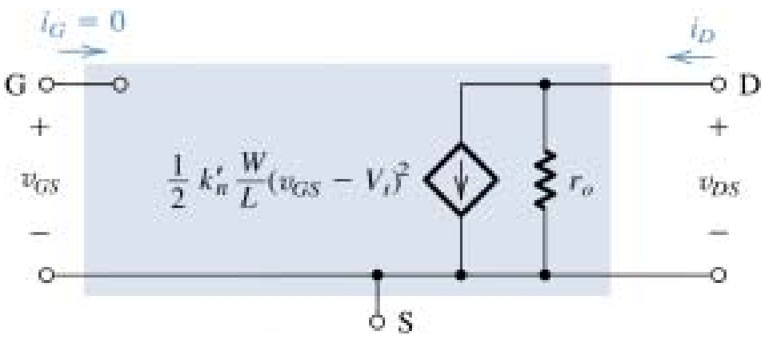
- ▶ has a physically implanted channel
- ▶ $V_{tn} < 0 \quad \rightarrow \quad i_{DS} > 0 \quad \text{for} \quad v_{GS} = 0$



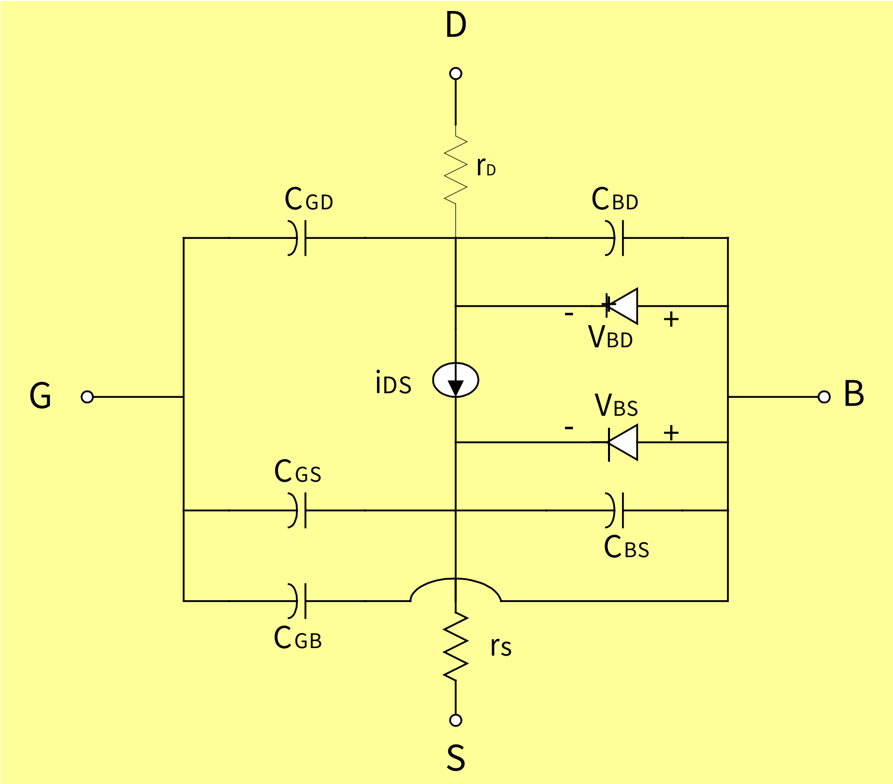
2. 대신호와 소신호 등가회로, 고주파 등가회로

⊙ Large-signal equivalent circuit

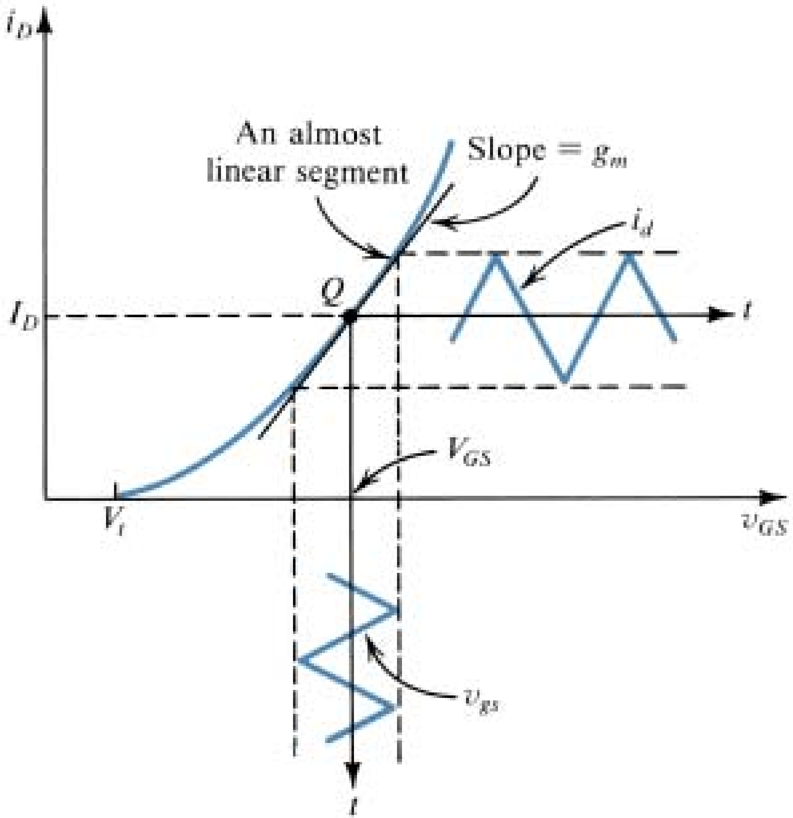
▶ simple model in saturation



▶ complete model



⊙ Small-signal approximation



▶ total current

$$i_D \approx I_D + i_d$$

▶ dc component

$$I_D = \frac{\beta_n}{2}(V_{GS} - V_t)^2$$

▶ ac signal component

$$i_d = \left[\left. \frac{\partial i_D}{\partial v_{GS}} \right|_{v_{GS}=V_{GS}} \right] \cdot v_{gs} = \beta_n (V_{GS} - V_t) \cdot v_{gs}$$

2. 대신호와 소신호 등가회로, 고주파 등가회로

▶ small-signal condition

$$v_{GS} = V_{GS} + v_{gs}$$

$$\begin{aligned} i_D &= \frac{\beta_n}{2}(V_{GS} + v_{gs} - V_t)^2 \\ &= \frac{\beta_n}{2}(V_{GS} - V_t)^2 + \beta_n(V_{GS} - V_t)v_{gs} + \frac{\beta_n}{2}v_{gs}^2 \\ &= I_D + i_d + i_{d(nl)} \end{aligned}$$

$$\beta_n(V_{GS} - V_t)v_{gs} >> \frac{\beta_n}{2}v_{gs}^2$$

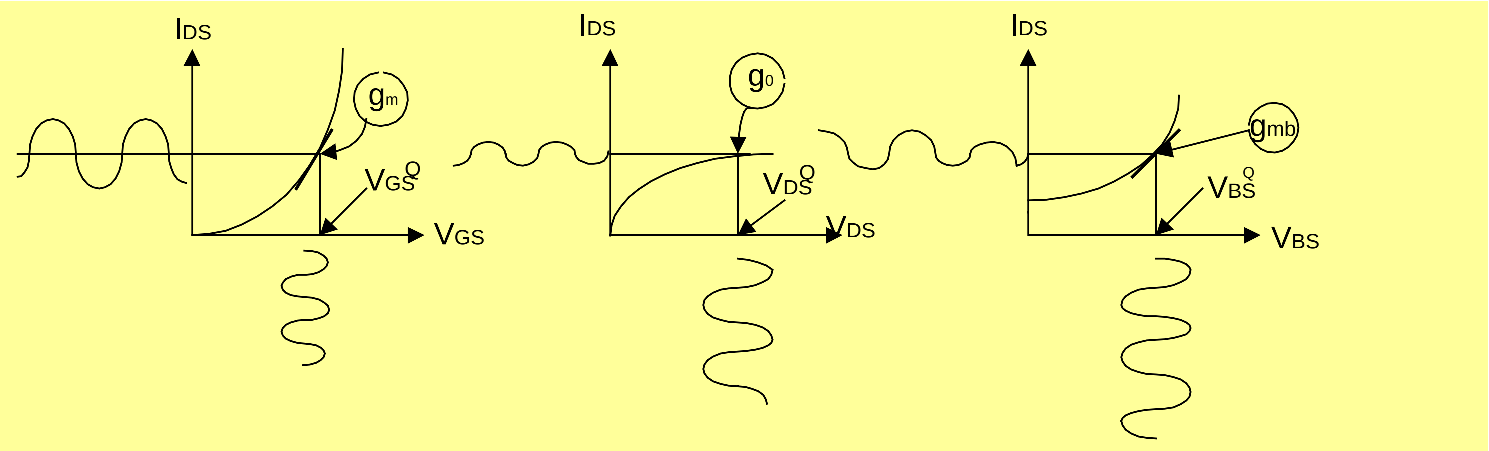
$$\therefore \quad v_{gs} << 2(V_{GS} - V_t) = 2V_{OV} \qquad (V_{OV} = V_{GS} - V_t)$$

⊙ MOSFET small-signal model

$$i_{DS} = \frac{\beta_n}{2}(v_{GS} - V_t)^2(1 + \lambda v_{DS})$$

$$= \frac{\beta_n}{2}\left[v_{GS} - V_{t0} - \gamma\left(\sqrt{2\phi_f + V_{SB}} - \sqrt{2\phi_f}\right)\right]^2(1 + \lambda v_{DS})$$

$$= f(v_{GS}, v_{DS}, v_{BS})$$



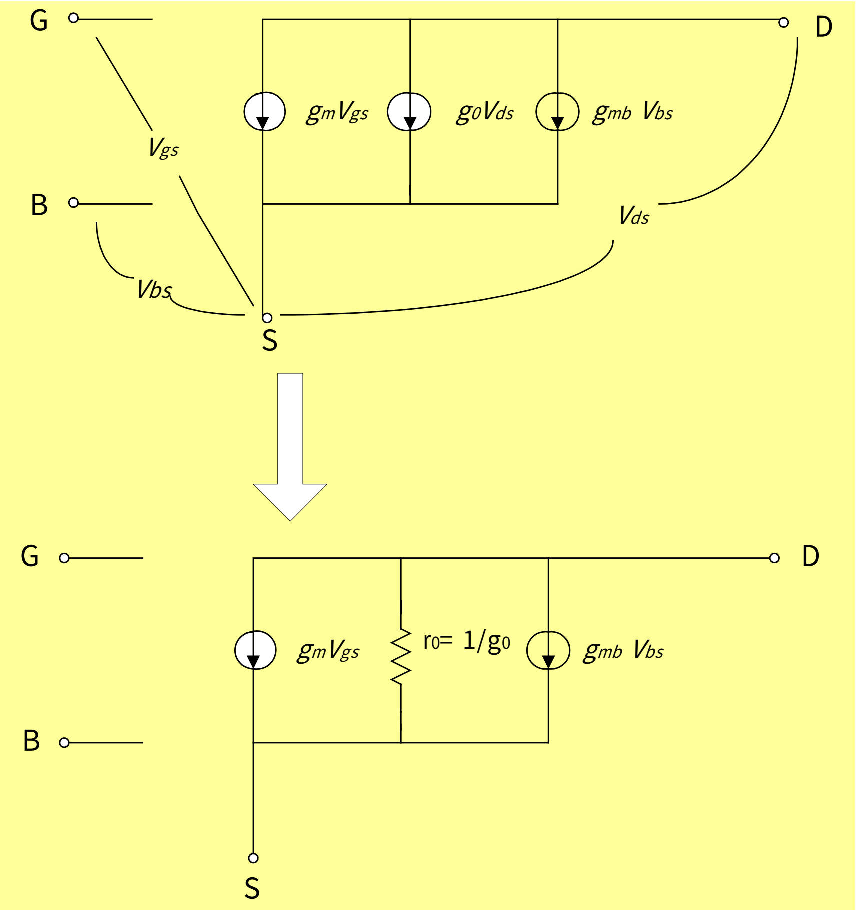
$$I_{DS} = f(V_{GS}, V_{DS}, V_{BS})$$

$$i_{ds} \approx \left[\left.\frac{\partial i_{DS}}{\partial v_{GS}}\right|_{v_{GS}=V_{GS}}\right] \cdot v_{gs} + \left[\left.\frac{\partial i_{DS}}{\partial v_{DS}}\right|_{v_{DS}=V_{DS}}\right] \cdot v_{ds} + \left[\left.\frac{\partial i_{DS}}{\partial v_{BS}}\right|_{v_{BS}=V_{BS}}\right] \cdot v_{bs}$$

$$= g_m \cdot v_{gs} + g_o \cdot v_{ds} + g_{mb} \cdot v_{bs}$$

⊙ MOSFET small-signal equivalent circuit

$$i_{ds} = g_m \cdot v_{gs} + g_o \cdot v_{ds} + g_{mb} \cdot v_{bs}$$



▶ transconductance

$$g_m = \beta_n (V_{GS} - V_{tn}) = \sqrt{2\beta_n I_{DS}} = \frac{2I_{DS}}{V_{GS} - V_{tn}}$$

▶ output conductance

$$g_o = \frac{\lambda I_{DS}}{1 + \lambda I_{DS}} \approx \lambda I_{DS}$$

▶ body transconductance

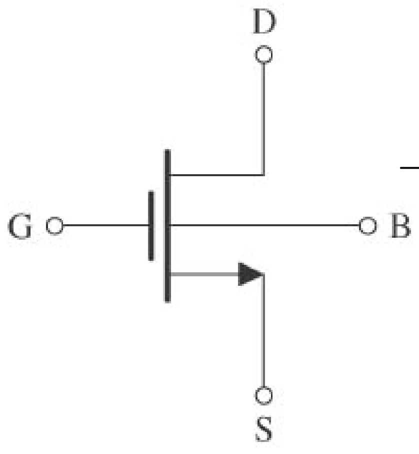
$$g_{mb} = \frac{\gamma}{2\sqrt{2\phi_f + V_{SB}}} = \chi \cdot g_m$$

$$(\chi < 1)$$

☞ $g_m > g_{mb} > g_o$

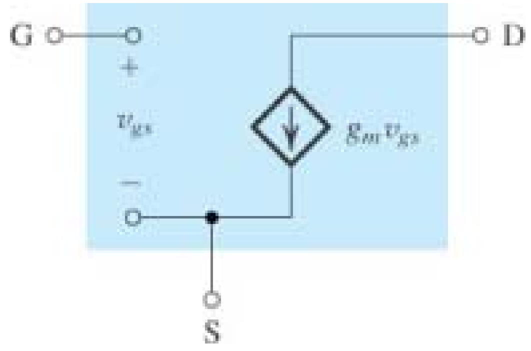
2. 대신호와 소신호 등가회로, 고주파 등가회로

Hybrid-π



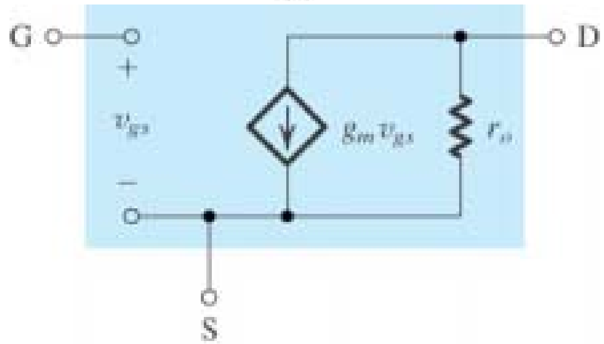
(a)

$\lambda = 0\ \&\ v_{SB} = 0$

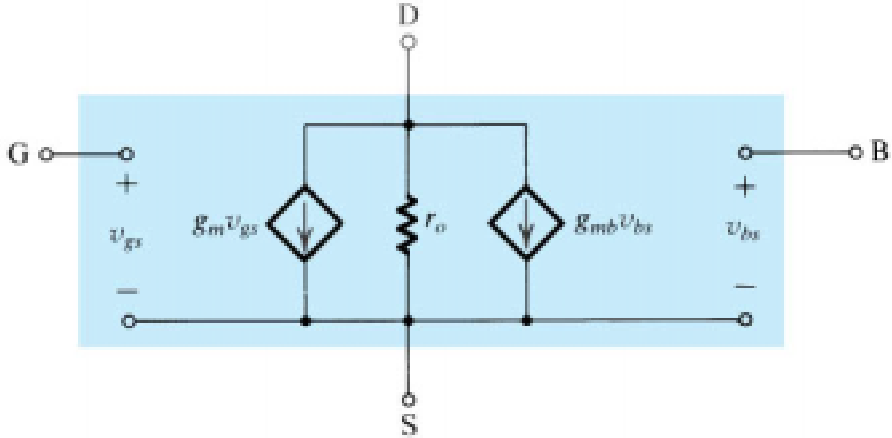


(a)

$\lambda \neq 0\ \&\ v_{SB} = 0$

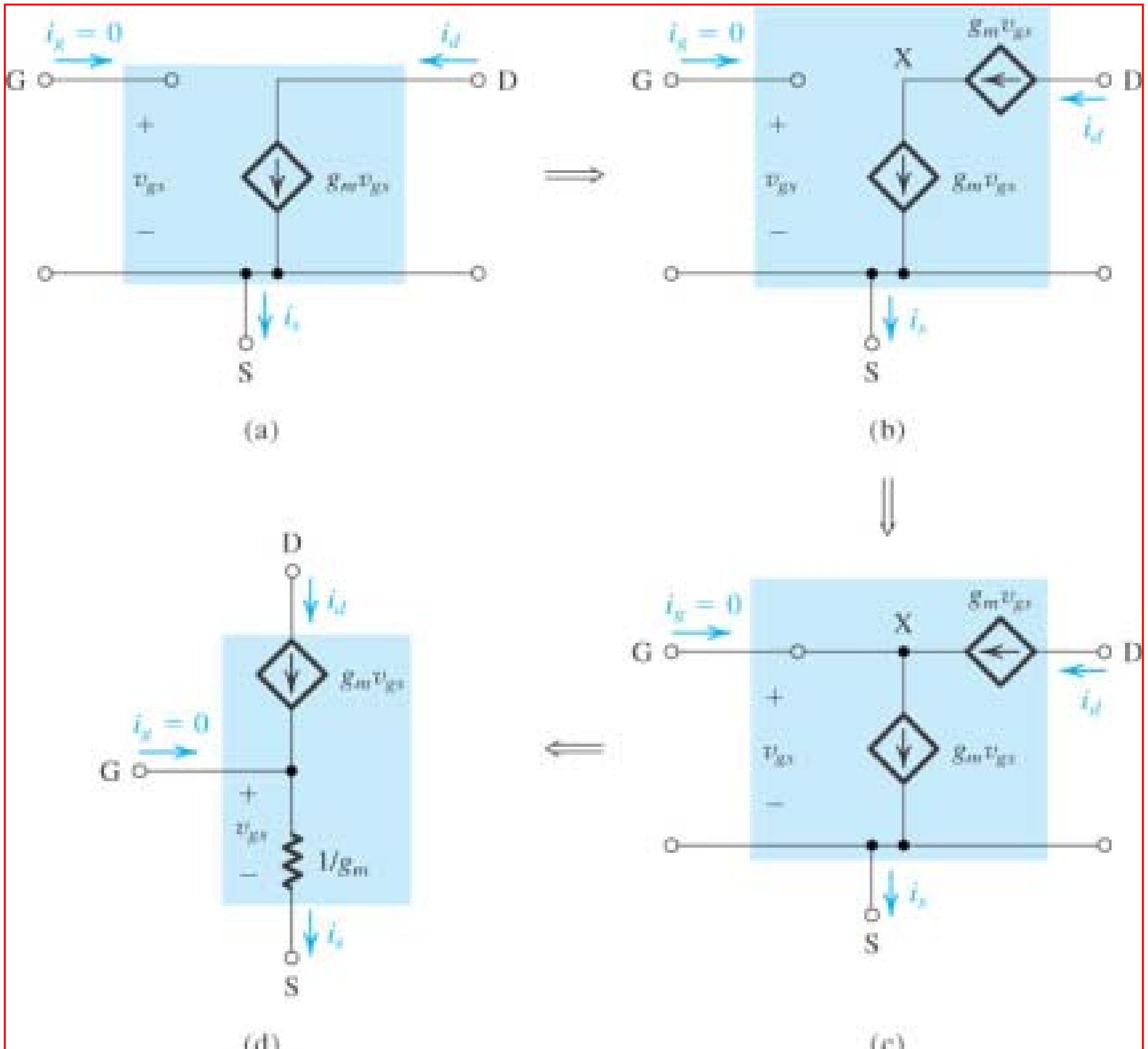


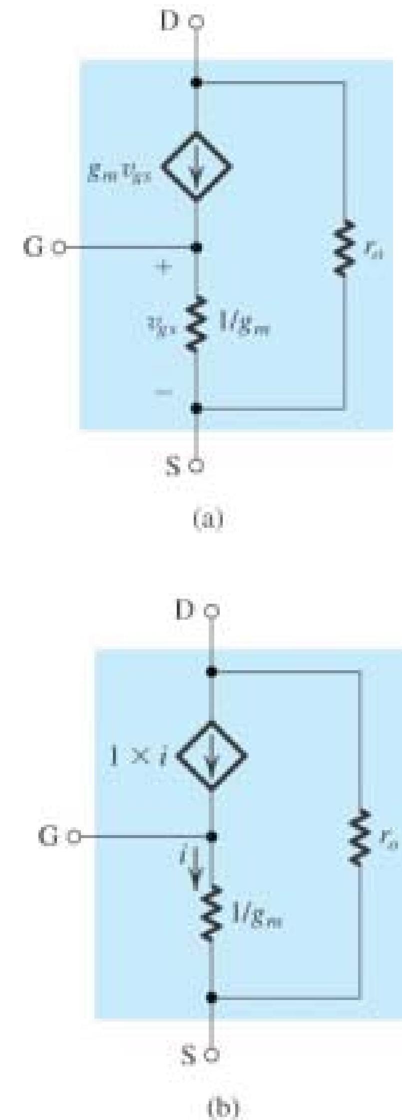
$\lambda \neq 0\ \&\ v_{SB} \neq 0$



(b)

