Electronic Circuits
Chapter 3: FET

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- MOSFET
- Current Voltage Characteristics
- MOSFET Circuits at DC
- Small Signal Operation and Models
- Basic MOSFET Amplifier Configurations

MOSFET

- **MOSFET**: **M**etal-**O**xide-**S**emiconductor **F**ield-**E**ffect **T**ransistor.

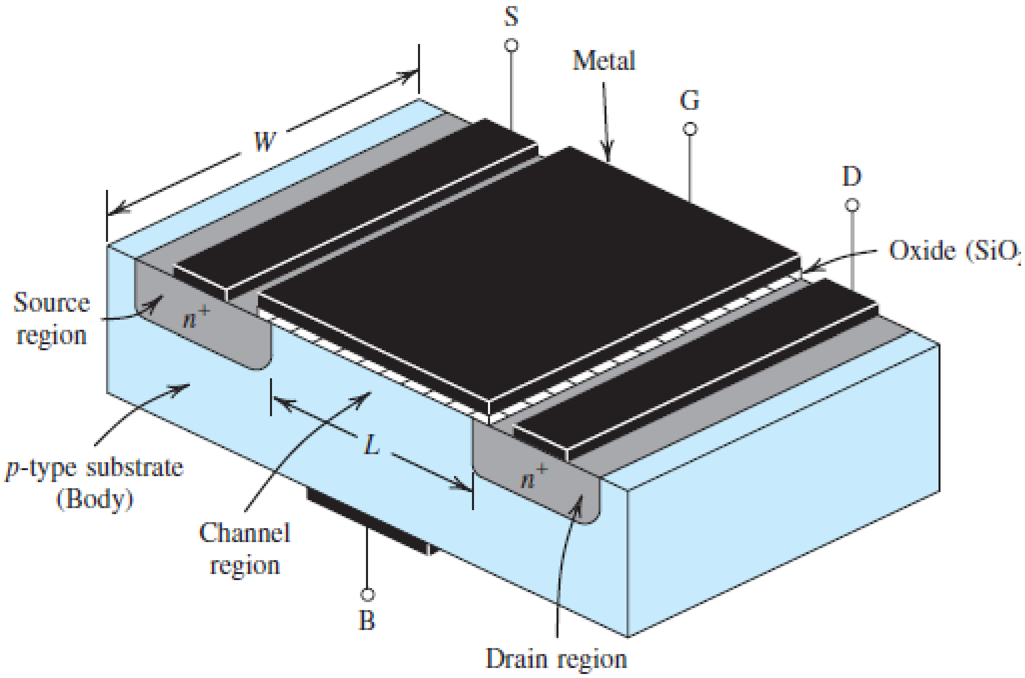
- According to the physics of the device, we can classify transistors into two main classes:

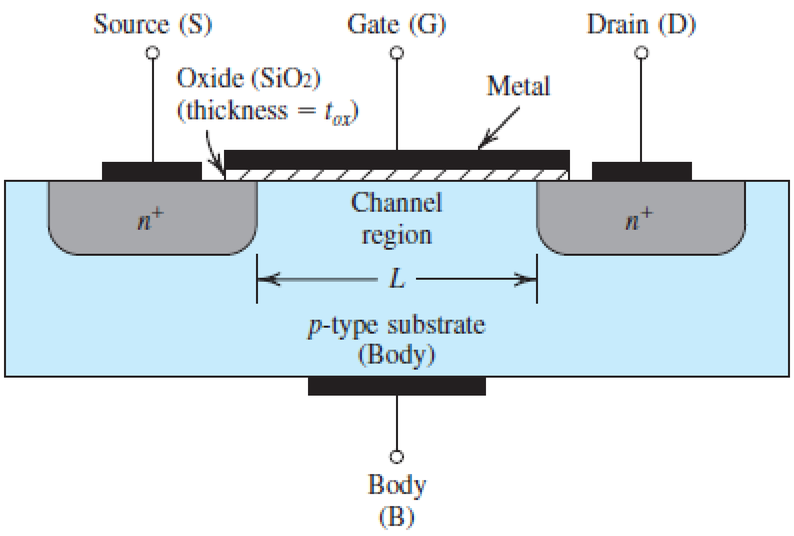
  - **Field Effect Transistors (FET)**: Conduction is controlled by electric field which is produced by voltage applied to the control terminals. So, the control draws no current and FET is a voltage- controlled device.