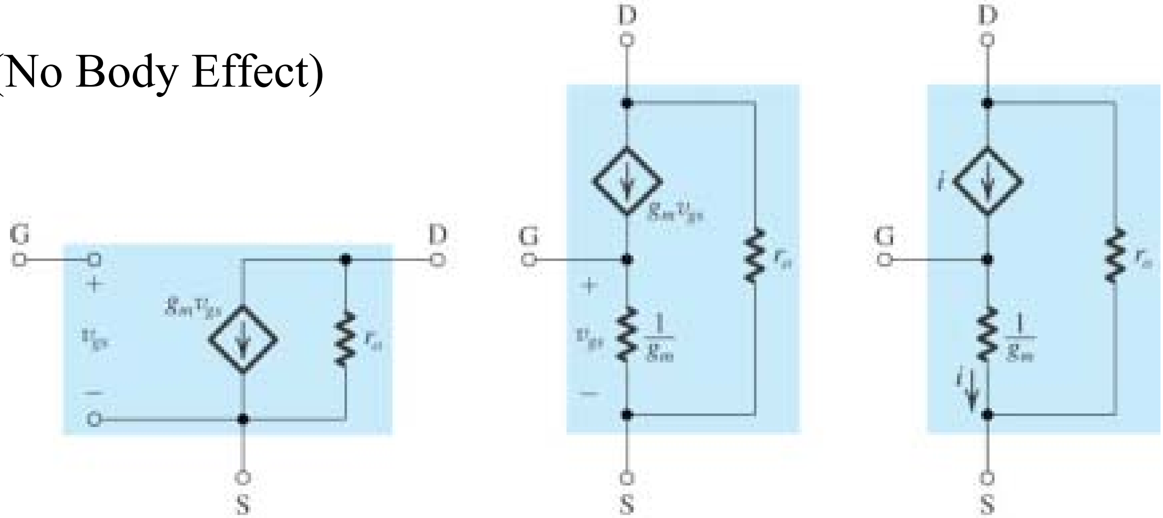
⊙ T-equivalent circuit



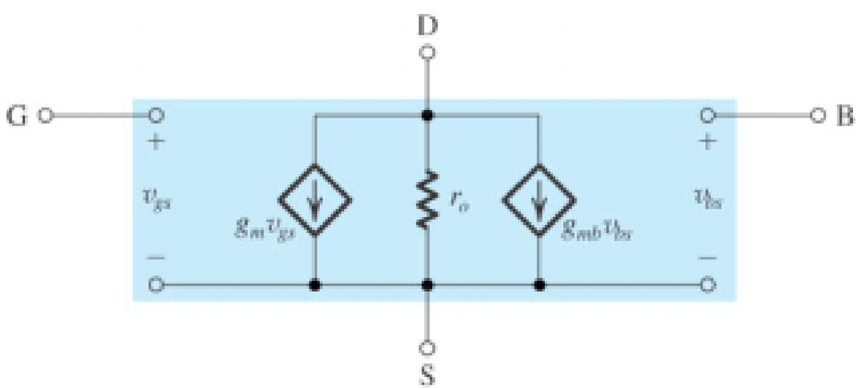


Summary (small-signal low-freq. equivalent circuit)

▶ $|V_{SB}|=0$ (No Body Effect)



▶ $|V_{SB}|\neq 0$ (including the Body Effect)



$$g_m = \beta_n V_{OV} = \sqrt{2\beta_n I_D} = \frac{2I_D}{V_{OV}}$$

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

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

⊙ Transconductance

▶ $g_m = \beta_n(V_{GS} - V_{tn}) = k_n'(W/L)(V_{GS} - V_{tn})$

▷ $\propto (V_{GS} - V_{tn})$

▷ $V_{GS}\uparrow \rightarrow g_m\uparrow$

$\rightarrow$ signal swing$\downarrow$

▶ $g_m = \sqrt{2\beta_n I_{DS}} = \sqrt{2k_n'(W/L)I_{DS}}$

▷ $\propto \sqrt{I_{DS}}$ for a given MOSFET (BJT: $\propto I_{DS}$)

▷ $\propto \sqrt{W/L}$ for a given bias current

▷ $I_{DS} = 1\text{mA},\ k_n' = 20\mu\text{A/V}^2$ $\rightarrow g_m = 0.2\text{mA/V}$ for $W/L = 1$

$\rightarrow g_m = 2\text{mA/V}$ for $W/L = 100$

(BJT: $g_m = 40\text{mA/V}$ for $I_C = 1\text{mA}$)

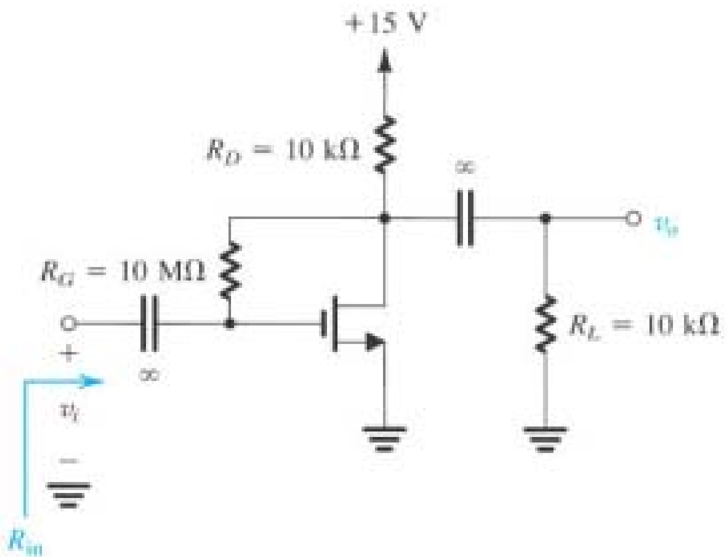
▶ $g_m = \dfrac{2I_{DS}}{V_{GS} - V_{tn}} = \dfrac{I_{DS}}{(V_{GS} - V_{tn})/2}$ (BJT: $g_m = \dfrac{I_C}{V_T}$)

※ $g_m = \beta \cdot V_{OV} = \sqrt{2\beta I_{DS}} = \dfrac{2I_{DS}}{V_{OV}}$ $(V_{OV} = V_{GS} - V_{tn})$

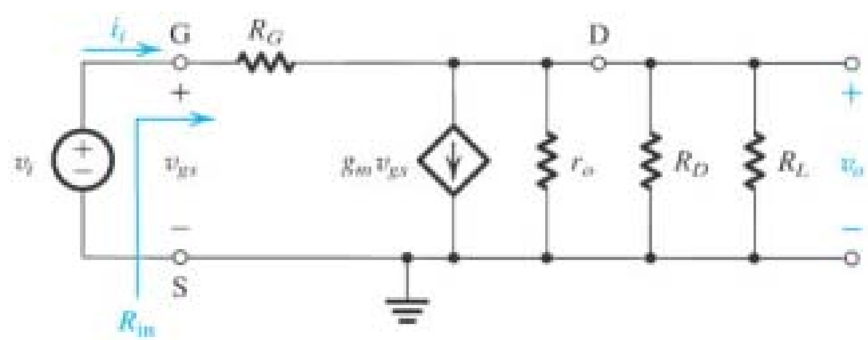
Example 2.1

Q) small-signal voltage gain & input resistance & the largest input signal?

$$V_{tn} = 1.5\text{V},\quad \beta_n = k_n^{'}(W/L) = 0.25\text{mA/V}^2,\quad V_A = 1/\lambda = 50\text{V}$$



(a)



(b)

<dc analysis>

$$I_D = \frac{\beta_n}{2}(V_{GS} - V_{tn})^2 = \frac{0.25}{2}(V_D - 1.5)^2$$

$$V_D = 15 - R_D I_D = 15 - 10 I_D$$

$$I_D = 1.06\text{mA}$$

$$V_D = 4.4\text{V}$$

2. 대신호와 소신호 등가회로, 고주파 등가회로

<ac analysis>

$$g_m = \beta_n V_{OV} = 0.25(4.4-1.5) = 0.725\text{mA/V} \qquad r_o = \frac{1}{\lambda I_D} = \frac{V_A}{I_D} = \frac{50}{1.06} = 47\text{k}\Omega$$

▶ voltage gain

$$A_v = \frac{v_o}{v_i} = -g_m(R_D \,//\, R_L \,//\, r_o) = -3.3\text{V/V}$$

▶ input resistance

$$i_i = \frac{v_i - v_o}{R_G} = \frac{v_i}{R_G}\left(1 - \frac{v_o}{v_i}\right) = \frac{v_i}{R_G}[1-(-3.3)] = \frac{4.3 v_i}{R_G} \qquad R_{in} = \frac{v_i}{i_i} = \frac{R_G}{4.3} = 2.33\text{M}\Omega$$

▶ the largest input signal

$$v_{DS} \ge v_{GS} - V_{tn} \quad \Rightarrow$$

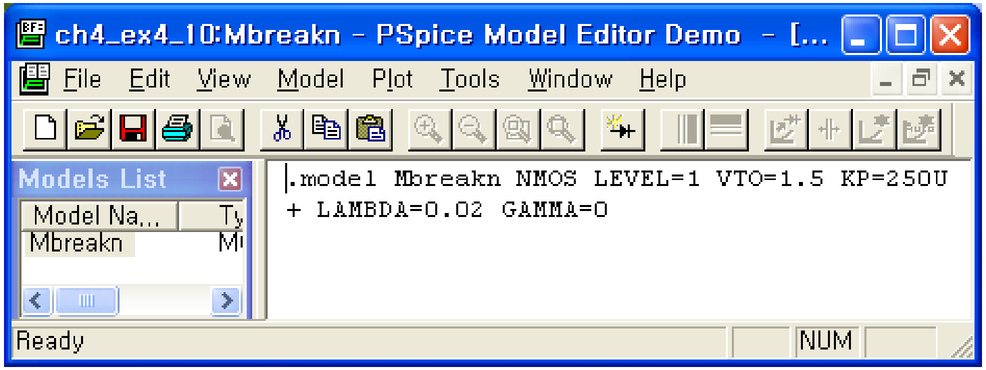
$$v_{DS\min} = v_{GS\max} - V_{tn}$$

$$V_{DS} - |A_v| v_{i\max} = V_{GS} + v_{i\max} - V_{tn}$$

$$4.4 - 3.3 v_{i\max} = 4.4 + v_{i\max} - 1.5$$

$$v_{i\max} = 0.34\text{V}$$

PSPICE Example



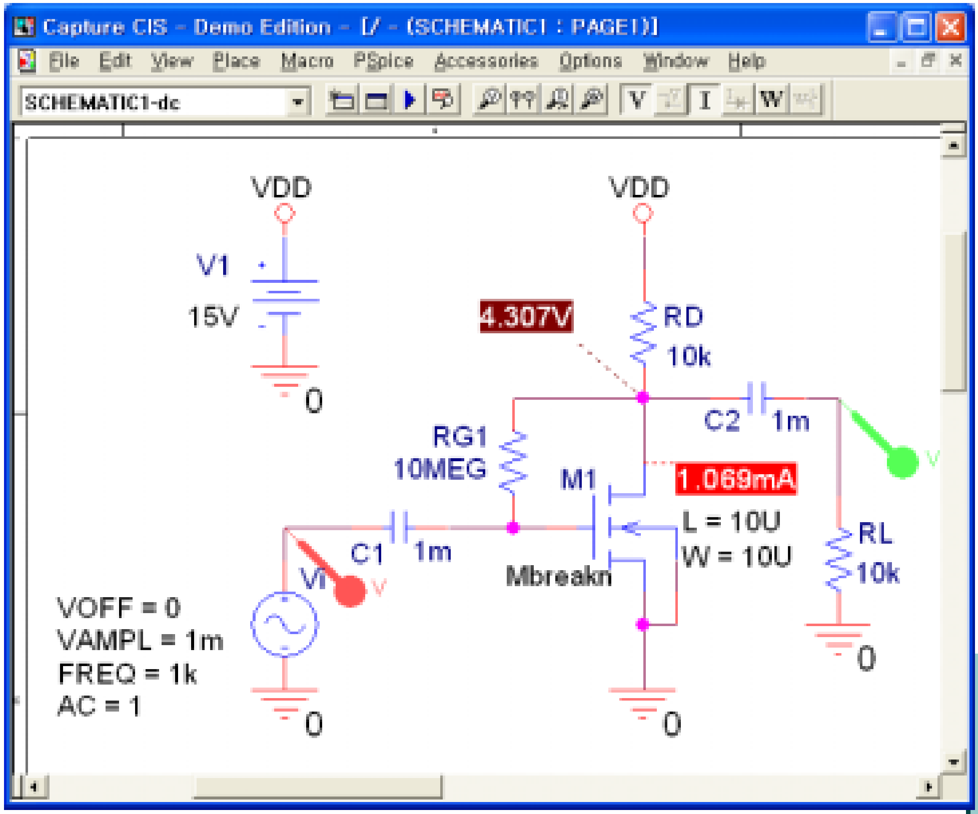
$V_t = 1.5\text{V} \rightarrow \text{VTO} = 1.5,\ \text{GAMMA} = 0$

$\beta_n = 0.25\text{mA/V}^2 \rightarrow \text{KP} = 250\text{U}$

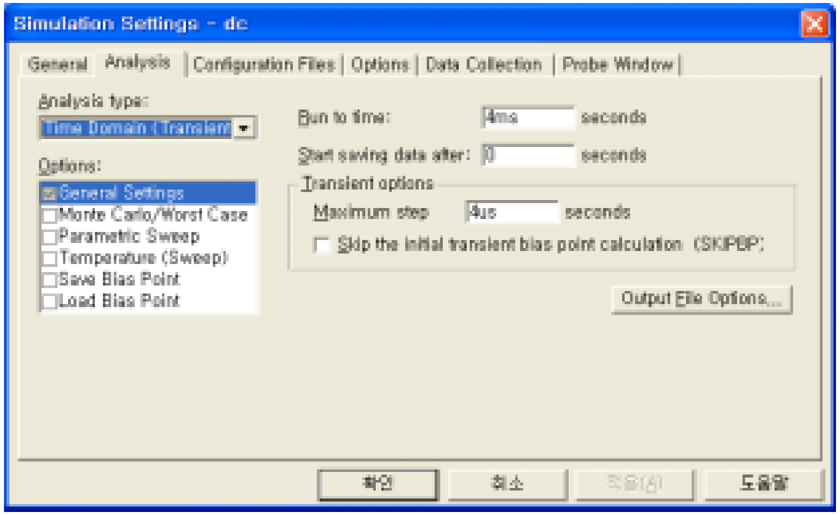
$\text{L} = 10\text{U},\ \text{W} = 10\text{U}$

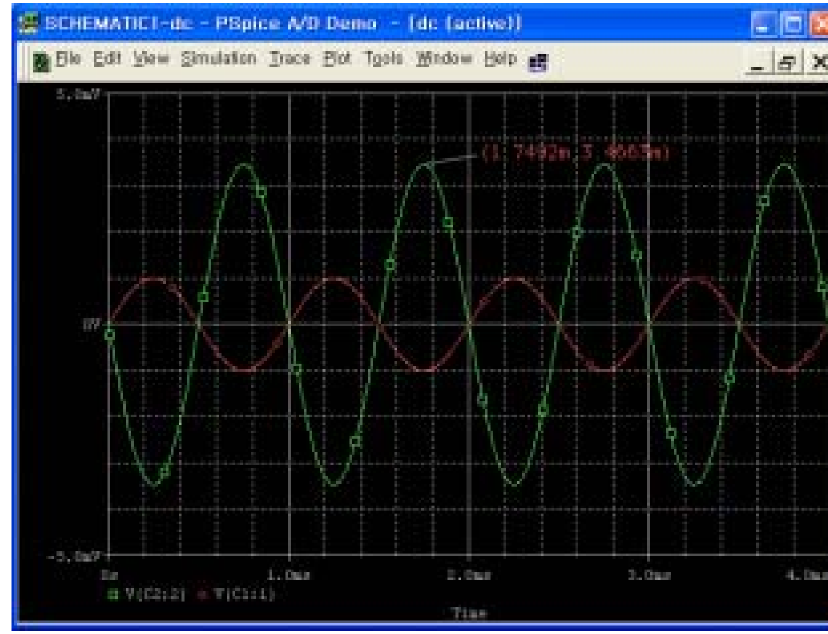
$V_A = 50\text{V} \rightarrow \lambda = 0.02$

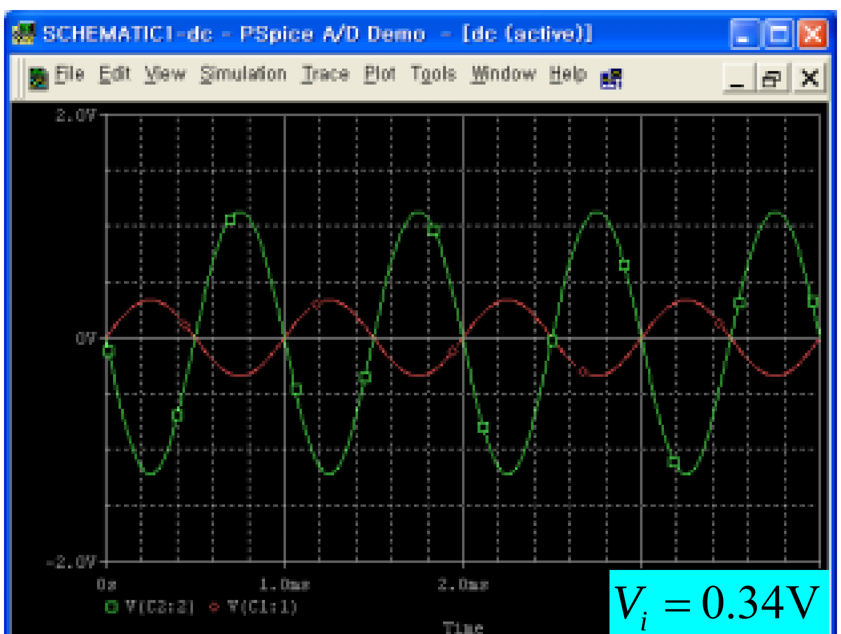
$\rightarrow \text{LAMBDA} = 0.02$

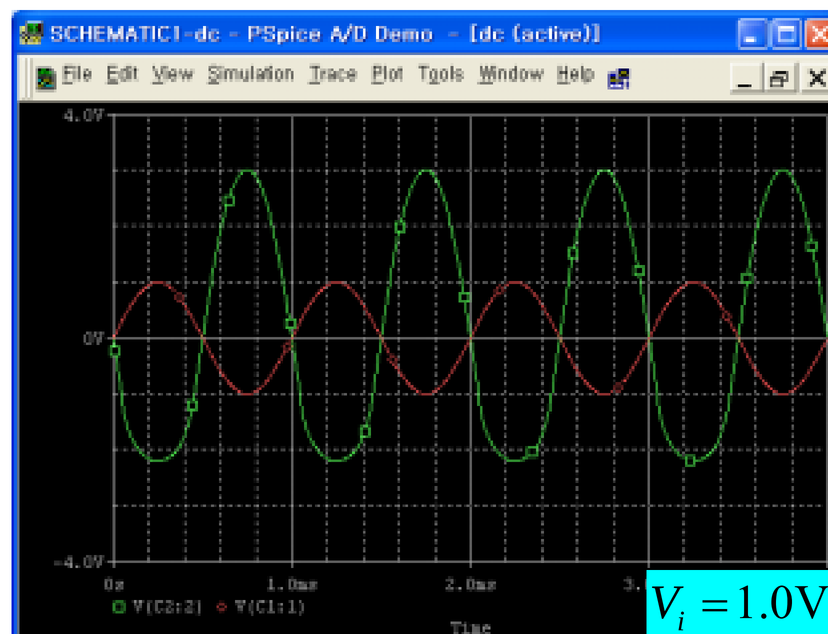


2. 대신호와 소신호 등가회로, 고주파 등가회로



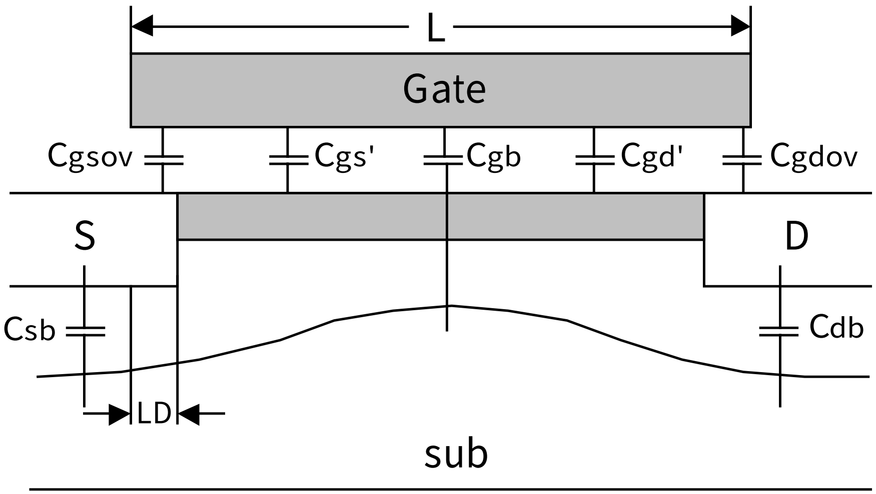


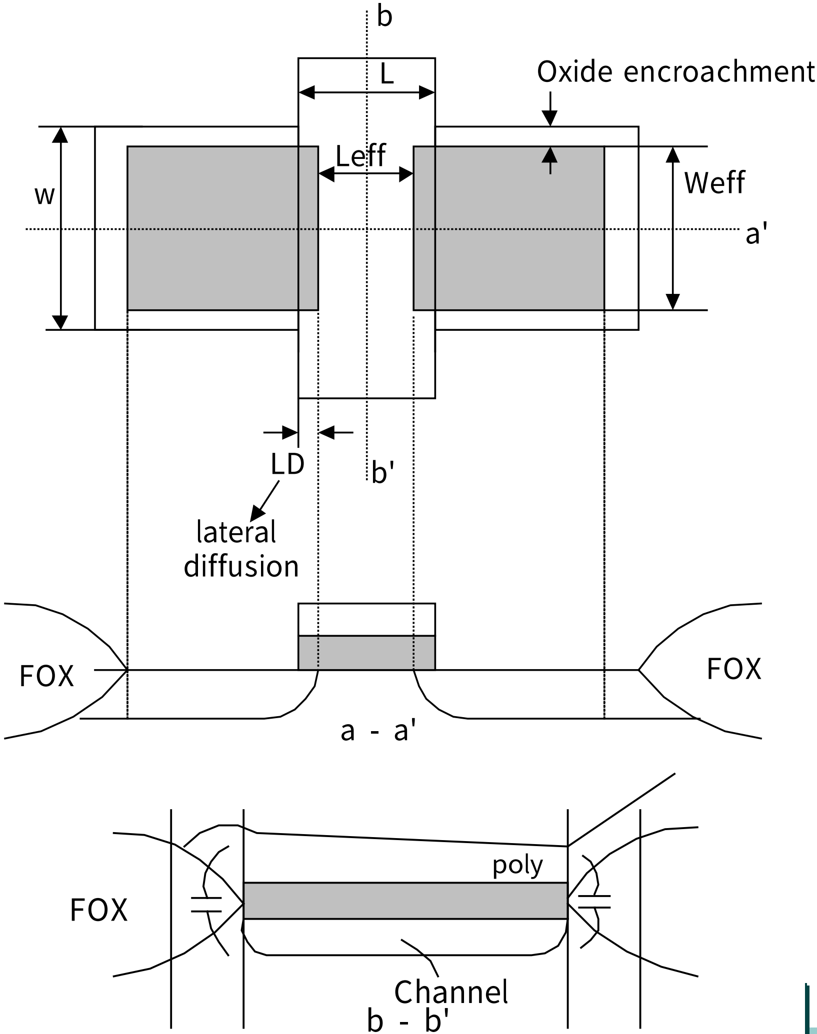




2. 대신호와 소신호 등가회로, 고주파 등가회로

⊙ Capacitors in MOSFET





$L_{eff} = L' = L - 2LD, \quad LD = L_{ov}$

$C_{gs} = C_{gs}' + C_{gsov}$: gate to source capacitance

$C_{gd} = C_{gd}' + C_{gdov}$: gate to drain capacitance

C_{gb} : gate to bulk capacitance (C_{gbov} is negligible)

C_{sb} : source to substrate capacitance

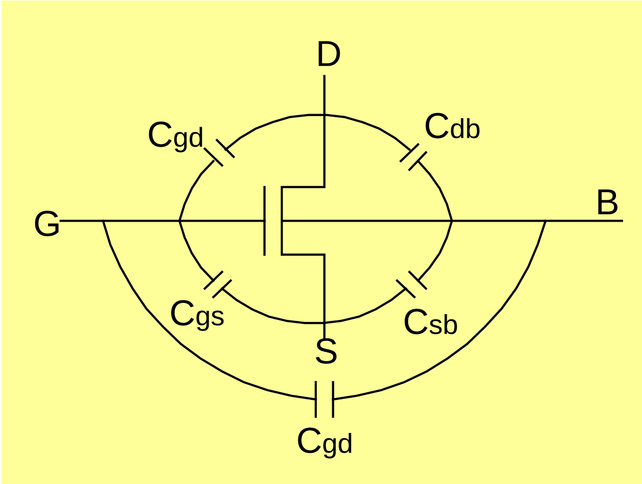
C_{db} : drain to substrate capacitance

2. 대신호와 소신호 등가회로, 고주파 등가회로

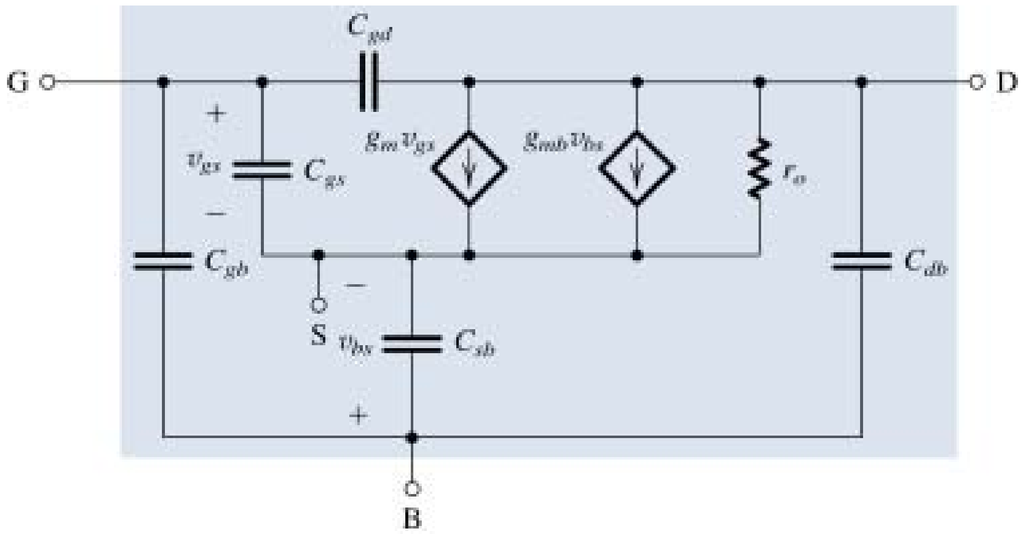
Region	Cutoff	Saturation	Linear
C_{gs}	$WL_{ov}C_{ox}$	$WC_{ox}[L_{ov}+(2/3)L']$	$WC_{ox}[L_{ov}+(1/2)L']$
C_{gd}	$WL_{ov}C_{ox}$	$WL_{ov}C_{ox}$	$WC_{ox}[L_{ov}+(1/2)L']$
C_{gb}	$WL'C_{ox}$	$(1/3)WL'(C_{ox}//C_{dep})$	0
C_{sb}	$A_sC_{ja}(V_{sb})+P_sC_{jp}(V_{sb})$	$A_sC_{ja}(V_{sb})+P_sC_{jp}(V_{sb})$ $+(2/3)WL'C_{ja}(V_{sb})$	$A_sC_{ja}(V_{sb})+P_sC_{jp}(V_{sb})$ $+(1/2)WL'C_{ja}(V_{sb})$
C_{db}	$A_dC_{ja}(V_{db})+P_dC_{jp}(V_{db})$	$A_dC_{ja}(V_{db})+P_dC_{jp}(V_{db})$	$A_dC_{ja}(V_{db})+P_dC_{jp}(V_{db})$ $+(1/2)WL'C_{ja}(V_{db})$
C_g	WLC_{ox}		WLC_{ox}

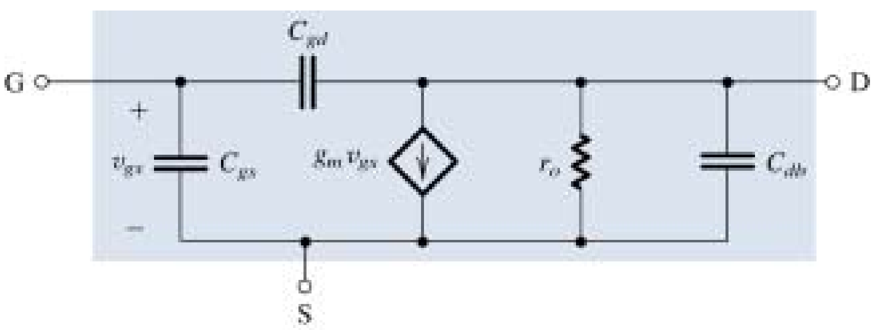
※ Total gate capacitance

$$C_g = C_{gs} + C_{gd} + C_{gb}$$

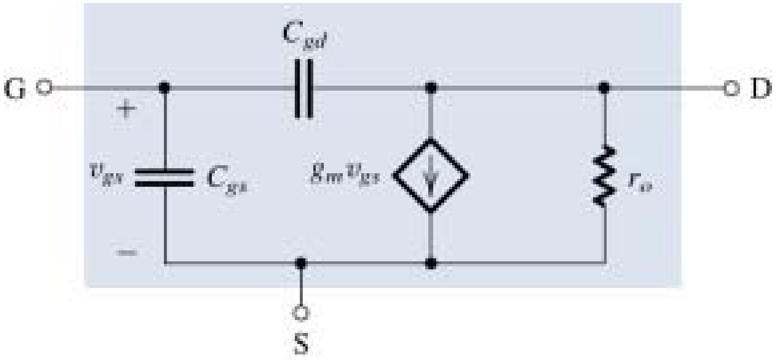


⊙ MOSFET high-frequency equivalent circuit



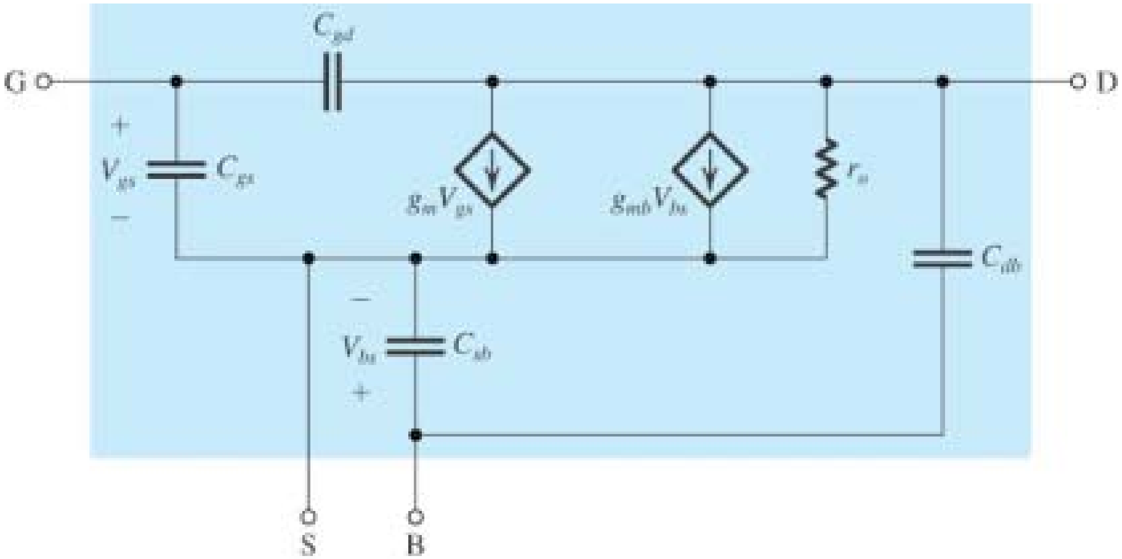


(b)



(c)

Summary (small-signal high-freq. equivalent circuit)



$$g_m = \beta_n V_{OV} = \sqrt{2\beta_n I_D} = \frac{2I_D}{V_{OV}}$$

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

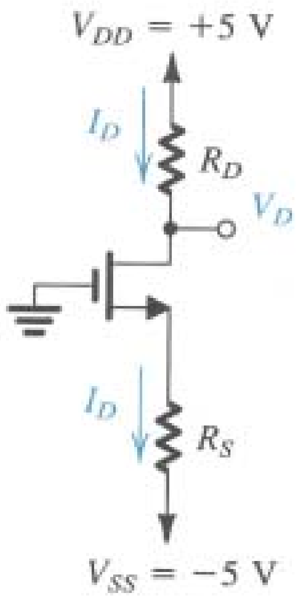
$$g_{mb} = \chi g_m = \frac{\gamma}{2\sqrt{2\phi_f + V_{SB}}} g_m$$

$$C_{gs} = \frac{2}{3} WLC_{ox} + WL_{ov}C_{ox}$$

$$C_{gd} = WL_{ov}C_{ox}$$

$$C_{sb} = \frac{C_{sb0}}{\sqrt{1 + \frac{V_{SB}}{V_0}}} \qquad C_{db} = \frac{C_{db0}}{\sqrt{1 + \frac{V_{DB}}{V_0}}}$$

⊙ Example 3.1



Design the circuit $R_D,\ R_S$?

$$I_D = 0.4\text{mA},\quad V_D = 1\text{V}$$

$$V_t = 2\text{V},\quad \mu_n C_{ox} = 20\mu\text{A/V}^2$$

$$L = 10\mu\text{m},\quad W = 400\mu\text{m},\quad \lambda = 0$$

▶ Solution

$$V_{GD} = -1\text{V} < V_t \quad \therefore \text{ saturation}$$

$$I_D = \frac{\mu_n C_{ox}}{2}\frac{W}{L}(V_{GS} - V_t)^2$$

$$0.4 = \frac{20\times10^{-3}}{2}\frac{400}{10}(V_{GS} - 2)^2 \quad \rightarrow \quad V_{GS} = 1 \text{ or } 3 \quad \rightarrow \quad V_{GS} = 3\text{V}$$

$$R_S = \frac{V_S - V_{SS}}{I_D} = \frac{-3-(-5)}{0.4} = 5\text{k}\Omega \qquad R_D = \frac{V_{DD} - V_D}{I_D} = \frac{5-1}{0.4} = 10\text{k}\Omega$$

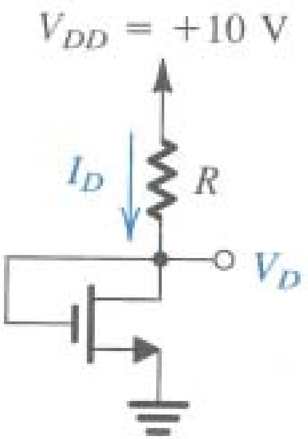
⊙ Example 3.2

Design the circuit $R,\ V_D$?

$$I_D = 0.4\text{mA}$$

$$V_t = 2\text{V},\ \mu_n C_{ox} = 20\mu\text{A/V}^2$$

$$L = 10\mu\text{m},\ W = 100\mu\text{m},\ \lambda = 0$$



▶ Solution

$$V_{GD} = 0\text{V} < V_t \quad \therefore \text{ saturation}$$

$$I_D = \frac{\mu_n C_{ox}}{2}\frac{W}{L}(V_{GS} - V_t)^2$$

$$0.4 = \frac{20\times 10^{-3}}{2}\frac{100}{10}(V_{GS} - 2)^2 \quad \rightarrow \quad V_{GS} = 4 \text{ or } 0 \quad \rightarrow \quad V_{GS} = V_D = 4\text{V}$$

$$R = \frac{V_{DD} - V_D}{I_D} = \frac{10 - 4}{0.4} = 15\text{k}\Omega$$

3. 직류 해석 (동작점 설정법)

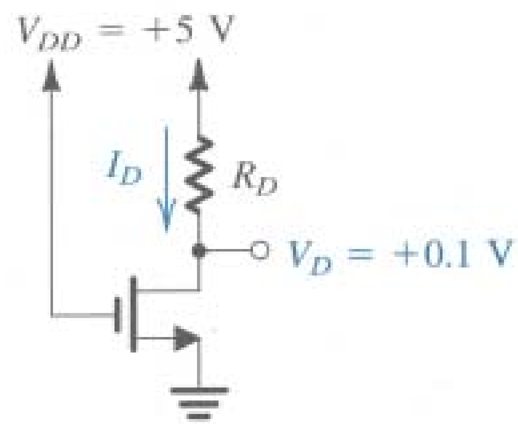
⊙ Example 3.3

Design the circuit R_D ?

$$V_D = 0.1\text{V}$$

$$V_t = 1\text{V},\ \beta_n = \mu_n C_{ox}(W/L) = 1\text{mA/V}^2$$

Effective resistance between D & S, r_D ?



▶ Solution

$$V_{GD} = 4.9\text{V} > V_t \quad \therefore \ \text{triode}$$

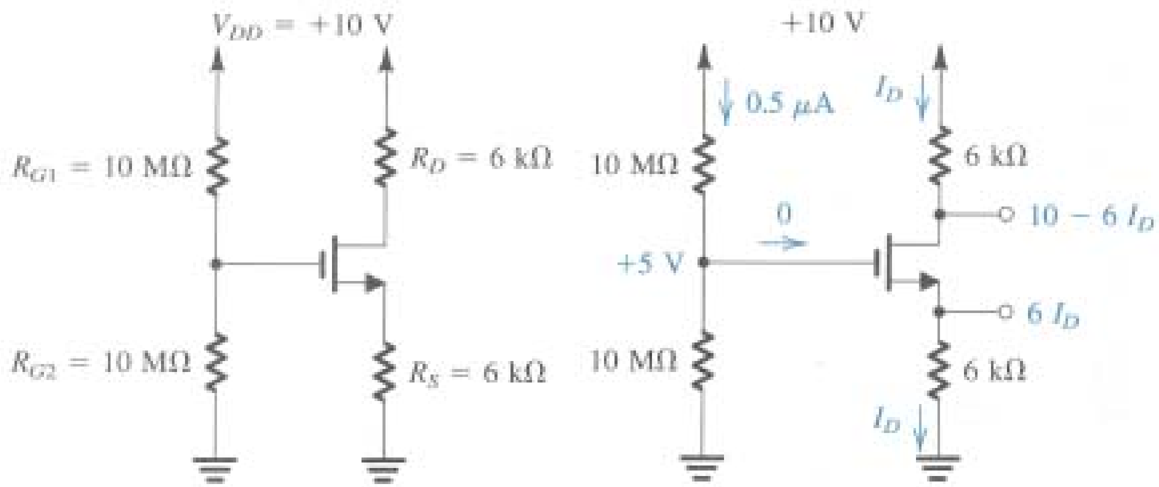
$$I_D = \beta_n\left[(V_{GS} - V_t)V_{DS} - \frac{V_{DS}^2}{2}\right] = 1\times\left[(5-1)\times 0.1 - \frac{0.01}{2}\right] = 0.359\text{mA}$$

$$R_D = \frac{V_{DD} - V_D}{I_D} = \frac{5-0.1}{0.395} = 12.4\text{k}\Omega$$

$$r_{DS} = \frac{V_{DS}}{I_D} = \frac{0.1}{0.395} = 253\Omega$$

⊙ Example 3.4

Determine the node voltages and the branch currents $(V_t = 1\text{V},\ \beta_n = 1\text{mA/V}^2, \lambda = 0)$



▶ Solution

Assume saturation :

$$V_{GS} = V_G - 6I_D = 5 - 6I_D \qquad I_D = \frac{\beta_n}{2}(V_{GS} - V_t)^2 = \frac{1}{2}(5 - 6I_D - 1)^2$$

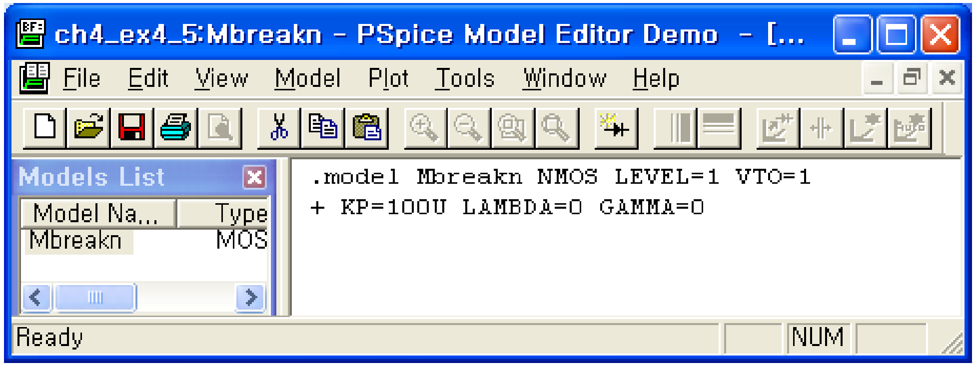
$$18I_D^2 - 25I_D + 8 = 0 \ \rightarrow\ I_D = 0.89\text{mA} \ \text{or}\ 0.5\text{mA}$$

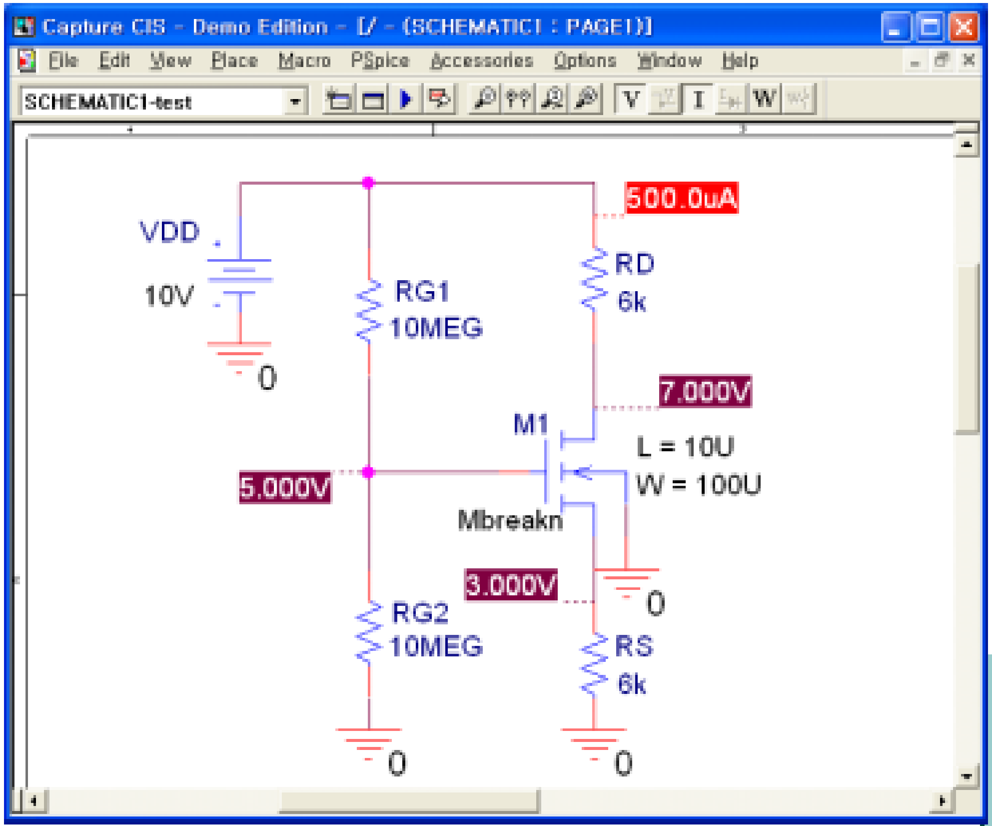
$$I_D = 0.89\text{mA} \ \rightarrow\ V_S = 0.89 \times 6 = 5.34\text{V} \ \rightarrow\ \text{cutoff} \qquad \therefore\ I_D = 0.5\text{mA}$$

$$V_S = 3\text{V},\ V_{GS} = 2\text{ V},\ V_D = 10 - 6 \times 0.5 = 7\text{V}$$

$$V_{GD} = -2\text{ V} < V_t \qquad \therefore\ \text{saturation}$$

PSPICE Example





$V_t = 1\text{V} \rightarrow \text{VTO} = 1,\ \text{GAMMA} = 0$

$\beta_n = 1\text{mA/V}^2 \rightarrow \text{KP} = 100\text{E-6}$
$\text{L} = 10\text{U},\ \text{W} = 100\text{U}$

$\lambda = 0 \rightarrow \text{LAMBDA} = 0$

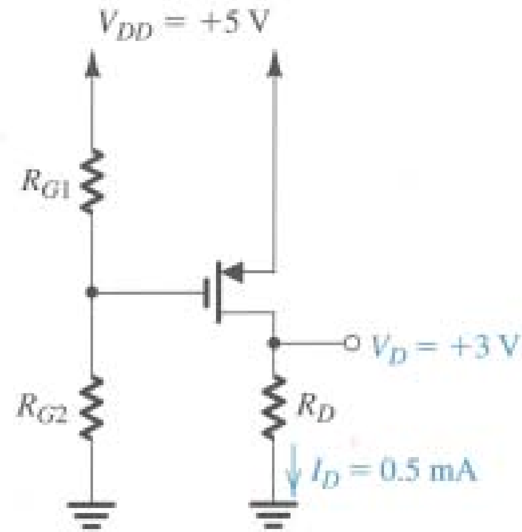
⊙ Example 3.5

Design the circuit (saturation)

$$I_D = 0.5\text{mA},\ \ V_D = 3\text{V}$$

$$V_t = -1\text{V},\ \beta_p = 1\text{mA/V}^2,\ \lambda = 0$$

Largest R_D for saturation ?