  - **Bipolar Junction Transistors (BJT)**: Diode-based device which is usually blocked unless the control terminals are forward- biased. So, the control is a current, and BJT is a current amplifier by nature.

MOSFET

- **MOSFET** is a four-terminal device: gate (**G**), source (**S**), drain (**D**) and body (**B**).
- **Two kinds of MOSFETs**: n-channel (**NMOS**) and p-channel (**PMOS**) devices.
- The device structure is basically symmetric in terms of drain and source.
- Source and drain terminals are specified by the operation voltage.



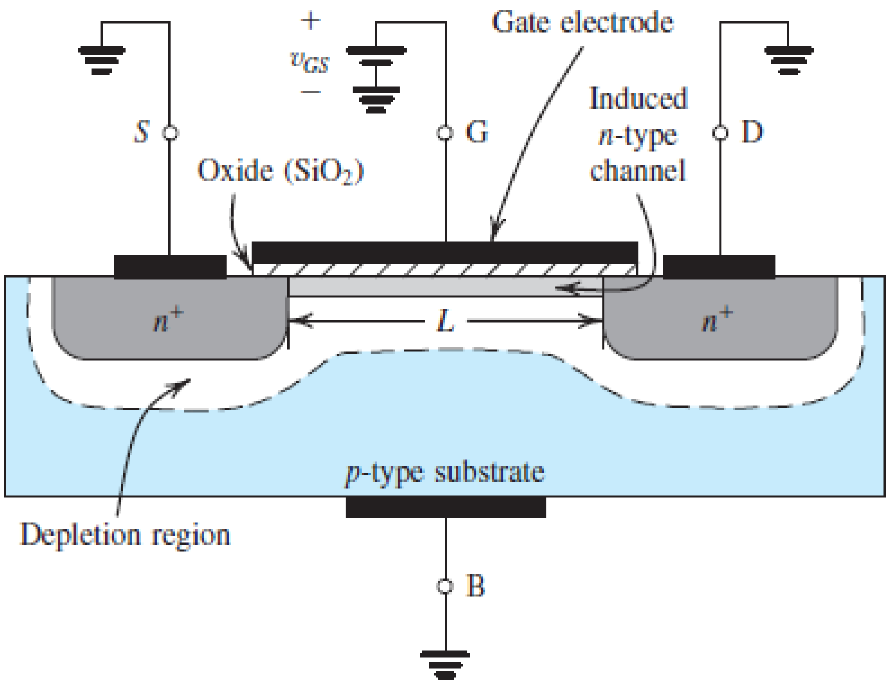


MOSFET

- Gate voltage exceeds a threshold voltage $v_{GS} > V_t$: electrons start to accumulate on the substrate surface. $V_t = 0.3 \div 1$ (V)

- The positive $v_{GS} > V_t$ is used to induce the channel and it is called **n-channel** enhancement type MOSFET.

- The induced n region *forms a channel for current flow from drain to source*.