▶ Solution

$$I_{SD} = \frac{\beta_p}{2}(V_{SG} - |V_t|)^2$$

$$0.5 = \frac{1}{2}(V_{SG} - 1)^2 \ \rightarrow\ V_{SG} = 2 \text{ or } 0 \ \rightarrow\ V_{SG} = 2\text{V}$$

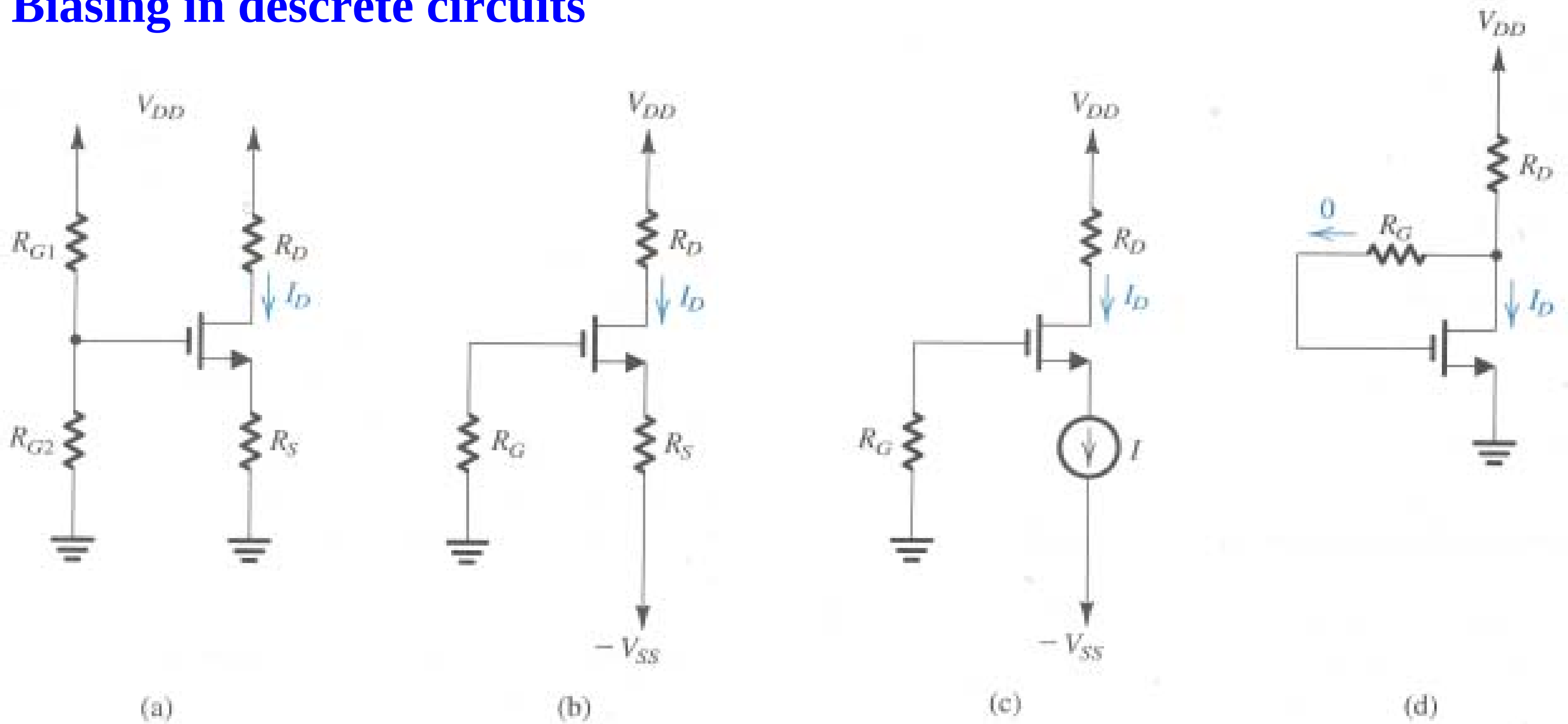
$$\therefore\ V_G = 3\text{V} \ \rightarrow\ R_{G1} = 2\text{M}\Omega \ \ \&\ R_{G2} = 3\text{M}\Omega, \qquad R_D = V_D / I_D = 6\text{k}\Omega$$

For saturation :

$$V_{DG} \le |V_t| \ \rightarrow\ V_D \le V_G + |V_t| = 4\text{V} \quad \therefore\ V_{D,\max} = 4\text{V},\ \ R_{D,\max} = 4/0.5 = 8\text{k}\Omega$$

3. 직류 해석 (동작점 설정법)

⊙ Biasing in descrete circuits



- ▶ Biasing or Bias design
  - ▷ establishment of a dc operating point for the transistors
  - ▷ stable and predictable I_D and V_{DS}
- ▶ somewhat easier ∵ $I_G = 0$ → R_{G1} & R_{G2} can be very high → high R_{in}
- ▶ self-bias resistor R_S → provides negative feedback → stabilize I_D
- ▶ R_D should be large for high gain but small enough for desired signal swing

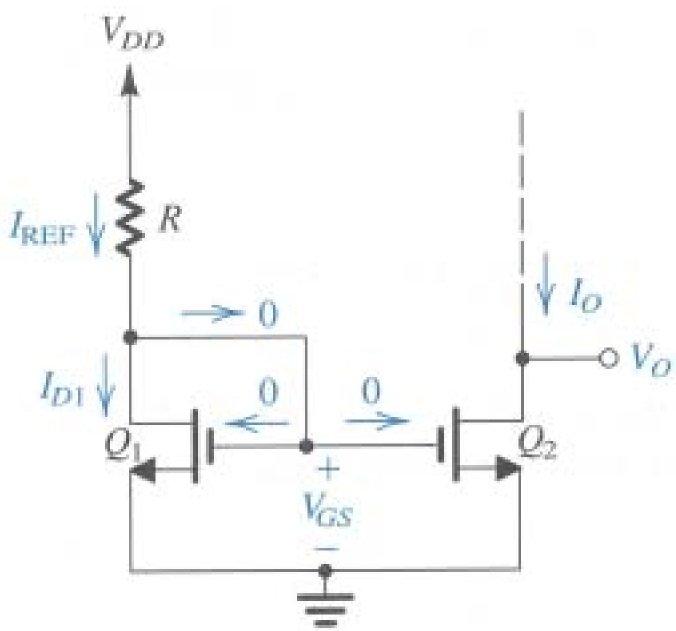
⊙ Biasing in integrated circuits

- ▶ the use of resistors are discouraged in MOS IC design
  - ▷ requires relatively large area
  - ▷ exhibits large tolerances
- ▶ the use of large coupling and bypass capacitors is impossible
- ▶ MOSFETs are utilized
  - ▷ can be fabricated in a small area
  - ▷ its parameters are relatively well controlled
- ▶ biasing of IC MOS amplifiers utilizes constant current sources

⊙ Basic MOSFET current source

- ▶ a simple MOS current source or current mirror
  - ▷ resistor R would be outside the IC chip

- ▶ assume $\lambda = 0$



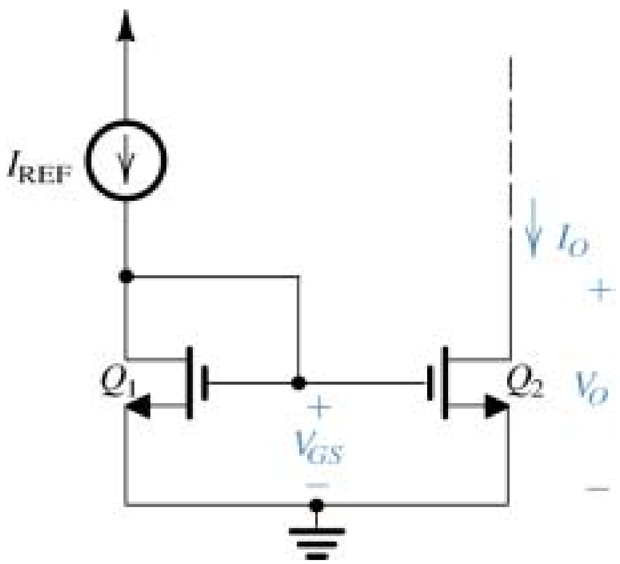
$$I_{D1} = \frac{k_n'}{2}\left(\frac{W}{L}\right)_1 (V_{GS} - V_t)^2$$

$$I_{D1} = I_{REF} = \frac{V_{DD} - V_{GS}}{R}$$

$$I_{D2} = I_O = \frac{k_n'}{2}\left(\frac{W}{L}\right)_2 (V_{GS} - V_t)^2$$

$$\frac{I_O}{I_{REF}} = \frac{(W/L)_2}{(W/L)_1}$$

⊙ Basic MOSFET current mirror



▶ Q2 should operate in saturation

$$V_O \geq V_{GS} - V_t$$

▶ channel-length modulation effect

$$\frac{I_O}{I_{REF}} = \frac{(W/L)_2(1+\lambda V_{DS2})}{(W/L)_1(1+\lambda V_{DS1})}$$

▶ finite output resistance

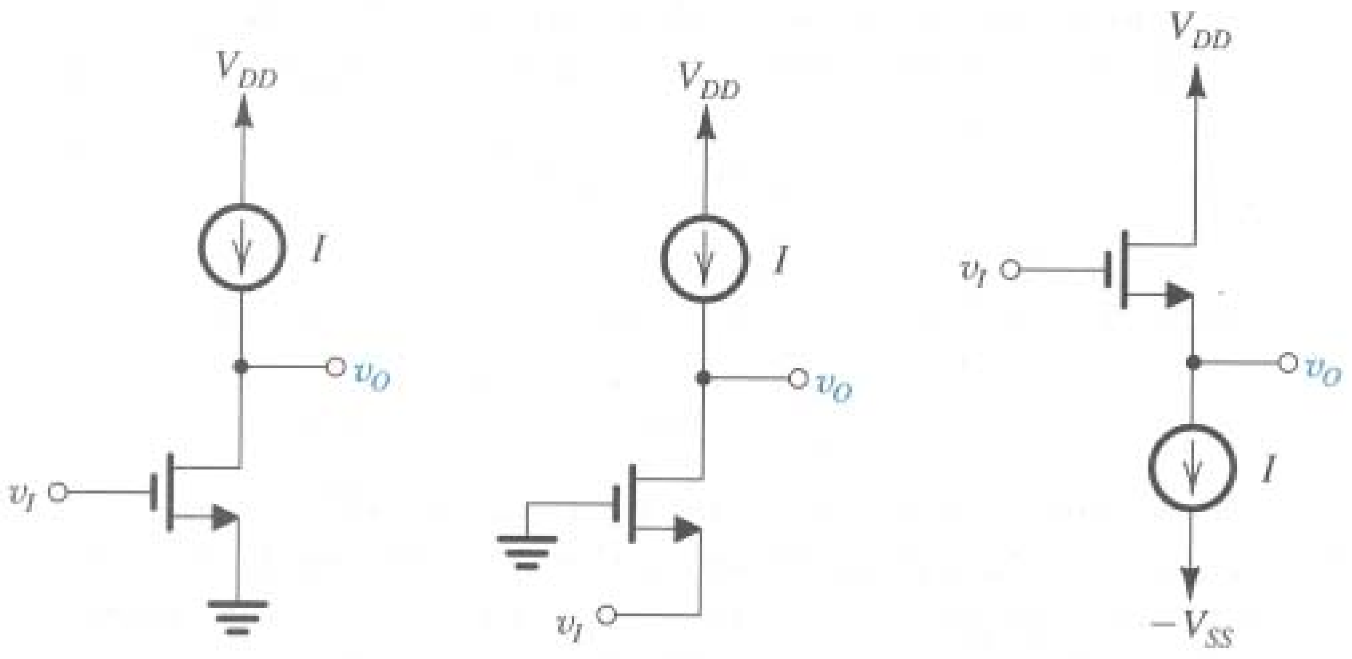
$$R_o = \frac{\Delta V_O}{\Delta I_O} = r_{o2} = \frac{V_{A2}}{I_O}$$

$$V_A \propto L \quad \therefore\ L \uparrow \rightarrow R_o \uparrow$$

4. 공통-소스, 게이트, 드레인 증폭기의 소신호 해석

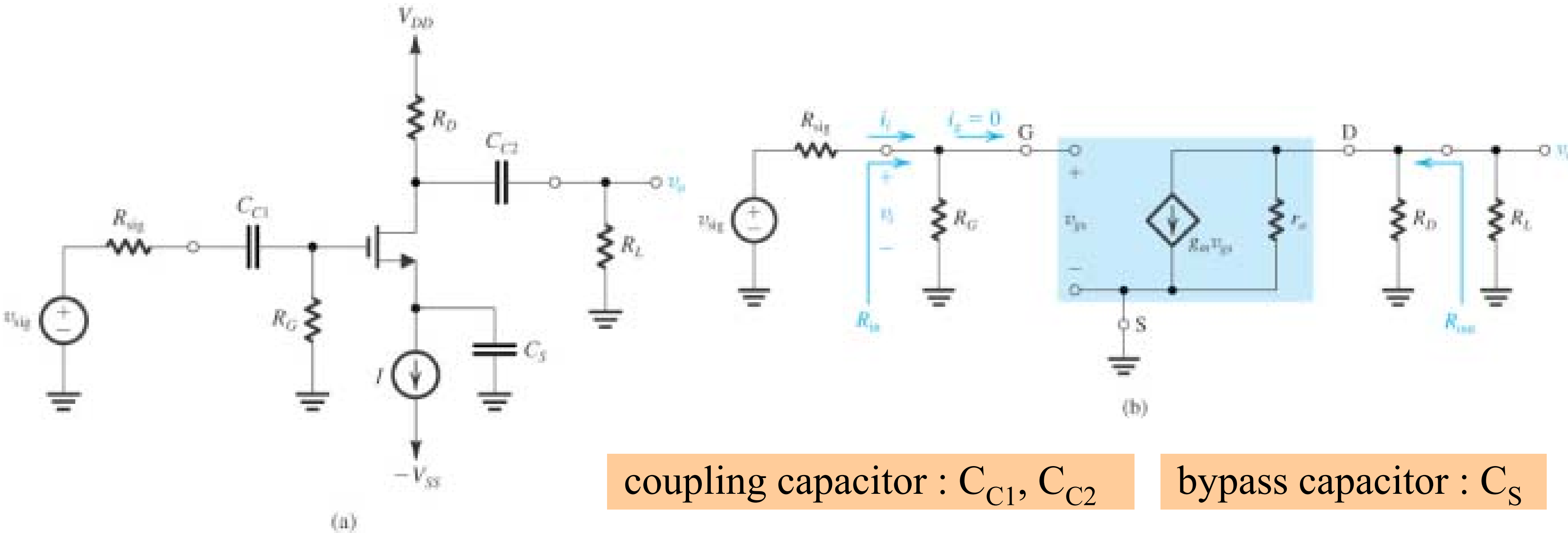
⊙ Basic configurations of single-stage IC MOS amplifiers

(a) Common-source (CS)
(b) Common-gate (CG)
(c) Common-drain (CD)



(a) (b) (c)

⊙ CMOS common-source amplifier

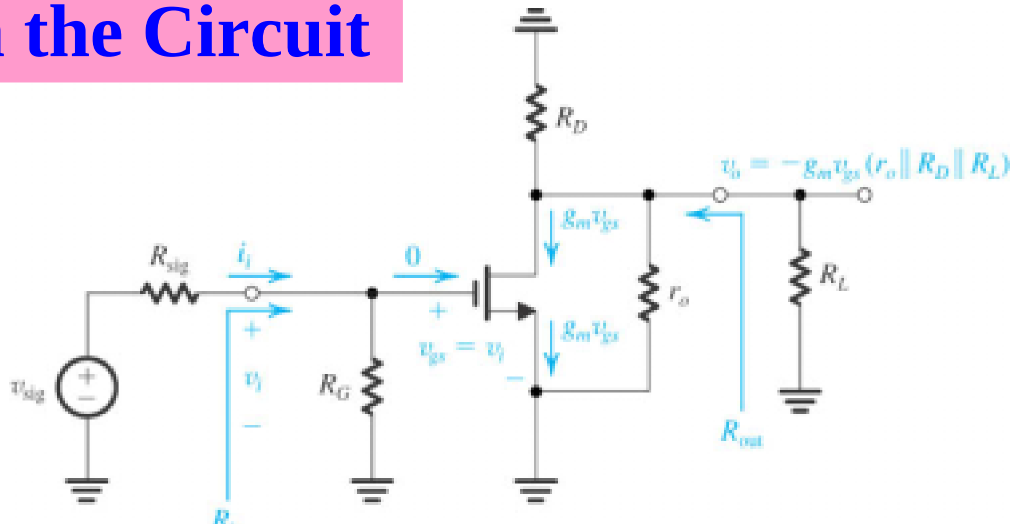


coupling capacitor : C_{C1}, C_{C2}

bypass capacitor : C_S

- ▶ input resistance : $R_{in} = R_G$
- ▶ output resistance : $R_{out} = r_o \,//\, R_D$
- ▶ voltage gain : $A_v = -g_m(r_o \,//\, R_D \,//\, R_L)$
- ▶ overall voltage gain : $G_v = -\dfrac{R_G}{R_G + R_{sig}} g_m(r_o \,//\, R_D \,//\, R_L)$
- ▶ applications : part of a larger amplifier circuit

Directly on the Circuit



(c)

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

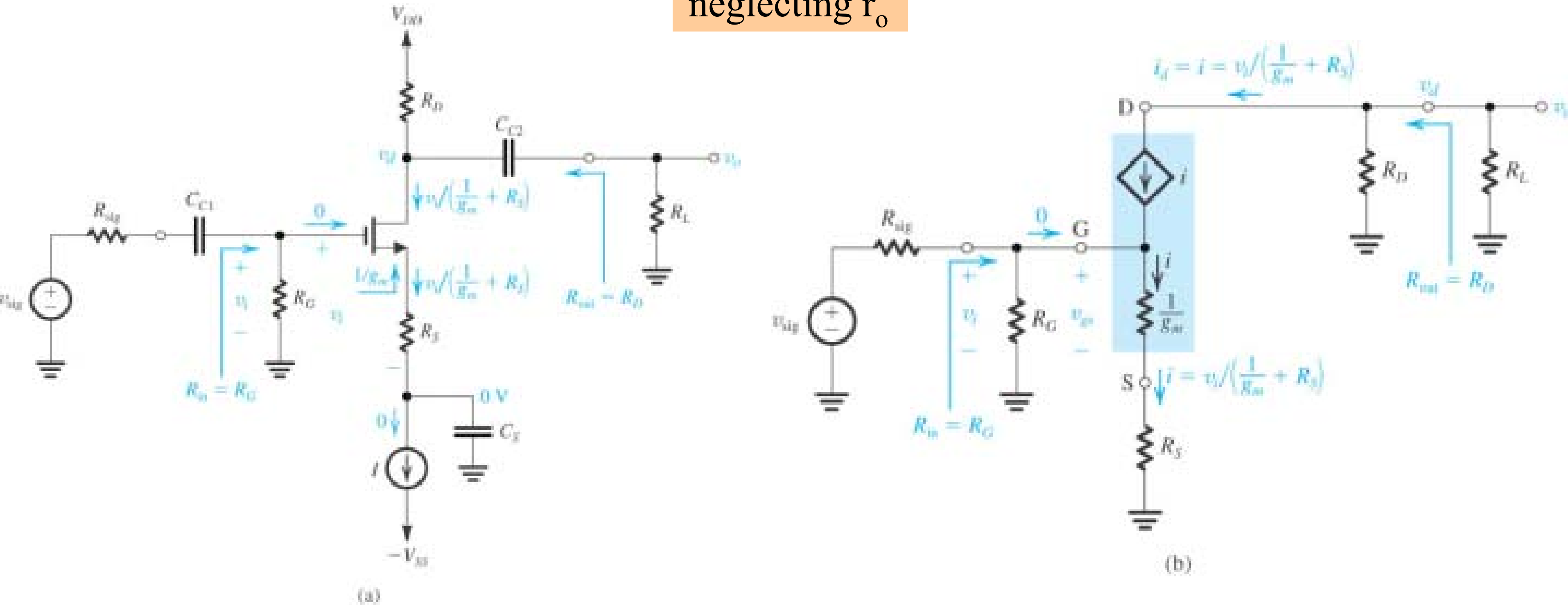
$$G_m \equiv \left.\frac{i_o}{v_i}\right|_{R_L=0} = -g_m \qquad R_{out,total} = r_o \,//\, R_D \,//\, R_L$$

$$A_v = \frac{v_o}{v_i} = G_m R_{out,total} = -g_m (r_o \,//\, R_D \,//\, R_L)$$

$$G_v = \frac{v_o}{v_{sig}} = \frac{v_i}{v_{sig}} \frac{v_o}{v_i} = -\frac{R_G}{R_G + R_{sig}} g_m (r_o \,//\, R_D \,//\, R_L)$$

⊙ CMOS common-source amplifier with a source resistance

neglecting r_o



▶ input resistance : $R_{in} = R_G$

▶ output resistance : $R_{out} = R_D$

4. 공통-소스, 게이트, 드레인 증폭기의 소신호 해석

▶ voltage gain :

$$v_{gs} = \frac{1/g_m}{(1/g_m) + R_S} v_i = \frac{v_i}{1 + g_m R_S}$$

$$i_d = i = \frac{v_i}{(1/g_m) + R_S} = \frac{g_m v_i}{1 + g_m R_S}$$

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

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

▶ overall voltage gain : $G_v = -\frac{R_G}{R_G + R_{sig}} \frac{g_m (R_D // R_L)}{1 + g_m R_S}$

▶ source degeneration resistor R_S : reduction of the gain by $1 + g_m R_S)$

Directly on the Circuit

$$v_i = v_{gs} + R_S i_d = i_d / g_m + R_S i_d = (1/g_m + R_S) i_d$$

$$G_m \equiv \left.\frac{i_o}{v_i}\right|_{R_L=0} = -\frac{i_d}{v_i} = -\frac{1}{1/g_m + R_S}$$

$$R_{out,total} = R_D // R_L$$

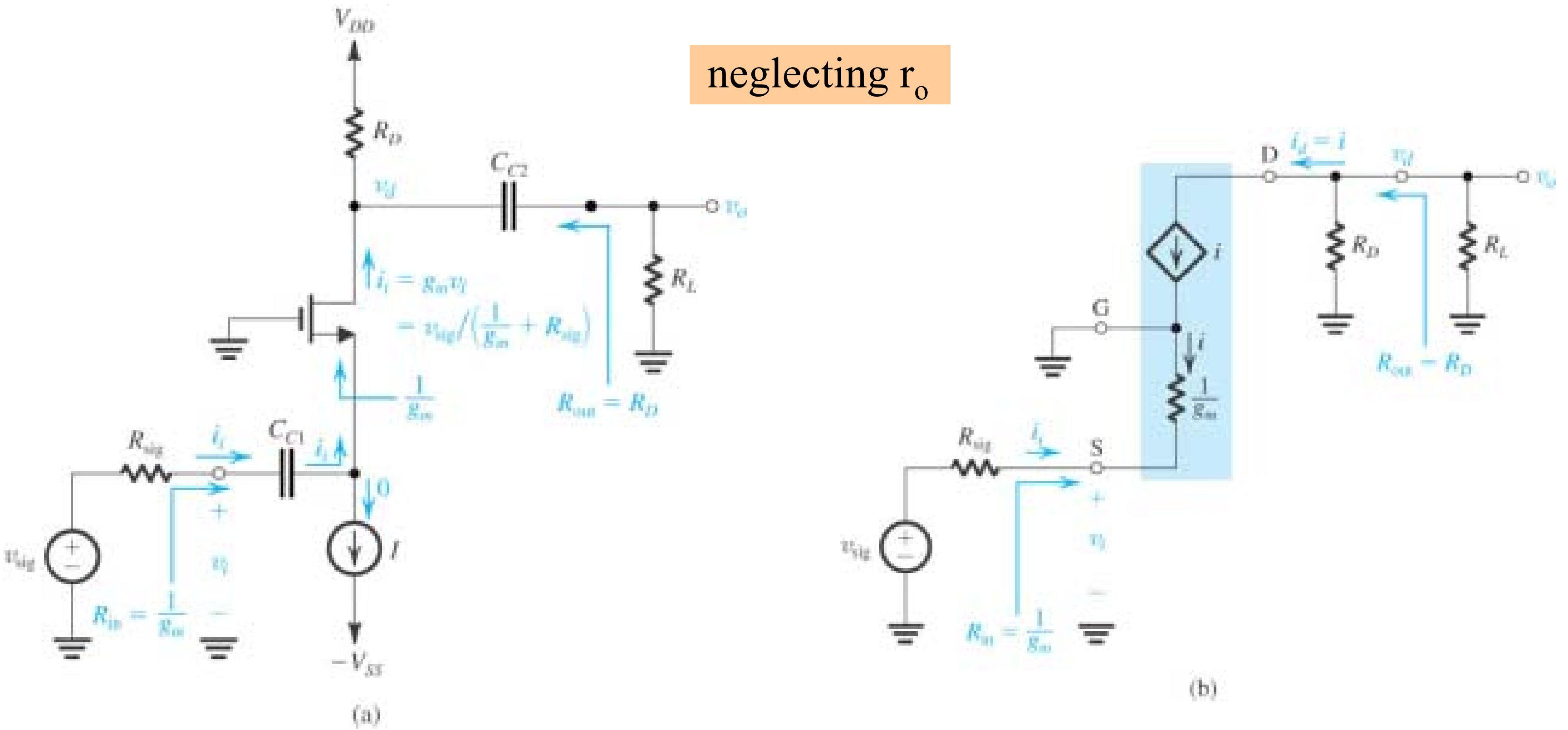
$$A_v = G_m R_{out,total} = -\frac{R_D // R_L}{1/g_m + R_S} = -\frac{g_m (R_D // R_L)}{1 + g_m R_S}$$

▶ useful interpretation :

$$A_v = -\frac{\text{total resistance in the drain}}{\text{total resistance in the source}} = -\frac{R_D // R_L}{1/g_m + R_S}$$

⊙ CMOS common-gate amplifier

neglecting r_o



▶ input resistance : $R_{in} = 1/g_m$

▶ output resistance : $R_{out} = R_D$

4. 공통-소스, 게이트, 드레인 증폭기의 소신호 해석

▶ voltage gain : $i_i = -i = -i_d = \frac{v_i}{R_{in}} = \frac{v_i}{1/g_m} = g_m v_i$

$$v_o = -i_d (R_D // R_L) = g_m (R_D // R_L) v_i$$

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

▶ overall voltage gain : $G_v = \frac{1/g_m}{1/g_m + R_{sig}} A_v = \frac{g_m (R_D // R_L)}{1 + g_m R_{sig}}$

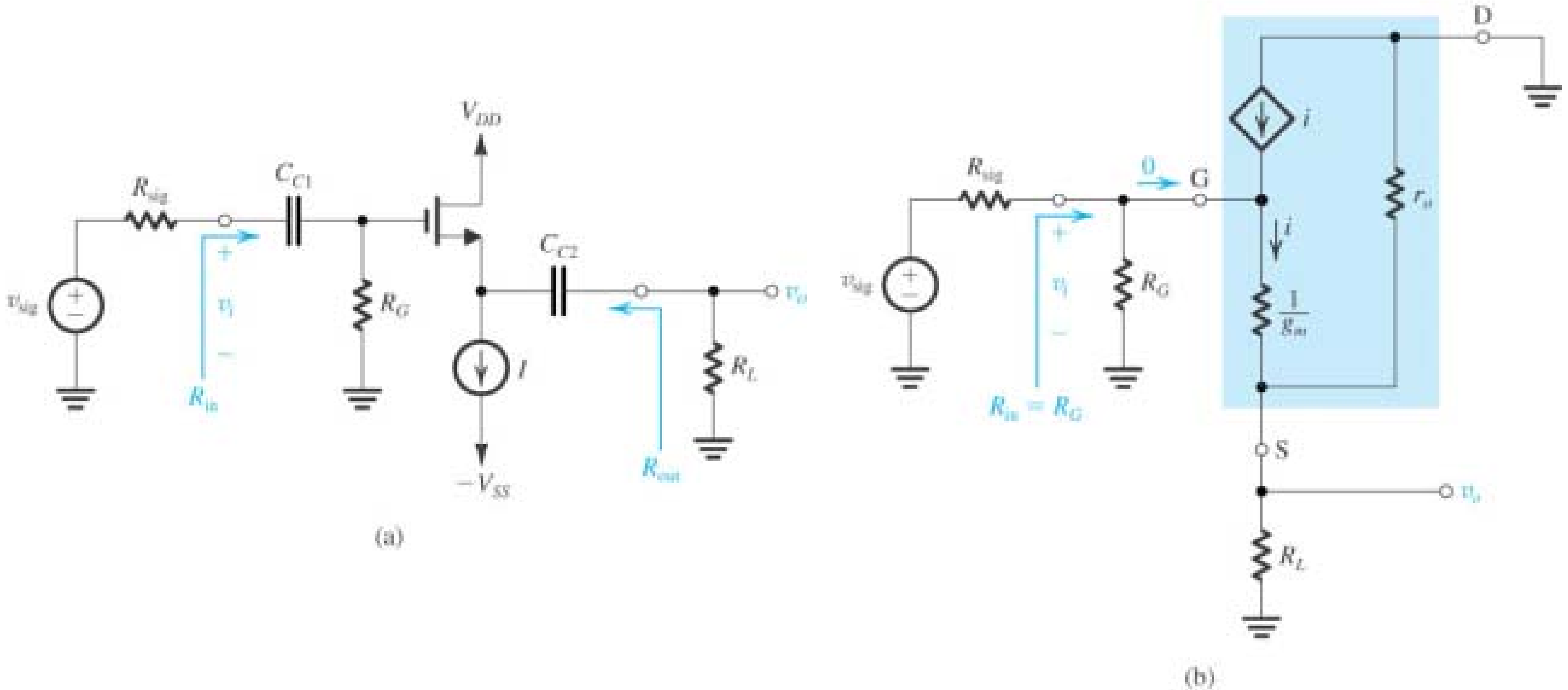
▶ applications : unity-gain current amplifier, cascode circuit

Directly on the Circuit

$$v_i = -v_{gs} = -i_d / g_m \qquad G_m \equiv \left. \frac{i_o}{v_i} \right|_{R_L = 0} = -\frac{i_d}{v_i} = g_m \qquad R_{out,total} = R_D // R_L$$

$$A_v = \frac{v_o}{v_i} = G_m R_{out,total} = g_m (R_D // R_L)$$

⊙ CMOS common-drain amplifier (Source follower)



▶ input resistance : $R_{in} = R_G$

4. 공통-소스, 게이트, 드레인 증폭기의 소신호 해석

▶ voltage gain :

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

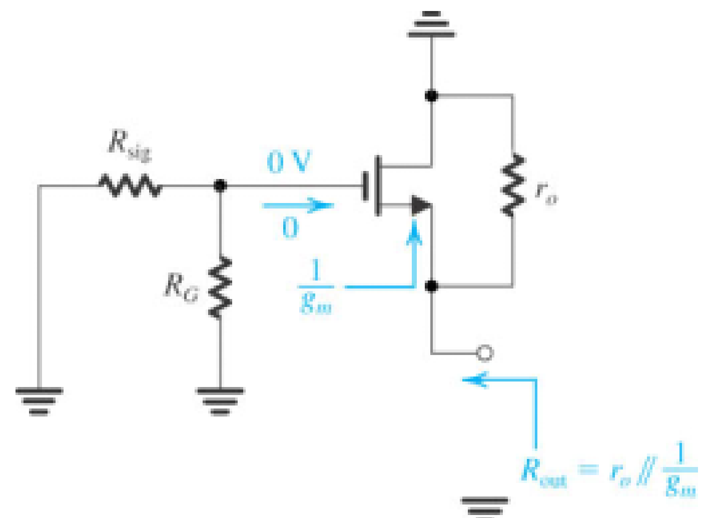
$$A_v = \frac{R_L // r_o}{(R_L // r_o) + 1/g_m} \cong \frac{R_L}{R_L + 1/g_m}, \qquad \text{for } r_o >> R_L$$

▶ overall voltage gain :

$$G_v = \frac{R_G}{R_G + R_{sig}} \frac{R_L // r_o}{(R_L // r_o) + 1/g_m} \cong 1, \quad \text{for } R_G >> R_{sig},\ r_o >> 1/g_m,\ r_o >> R_L$$

▶ output resistance :

$$R_{out} = r_o // \frac{1}{g_m} \cong \frac{1}{g_m}$$



(d)

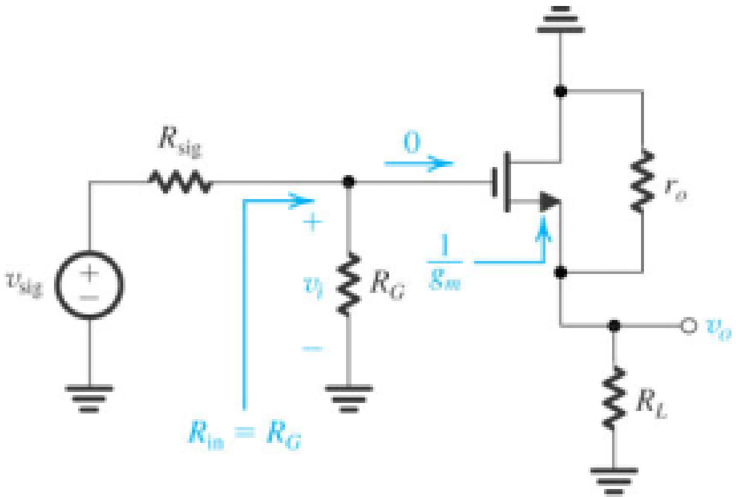
▶ applications :
unity-gain voltage amplifier
or voltage buffer
output stage in a multistage amplifier

Directly on the Circuit

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

$$R_{out,total} = R_L \,//\, r_o \,//\, \frac{1}{g_m} = \frac{(R_L \,//\, r_o)\frac{1}{g_m}}{(R_L \,//\, r_o) + \frac{1}{g_m}}$$

$$A_v = \frac{v_o}{v_i} = G_m R_{out,total} = \frac{R_L \,//\, r_o}{(R_L \,//\, r_o) + 1/g_m}$$



(c)

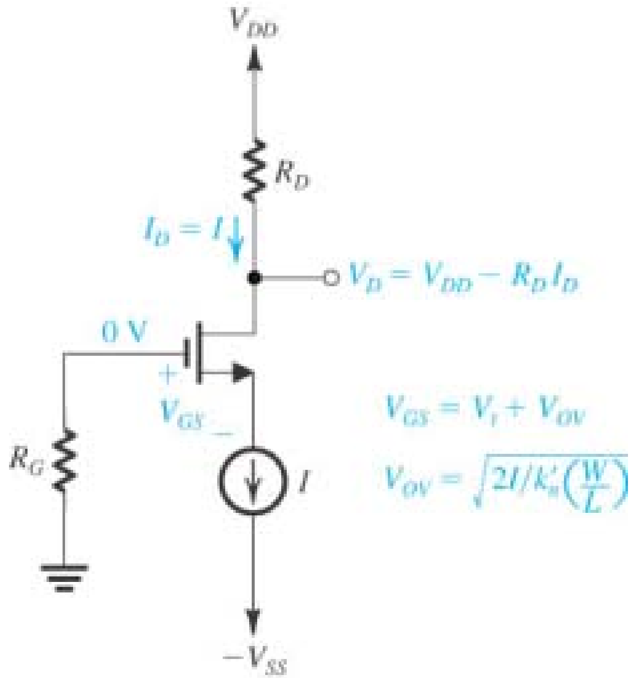
Comparison

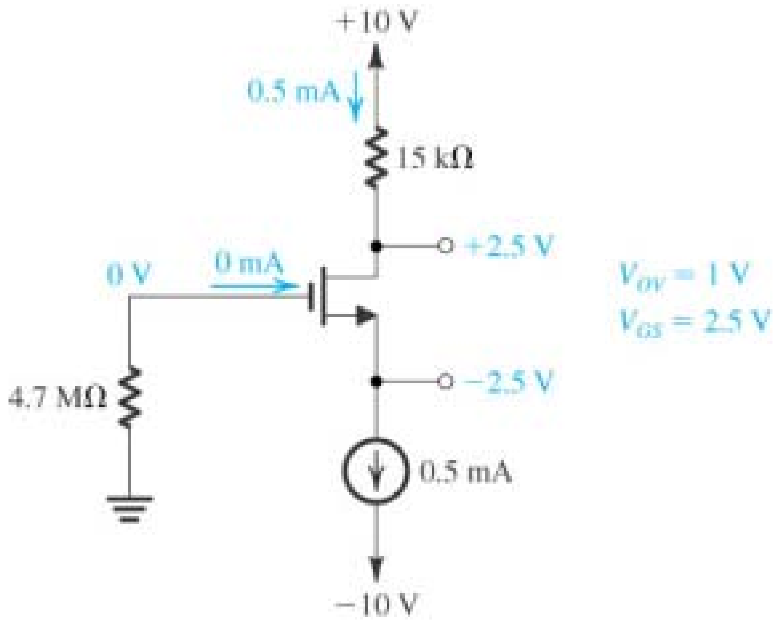
Neglecting Body Effect & r_o

	CS	CS_ R_S	CG	CD
R_{in}	R_G	R_G	$\frac{1}{g_m}$	R_G
R_{out}	R_D	R_D	R_D	$\frac{1}{g_m}$
A_{vo}	$-g_m R_D$	$-\frac{g_m R_D}{1+g_m R_S}$	$g_m R_D$	1

Example 4.1

$V_{tn} = 1.5\text{V}, \ \ \beta_n = k_n'(W/L) = 1\text{mA/V}^2, \ \ \lambda = 0, \ \ \gamma = 0$



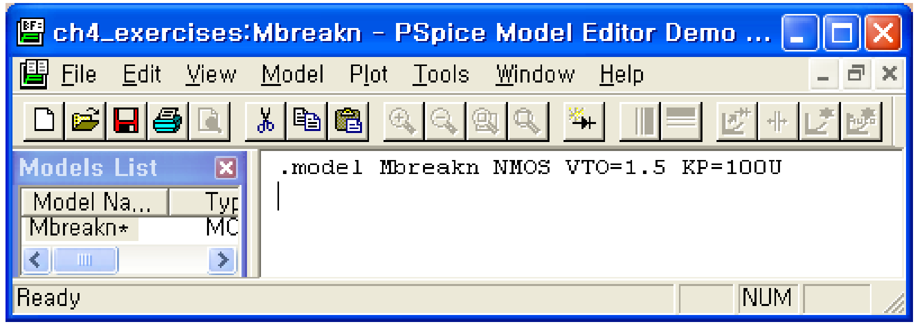


(a)

$$g_m = \beta_n V_{OV} = 1\text{mA/V}^2 \times 1\text{V} = 1\text{mA/V}$$

4. 공통-소스, 게이트, 드레인 증폭기의 소신호 해석

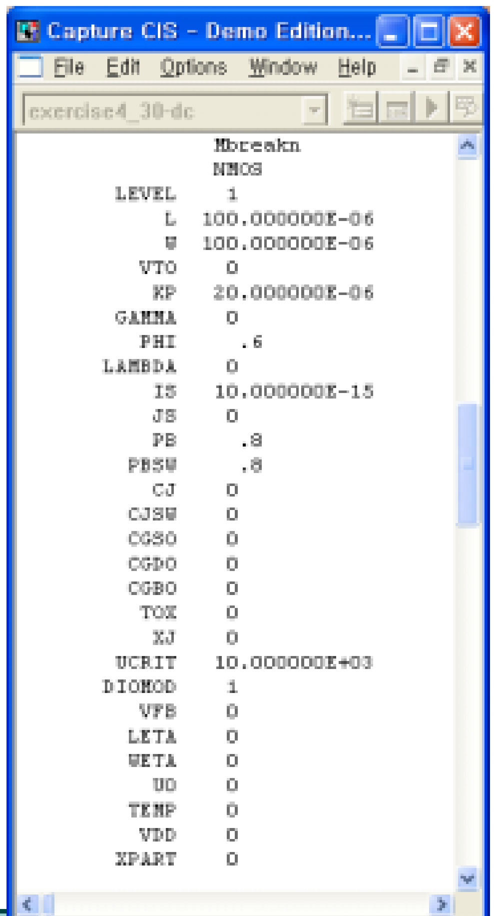
Default



$$V_t = 1.5\text{V} \;\rightarrow\; \text{VTO} = 1.5$$

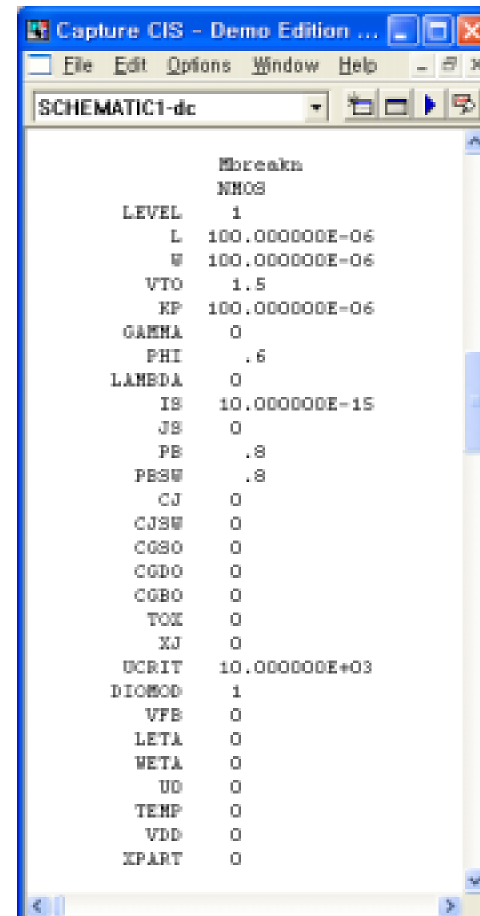
$$\beta_n = 1\text{mA/V}^2 \;\rightarrow\; \text{KP} = 100\text{E-6}$$

$$\text{L} = 1\text{U},\;\; \text{W} = 10\text{U}$$

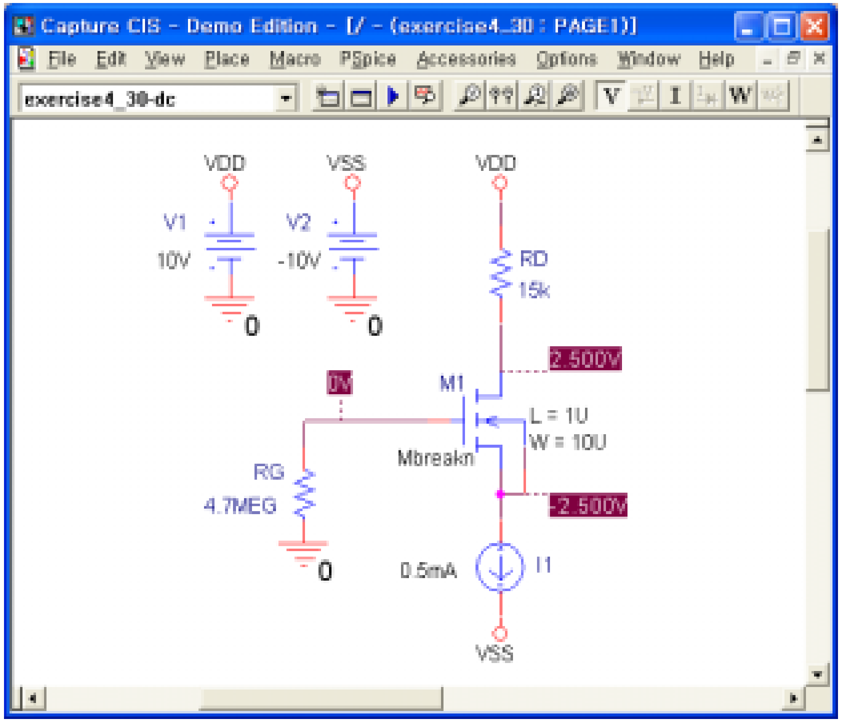


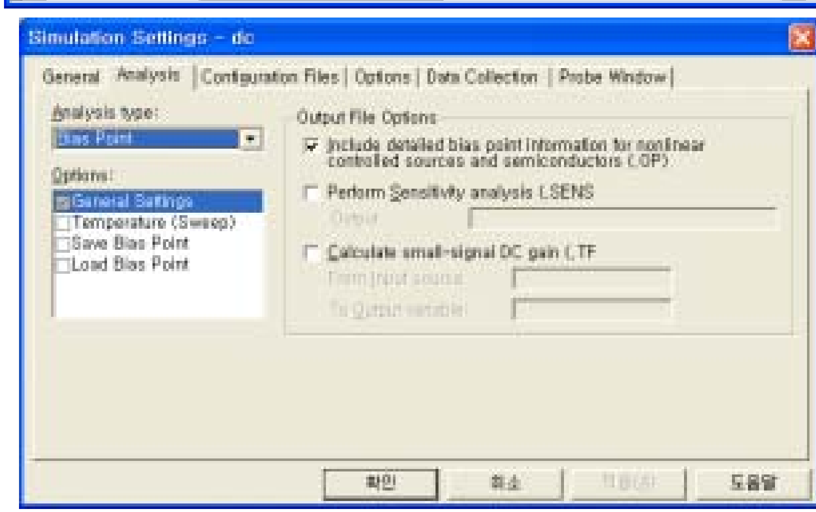
Click ‘PSpice’

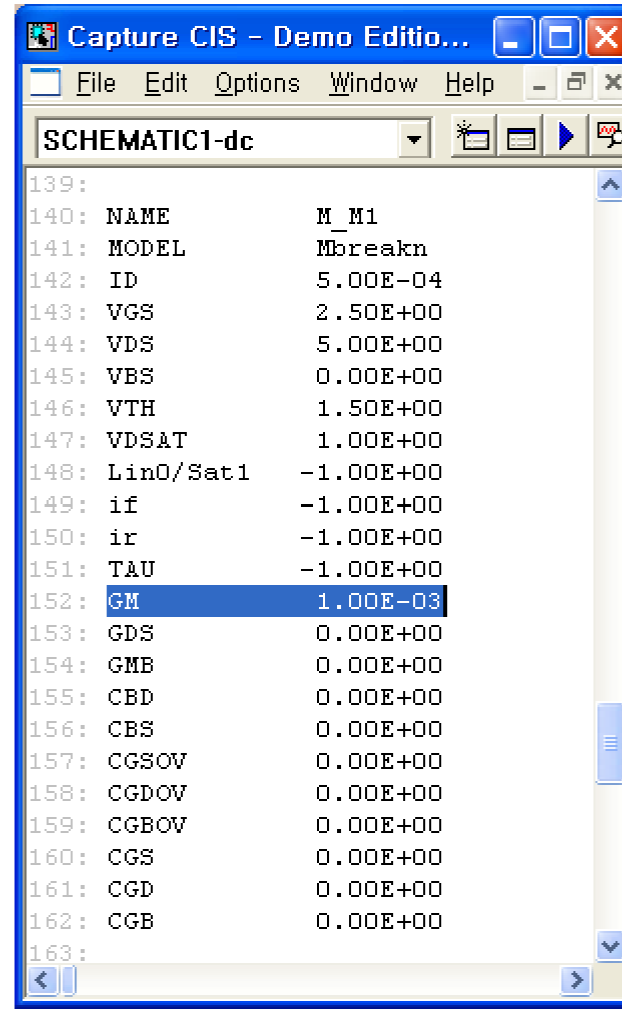
View
Output File



4. 공통-소스, 게이트, 드레인 증폭기의 소신호 해석





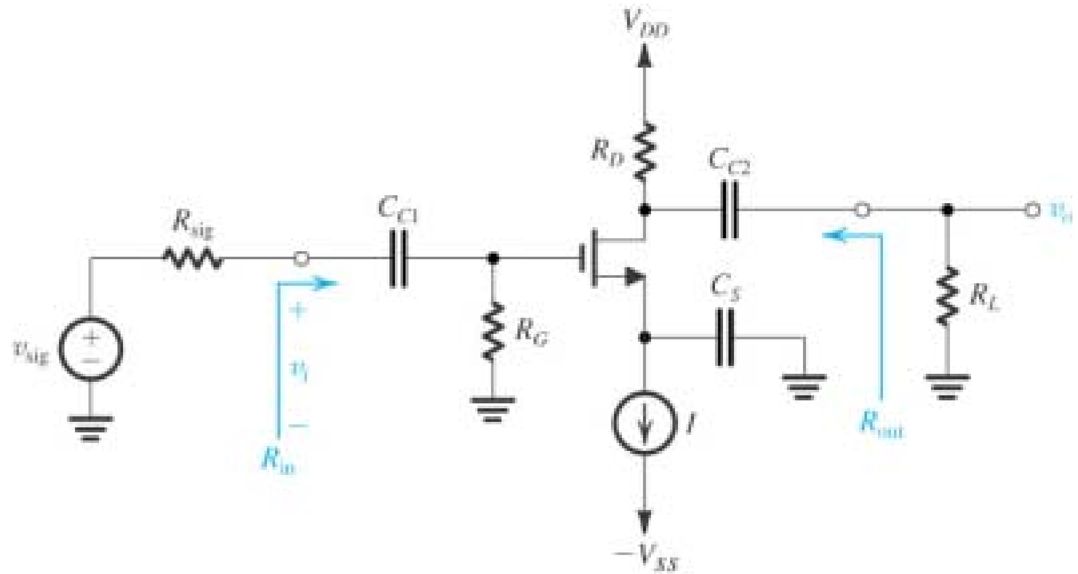


Example 4.2 <CS>

$$V_{tn} = 1.5\text{V}, \quad \lambda = 0, \quad \gamma = 0$$

$$\beta_n = k_n'(W/L) = 1\text{mA/V}^2$$

$$R_{sig} = 100\text{k}\Omega, \quad R_L = 15\text{k}\Omega$$



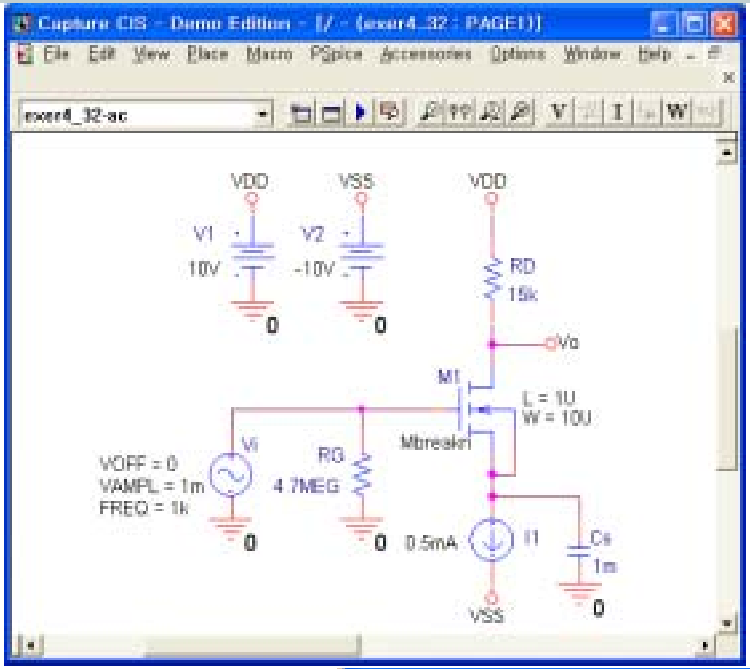
$$R_{in} = R_G = 4.7\text{M}\Omega$$

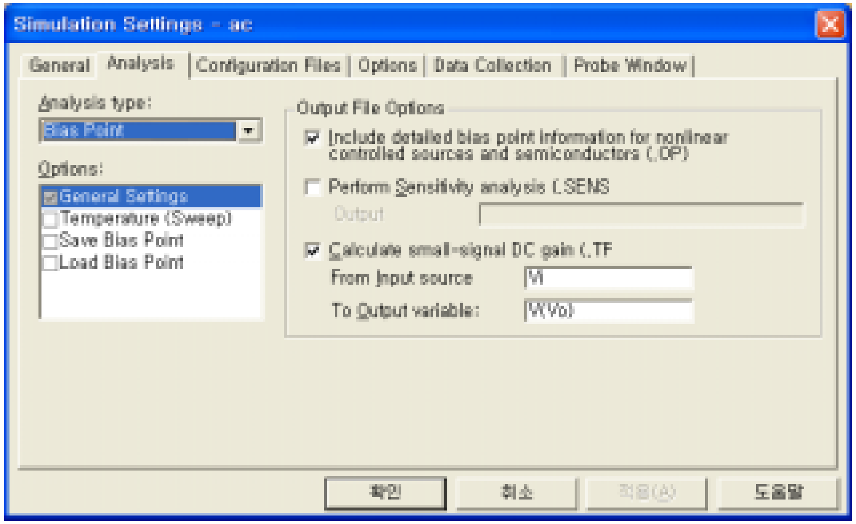
$$R_{out} = R_D = 15\text{k}\Omega$$

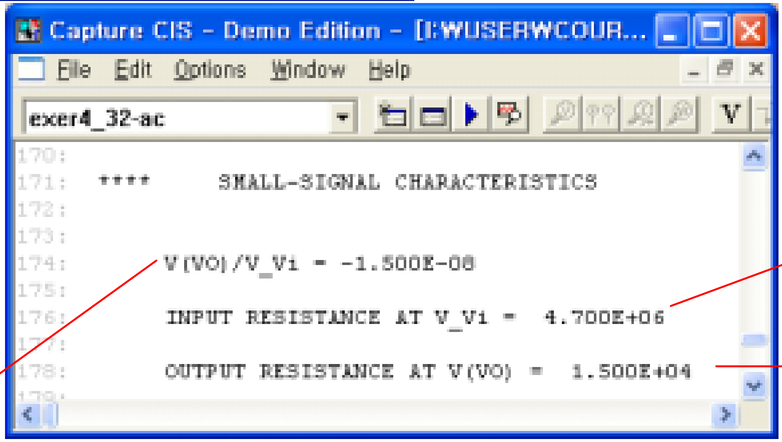
$$A_{vo} = -g_m R_D = -1\text{m} \times 15\text{k} = -15 \text{ V/V}$$

$$G_v = -\frac{R_G}{R_G + R_{sig}} g_m (R_D // R_L) = -7.34 \text{ V/V}$$

4. 공통-소스, 게이트, 드레인 증폭기의 소신호 해석







$$R_{in} = 4.7\text{M}\Omega$$

$$R_{out} = 15\text{k}\Omega$$

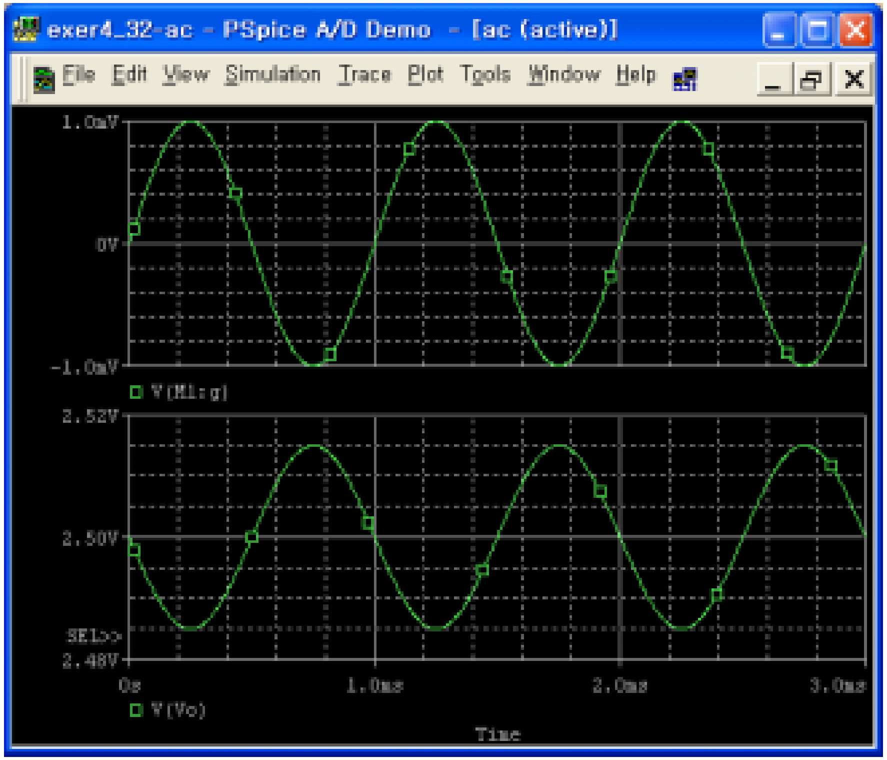
$$A_{vo} = -1.5\text{E-08} : \text{incorrect}$$

Due to dc gain

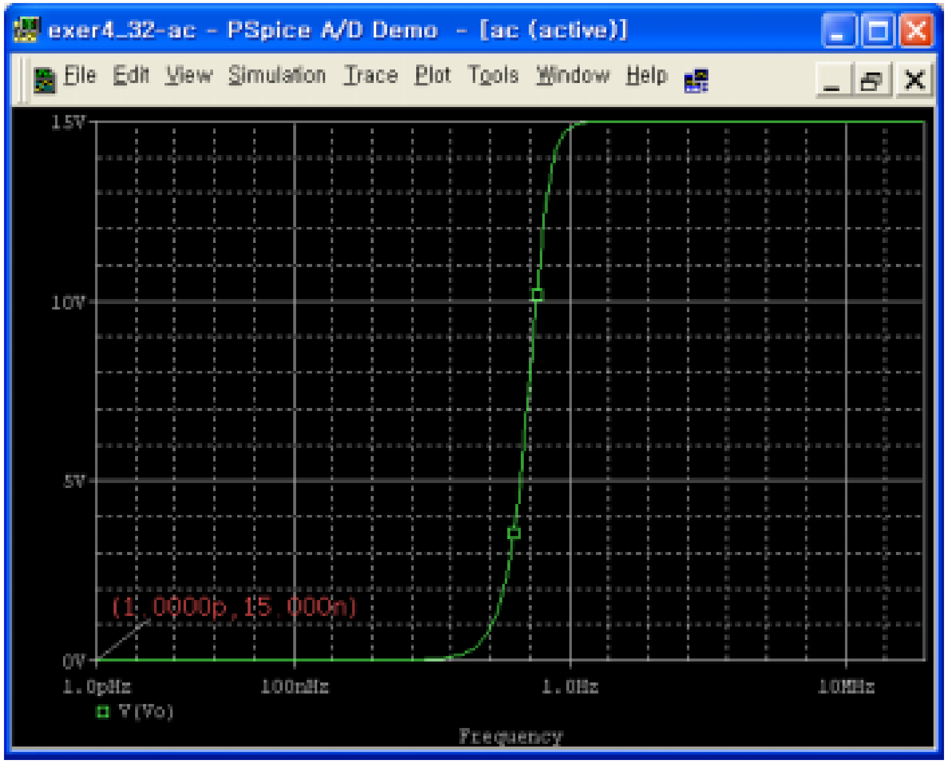
Why?

4. 공통-소스, 게이트, 드레인 증폭기의 소신호 해석

Transient analysis

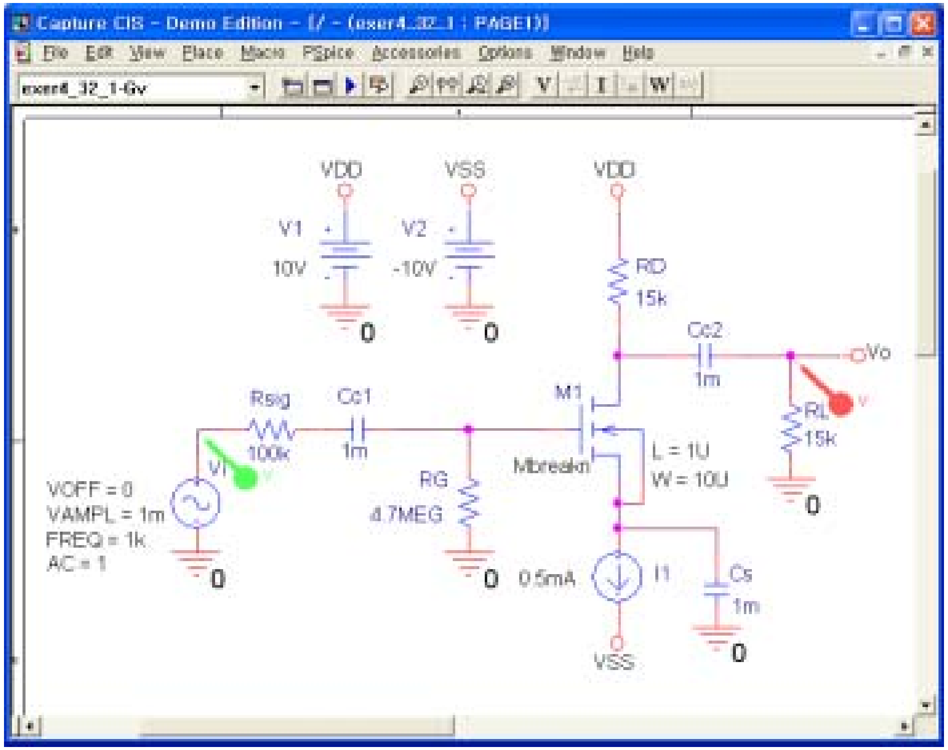


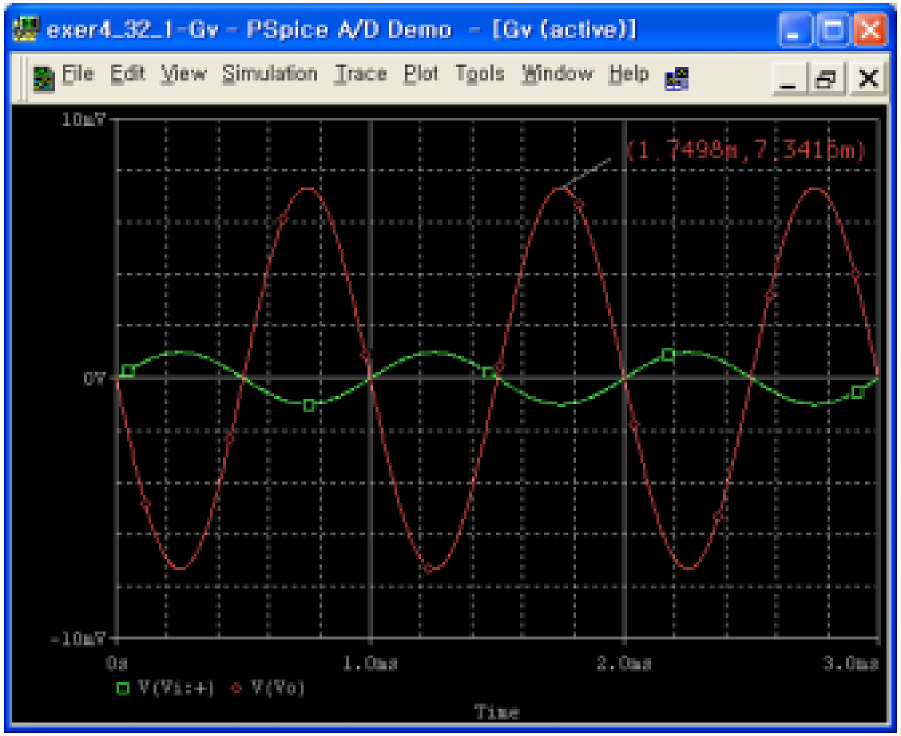
AC analysis



$$A_{vo} = -15\ \text{V/V}$$

4. 공통-소스, 게이트, 드레인 증폭기의 소신호 해석



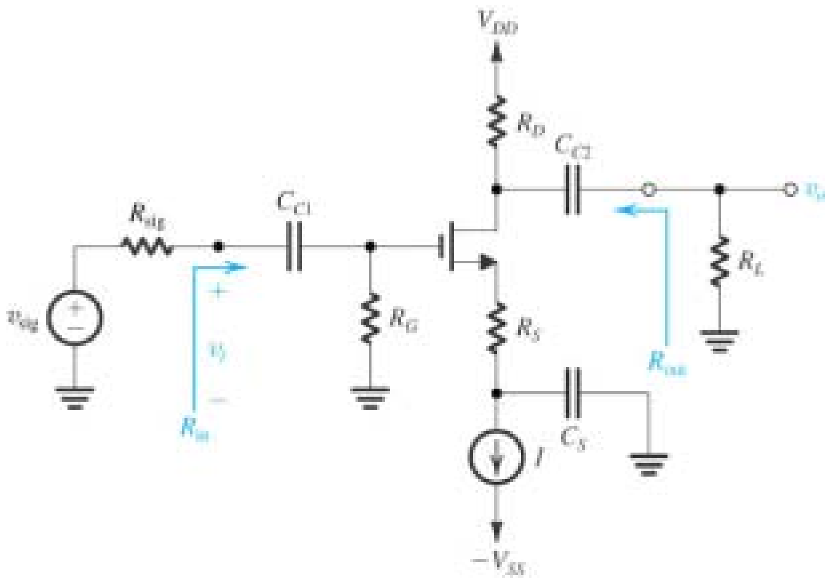


$$G_v = -7.34 \text{ V/V}$$

실습과제 1

1. 소스 degeneration 저항을 포함하는 Common-Source 구조에서 다음을 구하고 PSPICE로 검증하시오.

$$R_{in}, \quad R_{out}, \quad A_{vo} = \left.\frac{v_o}{v_i}\right|_{R_L=\infty}, \quad G_v = \frac{v_o}{v_{sig}}$$



$V_{tn} = 1.5\text{V}, \quad \lambda = 0, \quad \gamma = 0$

$\beta_n = k_n'(W/L) = 1\text{mA/V}^2, \quad I = 0.5\text{mA}$

$R_G = 4.7\text{M}\Omega, \quad R_D = 15\text{k}\Omega, \quad R_S = 2\text{k}\Omega$

$R_{sig} = 100\text{k}\Omega, \quad R_L = 15\text{k}\Omega$

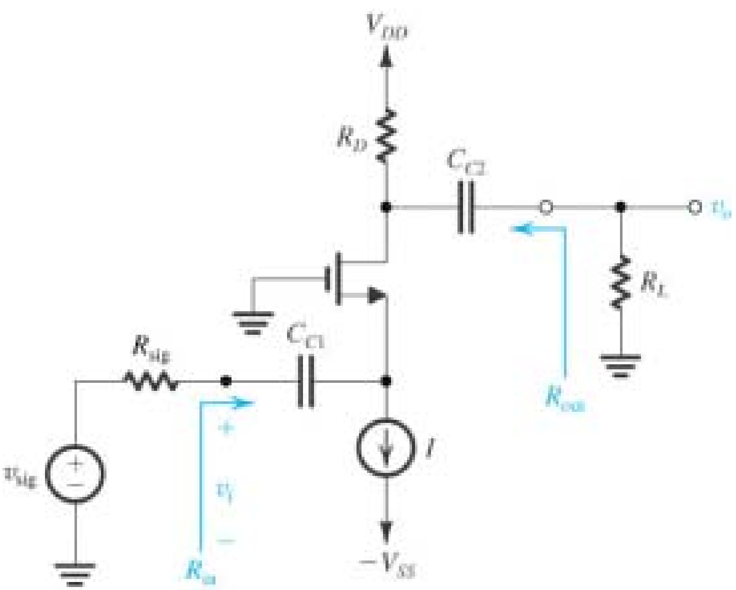
$C_{C1}, \ C_{C2}, \ C_S \ \rightarrow \ \infty$

2. $\lambda = 0.02, \quad R_S = 0\Omega$ 인 경우에 대해 반복

실습과제 2

1. Common-Gate 구조에서 다음을 구하고 PSPICE로 검증하시오.

$$R_{in},\quad R_{out},\quad A_{vo}=\left.\frac{v_o}{v_i}\right|_{R_L=\infty},\quad G_v=\frac{v_o}{v_{sig}}$$



$V_{tn}=1.5\text{V},\quad \lambda=0,\quad \gamma=0$

$\beta_n=k_n^{'}(W/L)=1\text{mA/V}^2$

$I=0.5\text{mA},\quad R_D=15\text{k}\Omega$

$R_{sig}=1\text{k}\Omega,\quad R_L=15\text{k}\Omega$

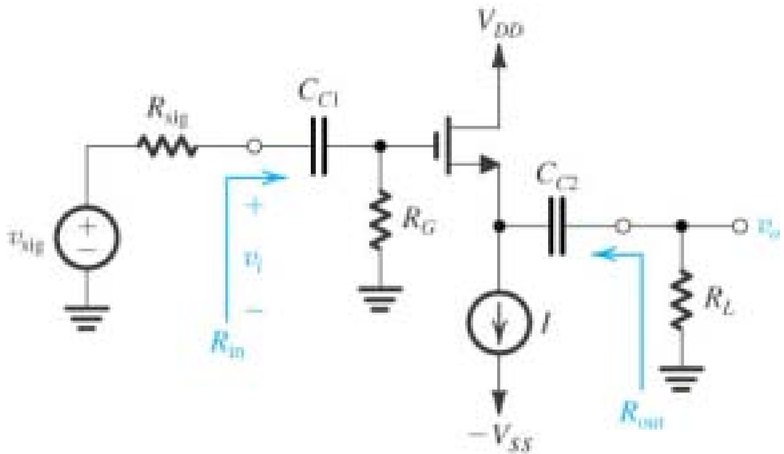
$C_{C1},\ C_{C2}\ \rightarrow\ \infty$

2. $R_{sig}=10\text{k}\Omega,\ 100\text{k}\Omega$ 인 경우에 대해 반복

실습과제 3

1. Common-Drain 구조에서 다음을 구하고 PSPICE로 검증하시오.

$$R_{in}, \quad R_{out}, \quad A_{vo} = \left.\frac{v_o}{v_i}\right|_{R_L=\infty}, \quad G_v = \frac{v_o}{v_{sig}}$$



$$V_{tn} = 1.5\text{V}, \quad \lambda = 0, \quad \gamma = 0$$

$$\beta_n = k_n'(W/L) = 1\text{mA/V}^2$$

$$I = 0.5\text{mA}, \quad R_G = 4.7\text{M}\Omega$$

$$R_{sig} = 100\text{k}\Omega, \quad R_L = 15\text{k}\Omega$$

$$C_{C1}, C_{C2} \rightarrow \infty$$

2. $\lambda = 0.02, \quad R_{sig} = 1\text{M}\Omega$ 인 경우에 대해 반복

⊙ Open-circuit time constants

▶ for determining the upper 3-dB frequency

$$F_H(s) = \frac{1 + a_1 s + a_2 s^2 + \cdots}{1 + b_1 s + b_2 s^2 + \cdots}$$

$$b_1 = \frac{1}{\omega_{P1}} + \frac{1}{\omega_{P2}} + \cdots + \frac{1}{\omega_{Pn_H}}$$

$$b_1 = \sum_{i=1}^{n_H} C_i R_{io}$$

If a dominant pole exists (say, P_1), then

$$b_1 \cong \frac{1}{\omega_{P1}} \quad \text{and} \quad \omega_H \cong \omega_{P1}$$

Thus,

$$\omega_H \cong 1 \Big/ \sum_{i=1}^{n_H} C_i R_{io}$$

▶ the method for determining b_1 is exact

▶ R_{i0} can be determined by

▷ $C_k = 0$ (open) for $k \neq i$

▷ $V_s = 0$ & $I_s = 0$

▷ determine the resistance seen by C_i

⊙ Miller's theorem

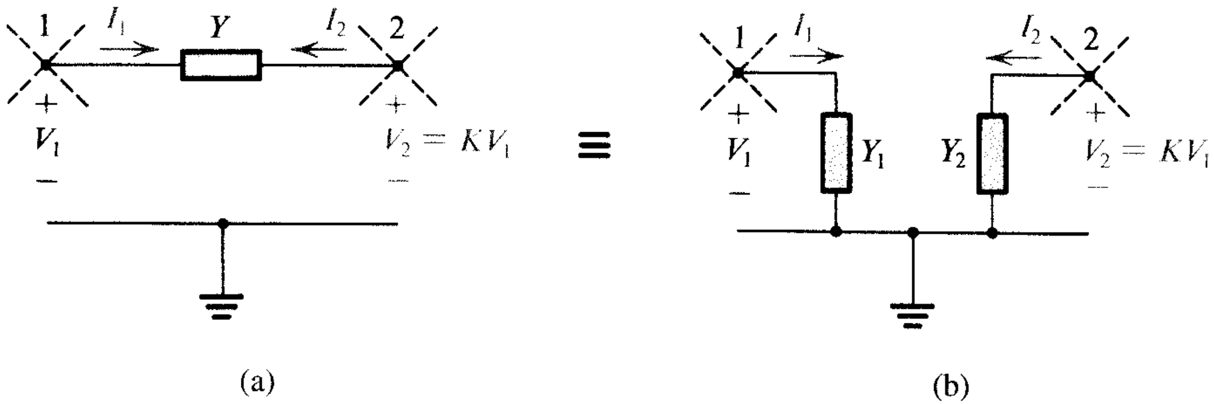


Fig. 7.18 Miller's theorem.

$$Y_1 = Y(1-K)$$
$$Y_2 = Y\left(1-\frac{1}{K}\right)$$
$$K = \frac{V_2}{V_1}$$

▶ An important caution

▷ the Miller equivalent circuit is valid only as long as the conditions that existed in the network when K was determined are not changed

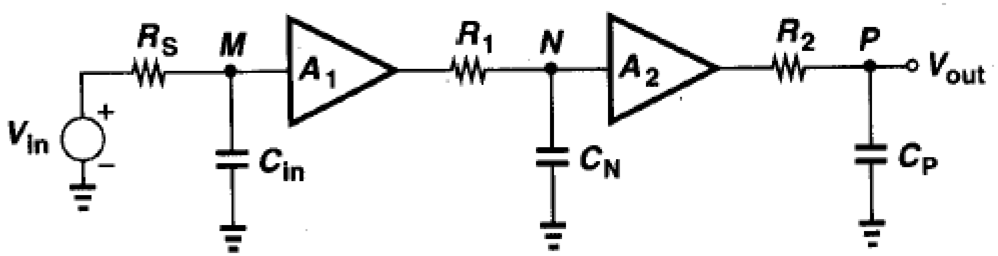
▷ Miller's theorem is very useful in determining the input impedance and the gain of an amplifier

▷ it cannot be used to determine its output resistance
∵ the change of K

5. 공통-소스, 게이트, 드레인 증폭기의 고주파 해석

⊙ Association of poles with nodes

▶ each node contributes one pole

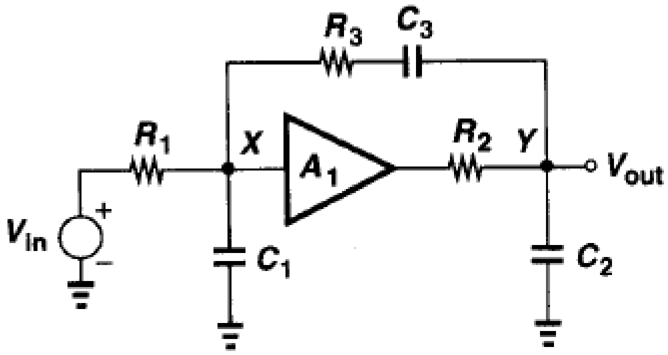


$$\frac{V_{out}}{V_{in}}(s) = \frac{A_1}{1+\frac{s}{\omega_M}} \cdot \frac{A_2}{1+\frac{s}{\omega_N}} \cdot \frac{1}{1+\frac{s}{\omega_P}}$$

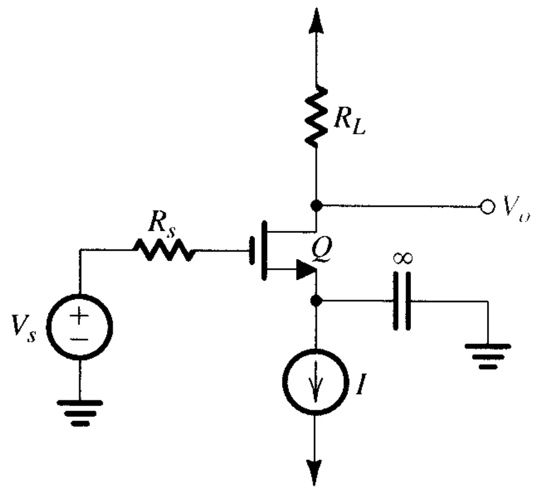
$$\omega_M = \frac{1}{R_S C_{in}}, \quad \omega_N = \frac{1}{R_1 C_N}, \quad \omega_P = \frac{1}{R_2 C_P}$$

▶ interaction between nodes

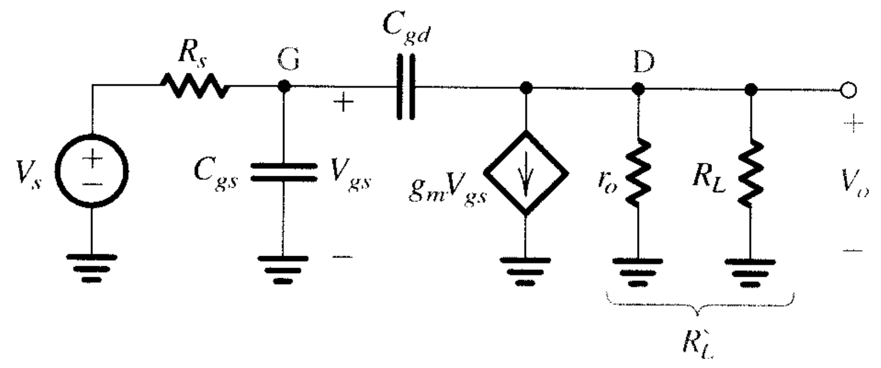
▷ difficult to calculate poles



⊙ High-frequency response of the CS amplifier



(a)

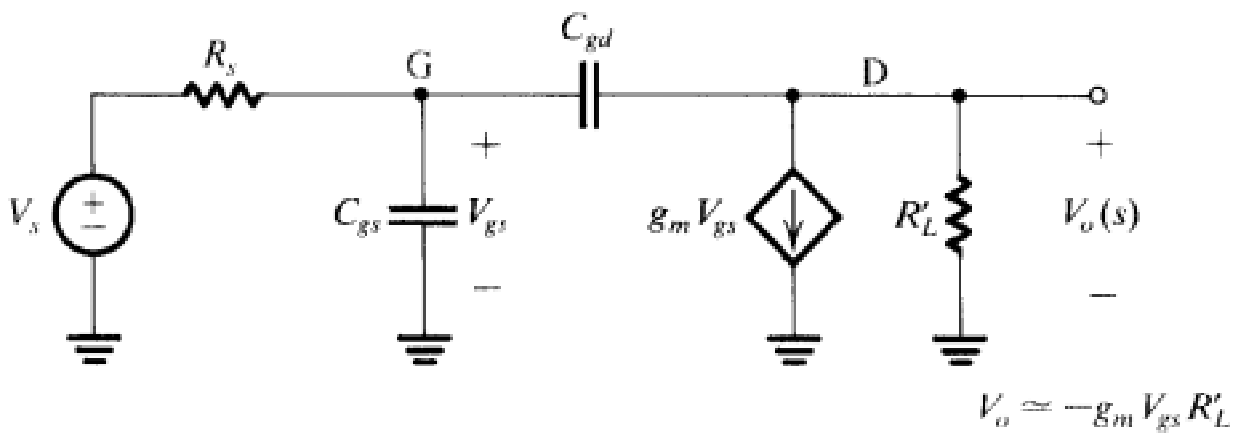


(a)

- ▶ three methods to determine the upper 3-dB freq.
  - ▷ method of open-circuit time constants
  - ▷ approximate method using Miller's theorem
  - ▷ method using the exact high-freq. transfer function

5. 공통-소스, 게이트, 드레인 증폭기의 고주파 해석

① Method of open-circuit time constants



$$
\begin{aligned}
R_{gs} &= R_s \\
R_{gd} &= R_s + R_L' + g_m R_s R_L' \\
\omega_H &= \frac{1}{C_{gs}R_{gs} + C_{gd}R_{gd}} \\
&= \frac{1}{C_{gs}R_s + C_{gd}(R_s + R_L' + g_m R_s R_L')}
\end{aligned}
$$

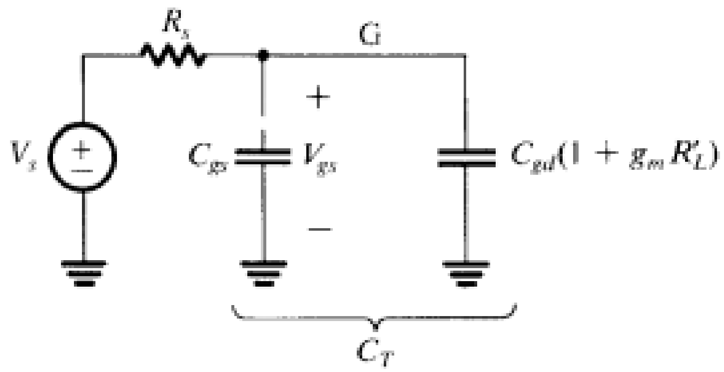
5. 공통-소스, 게이트, 드레인 증폭기의 고주파 해석

② Approximate method using Miller's theorem

▶ neglecting the current through C_{gd} in determining V_o

$$V_o \approx -g_m V_{gs} R_L' \qquad \therefore\ K = V_o / V_{gs} = -g_m V_{gs}$$

▶ 3-dB freq. & gain



$$C_T = C_{gs} + C_{gd}(1 + g_m R_L')$$

$$\omega_H = \frac{1}{C_T R_s} = \frac{1}{C_{gs} R_s + C_{gd}(R_s + g_m R_s R_L')}$$

$$A_H = \frac{A_M}{1 + s/\omega_H}, \quad A_M = -g_m R_L'$$

▶ the small feedback capacitance C_{gd}

▷ plays an important role in determining the high-freq. resp.

▷ gives rise to a large input cap. $C_{gd}(1 + g_m R_L')$ → Miller Effect

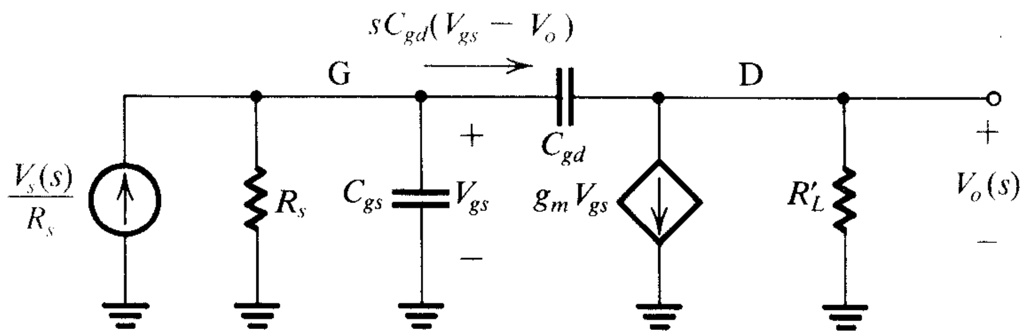
▶ To increase the upper 3-dB frequency

▷ $g_m R_L' \downarrow$ → reduce the midband gain

▷ $R_s \downarrow$ → might not always be possible

▷ use cascode configuration

③ Method using the exact high-freq. Transfer function



▶ transfer function

$$\frac{V_o(s)}{V_s(s)} = -A_M \frac{1 - \dfrac{s}{g_m / C_{gd}}}{1 + s[C_{gs}R_s + C_{gd}(R_s + R_L' + g_m R_s R_L')] + s^2 C_{gs} C_{gd} R_s R_L'}$$

▶ if the two poles are widely separated

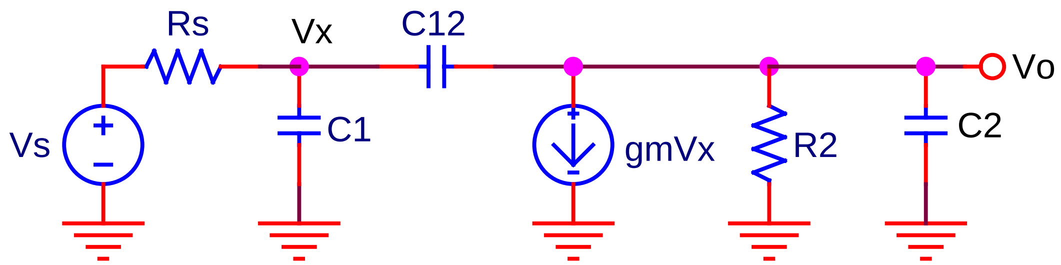
$$D(s) = \left(1 + \frac{s}{\omega_{P1}}\right)\left(1 + \frac{s}{\omega_{P2}}\right) = 1 + s\left(\frac{1}{\omega_{P1}} + \frac{1}{\omega_{P2}}\right) + \frac{s^2}{\omega_{P1}\omega_{P2}} \approx 1 + \frac{s}{\omega_{P1}} + \frac{s^2}{\omega_{P1}\omega_{P2}}$$

$$\omega_{P1} = \frac{1}{C_{gs}R_s + C_{gd}(R_s + R_L' + g_m R_s R_L')}$$

$$\omega_{P2} = \frac{C_{gs} + C_{gd}(1 + g_m R_L' + R_L'/R_s)}{C_{gs} C_{gd} R_L'} \approx \frac{g_m}{C_{gs}} \quad \text{for } g_m R_L' >> 1 \text{ and } R_L' < R_s$$

5. 공통-소스, 게이트, 드레인 증폭기의 고주파 해석

⊙ General high-frequency analysis of CS amplifiers



$$A_v(s)=\frac{V_o(s)}{V_s(s)}=\frac{\left(-\frac{g_m}{G_2}\right)\left(1-s\frac{C_{12}}{g_m}\right)}{1+s\left(\frac{C_2+C_{12}}{G_2}+\frac{C_1+C_{12}}{G_s}+\frac{g_mC_{12}}{G_sG_2}\right)+s^2\frac{C_1C_2+C_1C_{12}+C_2C_{12}}{G_sG_2}}$$

If $\omega_{P1} << \omega_{P2}$

$$D(s)=\left(1+\frac{s}{\omega_{P1}}\right)\left(1+\frac{s}{\omega_{P2}}\right)=1+s\left(\frac{1}{\omega_{P1}}+\frac{1}{\omega_{P2}}\right)+\frac{s^2}{\omega_{P1}\omega_{P2}}\approx 1+\frac{s}{\omega_{P1}}+\frac{s^2}{\omega_{P1}\omega_{P2}}$$

5. 공통-소스, 게이트, 드레인 증폭기의 고주파 해석

$$\omega_{P1} \approx \left(\frac{C_2 + C_{12}}{G_2} + \frac{C_1 + C_{12}}{G_s} + \frac{g_m C_{12}}{G_s G_2} \right)^{-1}$$

$$\omega_{P2} \approx \left(\frac{G_s G_2}{C_1 C_2 + C_1 C_{12} + C_2 C_{12}} \right) \frac{1}{\omega_{P1}}$$

$$= \left(\frac{G_s G_2}{C_1 C_2 + C_1 C_{12} + C_2 C_{12}} \right) \left(\frac{C_2 + C_{12}}{G_2} + \frac{C_1 + C_{12}}{G_s} + \frac{g_m C_{12}}{G_s G_2} \right)$$

$$\omega_Z = \frac{g_m}{C_{12}}$$

$$A_v(s) = A_M \frac{\left(1 - \dfrac{s}{\omega_Z}\right)}{\left(1 + \dfrac{s}{\omega_{P1}}\right)\left(1 + \dfrac{s}{\omega_{P2}}\right)}, \qquad A_M = -\frac{g_m}{G_2} = -g_m R_2$$

5. 공통-소스, 게이트, 드레인 증폭기의 고주파 해석

① $\omega_{P1} << \omega_{P2}$ & $g_m R_2 >> 1$

$$\omega_{P1} \approx \left(\frac{g_m C_{12}}{G_s G_2} \right)^{-1} = \frac{G_s}{(g_m R_2) C_{12}} = \frac{G_s}{|A_M| C_{12}} \qquad \omega_{P2} \approx \frac{g_m C_{12}}{C_1 C_2 + C_1 C_{12} + C_2 C_{12}}$$

② $\omega_{P1} << \omega_{P2}$ & $g_m R_2 >> 1$ & $C_2 \approx 0$

$$\omega_{P1} \approx \frac{G_s}{(g_m R_2) C_{12}} = \frac{G_s}{|A_M| C_{12}} \qquad \omega_{P2} \approx \frac{g_m}{C_1}$$

③ $\omega_{P1} << \omega_{P2}$ & $C_1 \approx C_2$ & $R_2 << R_s \rightarrow g_m R_2 \approx 1$

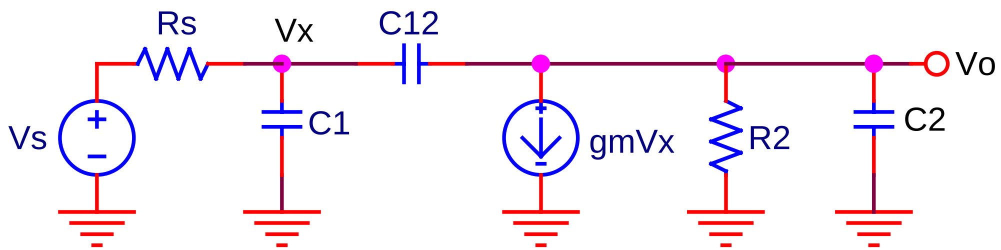
$$\omega_{P1} \approx \left(\frac{C_1 + C_{12}}{G_s} + \frac{C_{12}}{G_s} \right)^{-1} = \frac{G_s}{C_1 + 2C_{12}} \qquad \omega_{P2} \approx \frac{G_s G_2}{C_2 (C_1 + 2C_{12})} \frac{1}{\omega_{P1}} = \frac{G_2}{C_2}$$

④ $R_s \approx 0$

$$A_v(s) = \frac{\left(-\frac{g_m}{G_2} \right) \left(1 - s \frac{C_{12}}{g_m} \right)}{1 + s \left(\frac{C_2 + C_{12}}{G_2} \right)} = A_M \frac{\left(1 - \frac{s}{\omega_Z} \right)}{\left(1 + \frac{s}{\omega_{P1}} \right)}$$

⊙ Zero in the CS amplifier

- ▶ zero arises from direct coupling of the input to the output through C_{12}
- ▶ C_{12} provides a feedforward path at high frequencies



$$V_o(s) = Z_L[sC_{12}(V_x - V_o) - g_m V_x]$$

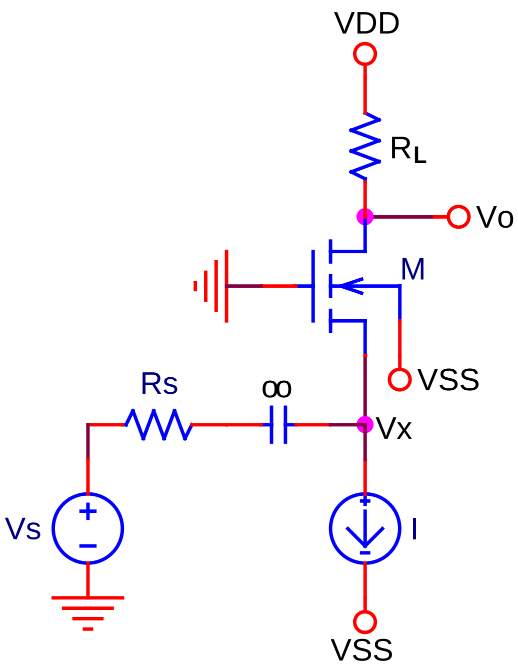
$$= \frac{Z_L(sC_{12} - g_m)V_x}{1 + Z_L sC_{12}}, \qquad Z_L = R_2 \,//\, \frac{1}{sC_2}$$

$$V_o(s_z) = 0 \;\rightarrow\; \begin{cases} Z_L(s_z) = \dfrac{R_2}{1 + s_z C_2 R_2} = 0 \;\rightarrow\; s_z = \infty \\ s_z C_{12} - g_m = 0 \;\rightarrow\; s_z = \dfrac{g_m}{C_{12}} \end{cases}$$

⊙ High-frequency response of the CG amplifier

▶ the high-freq. Response of the CS amplifier is limited by the Miller effect caused by the feedback capacitor C_{gd}

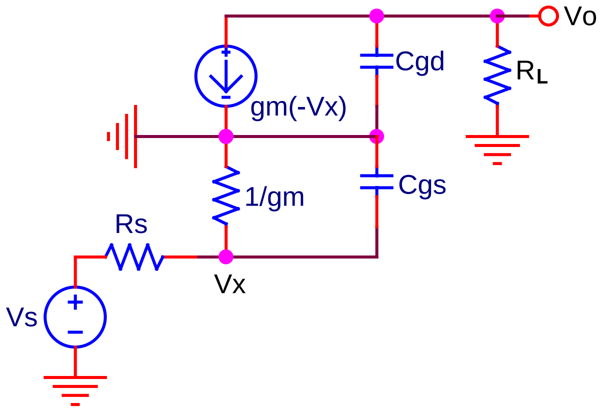
▶ CG amplifier
- ▷ no feedback capacitor between the input and output
- ▷ no Miller effect → improved bandwidth

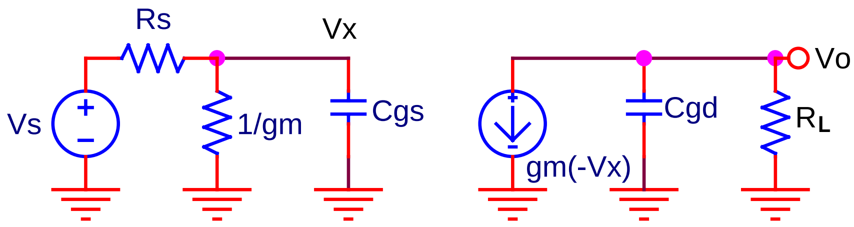


▶ Analysis methods
- ▷ using the T equivalent circuit
  → STC(Single Time Constant) networks
- ▷ directly from the circuit

5. 공통-소스, 게이트, 드레인 증폭기의 고주파 해석

① Using the T equivalent circuit





(λ effect & body effect are ignored)

▶ 1^{st} STC network

▷ low-frequency or midband gain : $A_{M1} = \dfrac{V_x}{V_s} = \dfrac{1/g_m}{R_s + 1/g_m} = \dfrac{1}{1 + g_m R_s}$

▷ time constant : $\tau_1 = C_{gs}\left(R_s // \dfrac{1}{g_m}\right)$

▷ transfer function : $A_1(s) = \dfrac{V_x(s)}{V_s(s)} = A_{M1}\dfrac{1}{1 + s/\omega_{P1}}, \qquad \omega_{P1} = \dfrac{1}{\tau_1}$

5. 공통-소스, 게이트, 드레인 증폭기의 고주파 해석

▶ 2nd STC network

▷ low-frequency or midband gain : $A_{M2} = \dfrac{V_o}{V_x} = g_m R_L$

▷ time constant : $\tau_2 = C_{gd} R_L$

▷ transfer function : $A_2(s) = \dfrac{V_o(s)}{V_x(s)} = A_{M2} \dfrac{1}{1 + s/\omega_{P2}}$, $\omega_{P2} = \dfrac{1}{\tau_2}$

▶ overall transfer function

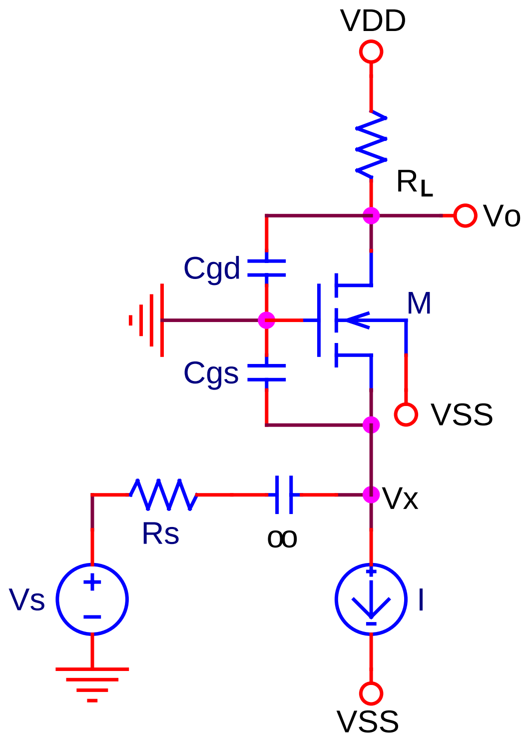
$$A(s) = \frac{V_o(s)}{V_s(s)} = A_1(s)A_2(s) = A_M \left(\frac{1}{1 + s/\omega_{P1}} \right) \left(\frac{1}{1 + s/\omega_{P2}} \right)$$

$$A_M = A_{M1} A_{M2} = \frac{g_m R_L}{1 + g_m R_s}$$

$$\omega_{P1} = \frac{1}{C_{gs} \left(R_s // \dfrac{1}{g_m} \right)} \qquad \omega_{P2} = \frac{1}{C_{gd} R_L}$$

☞ which one is dominant? → depends on R_s & R_L & C_L

② Directly from the circuit



▶ midband gain

$$\frac{V_x}{V_s} = \frac{1/g_m}{R_s + 1/g_m} = \frac{1}{1+g_m R_s} \qquad \frac{V_o}{V_x} = g_m R_L$$

$$\therefore \; A_M = \frac{V_o}{V_s} = \frac{g_m R_L}{1+g_m R_s}$$

▶ time constants

▷ @ Vx : $\tau_1 = C_{gs}\left(R_s // \frac{1}{g_m}\right)$

▷ @ Vo : $\tau_2 = C_{gd} R_L$

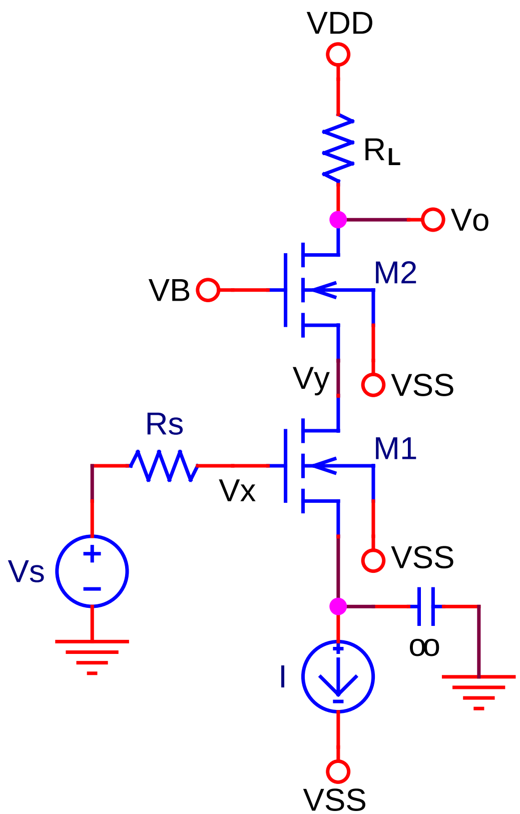
▶ transfer function

$$\frac{V_o(s)}{V_s(s)} = A_M \left(\frac{1}{1+s/\omega_{P1}}\right)\left(\frac{1}{1+s/\omega_{P2}}\right)$$

$$\omega_{P1} = \frac{1}{\tau_1} \qquad \omega_{P2} = \frac{1}{\tau_2}$$

⊙ The cascode configuration

▶ combines the advantages of the CS and CG circuits

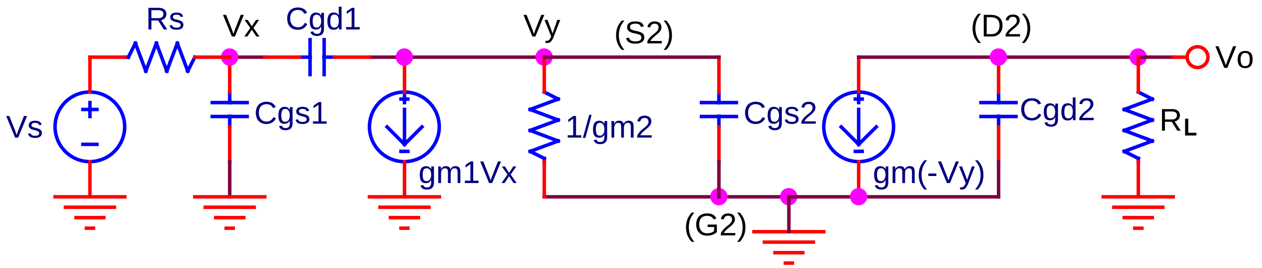


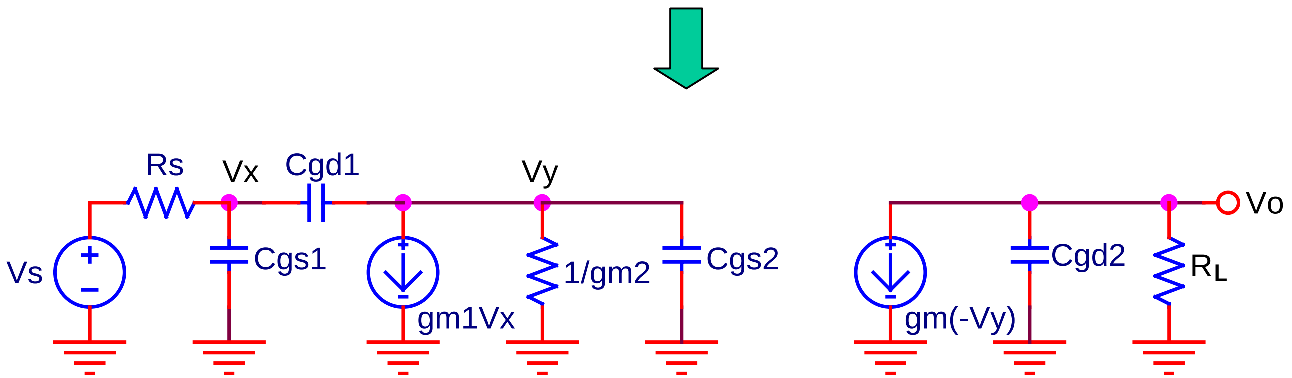
▶ Analysis methods
- ▷ using the equivalent circuits
- ▷ directly from the circuit

5. 공통-소스, 게이트, 드레인 증폭기의 고주파 해석

① Using the equivalent circuits

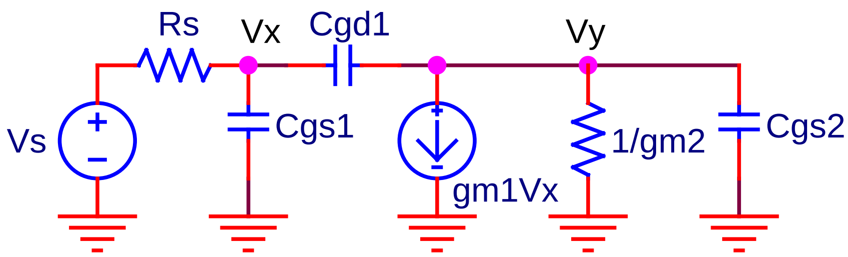
(λ effect & body effect are ignored)





5. 공통-소스, 게이트, 드레인 증폭기의 고주파 해석

▶ left circuit : CS amplifier



$$C_1 = C_{gs1},\quad C_{12} = C_{gd1},\quad C_2 = C_{gs2}$$

$$g_m = g_{m1},\quad R_2 = 1/g_{m2}$$

③ $\omega_{P1} << \omega_{P2}$ & $C_1 \approx C_2$ & $R_2 << R_s \rightarrow g_m R_2 \approx 1$

$$\omega_{P1} \approx \frac{G_s}{C_1 + 2C_{12}} \qquad \omega_{P2} \approx \frac{G_2}{C_2} \qquad \omega_Z = \frac{g_m}{C_{12}}$$

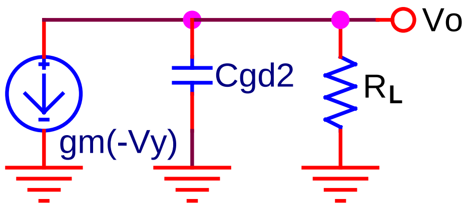
$$K_1 = \frac{V_y}{V_s} = -g_m R_2 = -g_{m1}\frac{1}{g_{m2}} \approx -1$$

$$\omega_{P1} \approx \frac{1}{R_s(C_{gs1} + 2C_{gd1})}$$

$$\omega_{P2} \approx \frac{g_{m2}}{C_{gs2}} \qquad \omega_Z = \frac{g_{m1}}{C_{gd1}}$$

5. 공통-소스, 게이트, 드레인 증폭기의 고주파 해석

▶ right circuit : STC network



$$K_2 = \frac{V_o}{V_y} = g_{m2}R_L \qquad \omega_{P3} = \frac{1}{C_{gd2}R_L}$$

▶ overall gain

$$\frac{V_o(s)}{V_s(s)} = A_M \frac{\left(1-\frac{s}{\omega_Z}\right)}{\left(1+\frac{s}{\omega_{P1}}\right)\left(1+\frac{s}{\omega_{P2}}\right)\left(1+\frac{s}{\omega_{P3}}\right)}, \qquad A_M = K_1K_2 = -g_{m2}R_L$$

☞ which pole is dominant? → depends on R_s & R_L & C_L

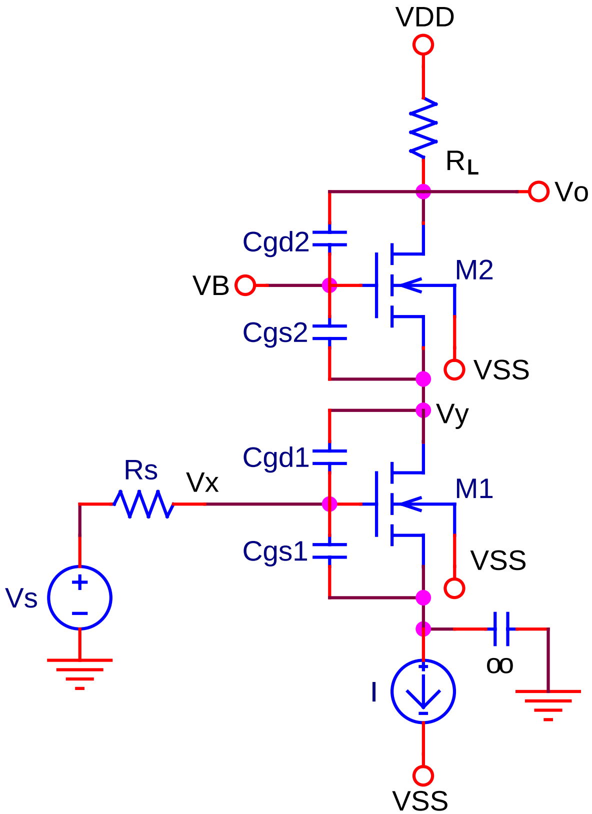
⊙ in integrated amplifiers
▷ R_s is small
▷ active loads are used → R_L is large
▷ load capacitor C_L exists

$$\omega_{P3} = \frac{1}{(C_{gd2}+C_L)R_L}$$

→ dominant

5. 공통-소스, 게이트, 드레인 증폭기의 고주파 해석

② Directly from the circuit



▶ midband gain

$$\frac{V_x}{V_s}=1,\quad \frac{V_y}{V_x}=-g_{m1}\frac{1}{g_{m2}}=-1,\quad \frac{V_o}{V_y}=g_{m2}\mathrm{R_L}$$

$$\therefore\ A_M=\frac{V_o}{V_s}=\frac{V_x}{V_s}\frac{V_y}{V_x}\frac{V_o}{V_y}=-g_{m2}R_L$$

▶ poles

▷ Miller effect can be ignored ∵ small gain

▷ $\mathrm{C_{gd1}}$ is usually small

$$@\,\mathrm{V_x}:\quad \omega_{P1}\approx\frac{1}{R_sC_{gs1}}$$

$$@\,\mathrm{V_y}:\quad \omega_{P2}\approx\frac{1}{C_{gs2}(1/g_{m2})}=\frac{g_{m2}}{C_{gs2}}$$

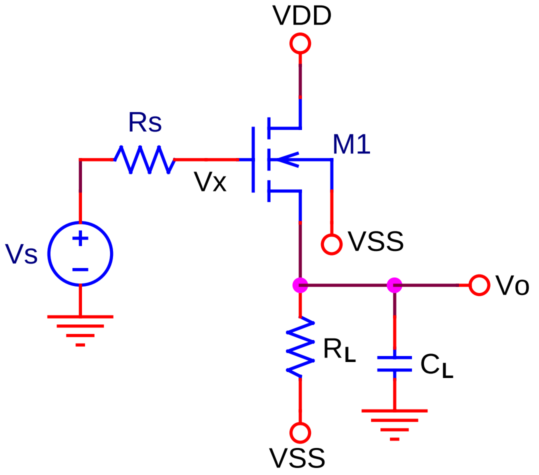
$$@\,\mathrm{V_o}:\quad \omega_{P3}=\frac{1}{C_{gd2}R_L}$$

▶ zero

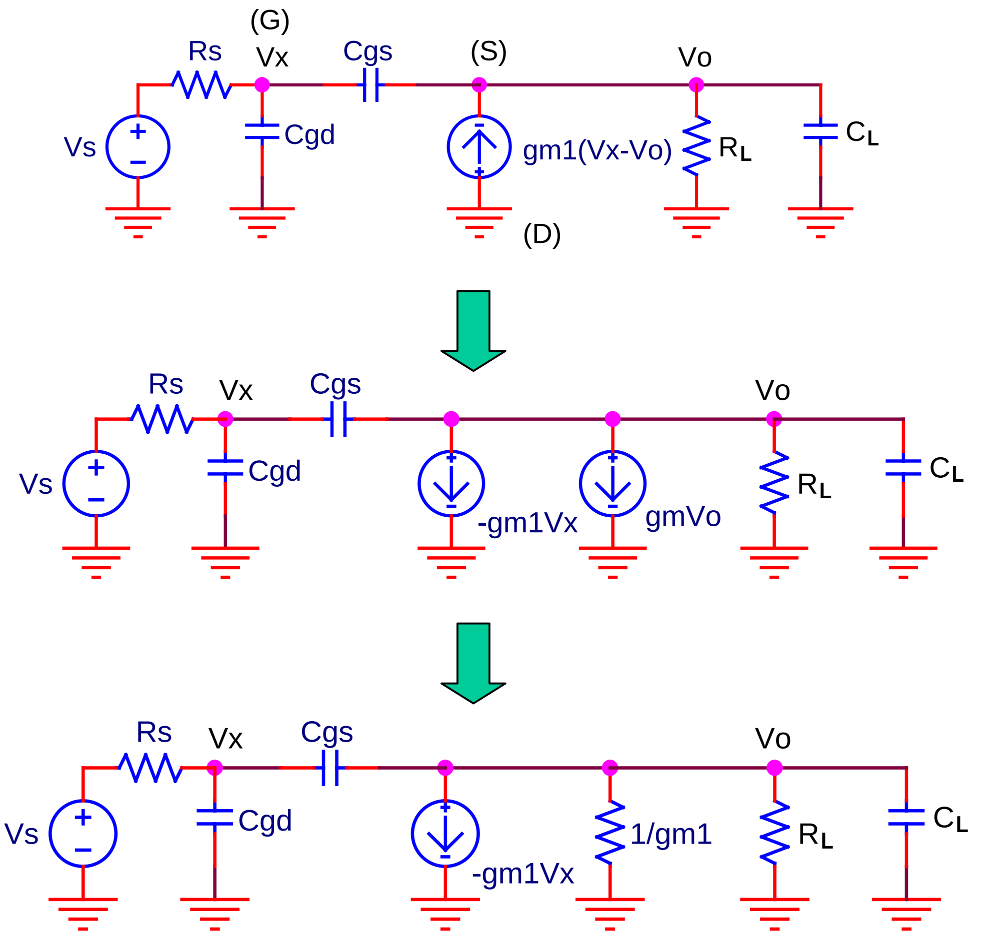
$$\omega_Z=\frac{g_{m1}}{C_{gd1}}$$

5. 공통-소스, 게이트, 드레인 증폭기의 고주파 해석

⊙ High-frequency response of the CD amplifier



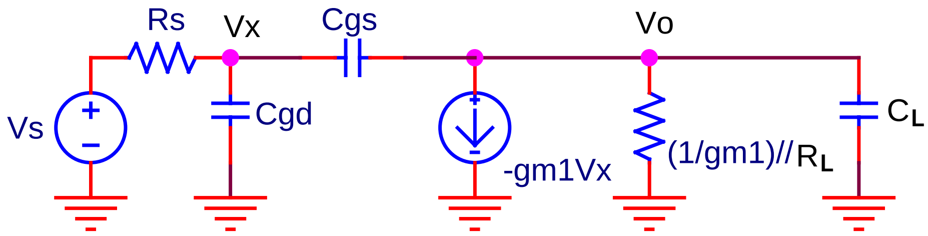
(λ effect & body effect are ignored)



(same architecture as that of CS amplifiers)

5. 공통-소스, 게이트, 드레인 증폭기의 고주파 해석

▶ equivalent circuit



$$C_1 = C_{gd}, \quad C_{12} = C_{gs}, \quad C_2 = C_L$$
$$g_m = -g_{m1}, \quad R_2 = (1/g_{m1}) // R_L$$

▶ transfer function

$$A_v(s) = A_M \frac{\left(1 - \frac{s}{\omega_Z}\right)}{\left(1 + \frac{s}{\omega_{P1}}\right)\left(1 + \frac{s}{\omega_{P2}}\right)}$$

▶ midband gain

$$A_M = -g_m R_2 = -(-g_{m1})R_2 = \frac{g_{m1}R_L}{1 + g_{m1}R_L}$$

▶ zero

$$\omega_Z = \frac{g_m}{C_{12}} = \frac{-g_{m1}}{C_{gs}}$$

5. 공통-소스, 게이트, 드레인 증폭기의 고주파 해석

▶ poles

① R_S : large & C_L : small

$$\omega_{P1} \approx \left(\frac{C_2 + C_{12}}{G_2} + \frac{C_1 + C_{12}}{G_s} + \frac{g_m C_{12}}{G_s G_2} \right)^{-1}$$

$$\approx \left(\frac{C_1 + C_{12}}{G_s} + \frac{g_m C_{12}}{G_s G_2} \right)^{-1} = \left(\frac{C_{gd} + C_{gs}}{G_s} - \frac{g_{m1} C_{gs}}{G_s G_2} \right)^{-1}$$

$$= \frac{1}{R_s \left(C_{gd} + \dfrac{C_{gs}}{1 + g_{m1} R_L} \right)} \approx \frac{1}{R_s C_{gd}}$$

$$R_L > \frac{1}{g_{m1}} \quad \rightarrow \quad g_{m1} R_L > 1$$

$$\rightarrow R_2 = R_L // \frac{1}{g_{m1}} \approx \frac{1}{g_{m1}}$$

$$\rightarrow g_{m1} R_2 \approx 1$$

$$\omega_{P2} \approx \left(\frac{G_s G_2}{C_1 C_2 + C_1 C_{12} + C_2 C_{12}} \right) \frac{1}{\omega_{P1}} \approx \left(\frac{G_s G_2}{C_1 C_{12}} \right) \frac{1}{\omega_{P1}} = \frac{G_2}{C_{12}} = \frac{g_{m1}}{C_{gs}}$$

② R_S : small & C_L : large

$$\omega_{P1} \approx \left(\frac{C_2 + C_{12}}{G_2} + \frac{C_1 + C_{12}}{G_s} + \frac{g_m C_{12}}{G_s G_2} \right)^{-1}$$

$$\approx \left(\frac{C_2 + C_{12}}{G_2} \right)^{-1} = \frac{G_2}{C_{gs} + C_L} \approx \frac{g_{m1}}{C_L}$$

$$\omega_{P2} \approx \left(\frac{G_s G_2}{C_1 C_2 + C_1 C_{12} + C_2 C_{12}} \right) \frac{1}{\omega_{P1}} \approx \frac{G_s G_2}{(C_1 + C_{12}) C_2} \frac{C_2 + C_{12}}{G_2} \approx \frac{1}{R_s (C_{gs} + C_{gd})}$$

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