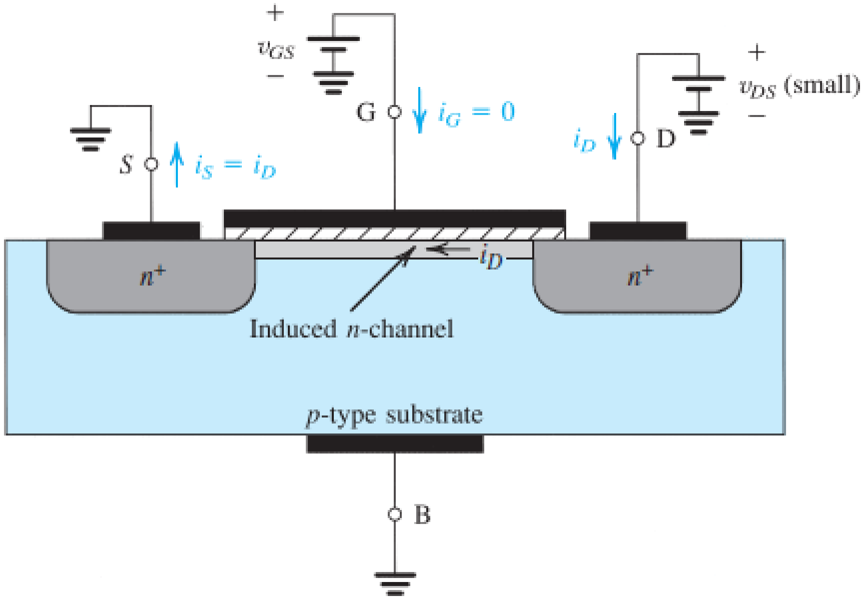


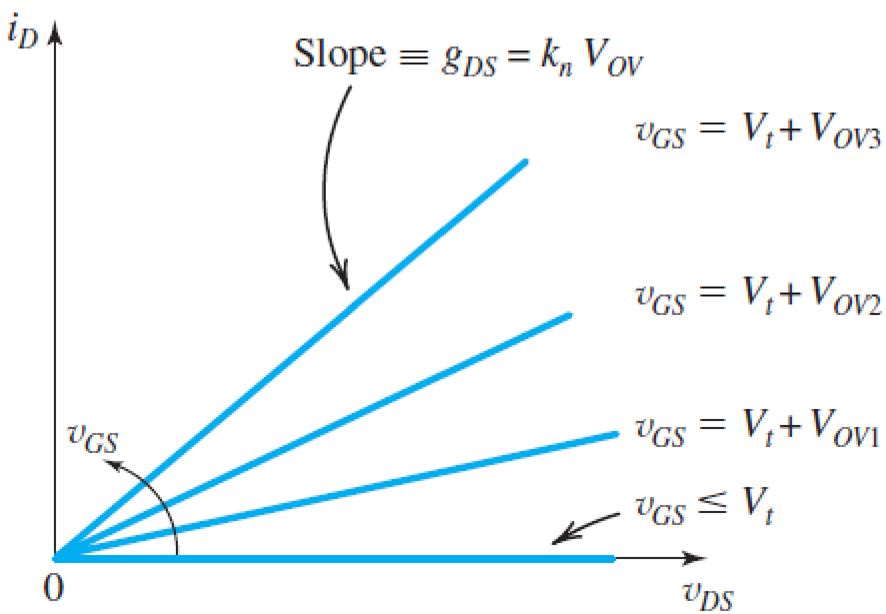
- *The field controls the amount of charge* in the channel and determines the channel conductivity.

MOSFET – Small v_{DS}

- ***Small v_{DS} is applied***: free electrons travel from source to drain through the induced n-channel.

- The resulting current i_D flows from drain to source (opposite to the direction of the flow of negative charge).





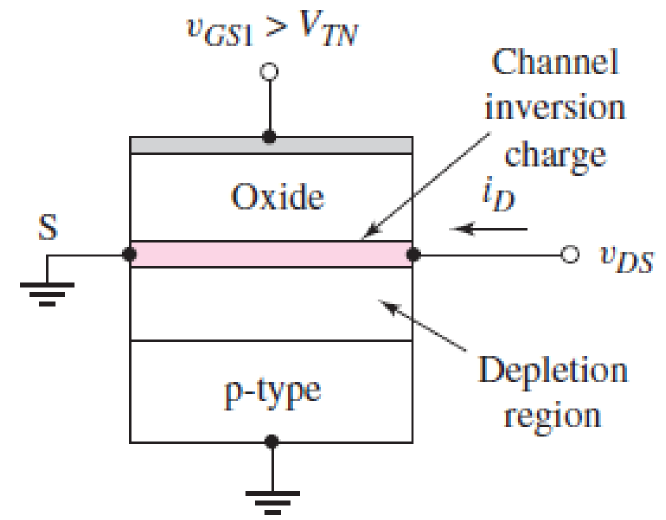
- The resulting current i_D flows from drain to source (opposite to the direction of the flow of negative charge).

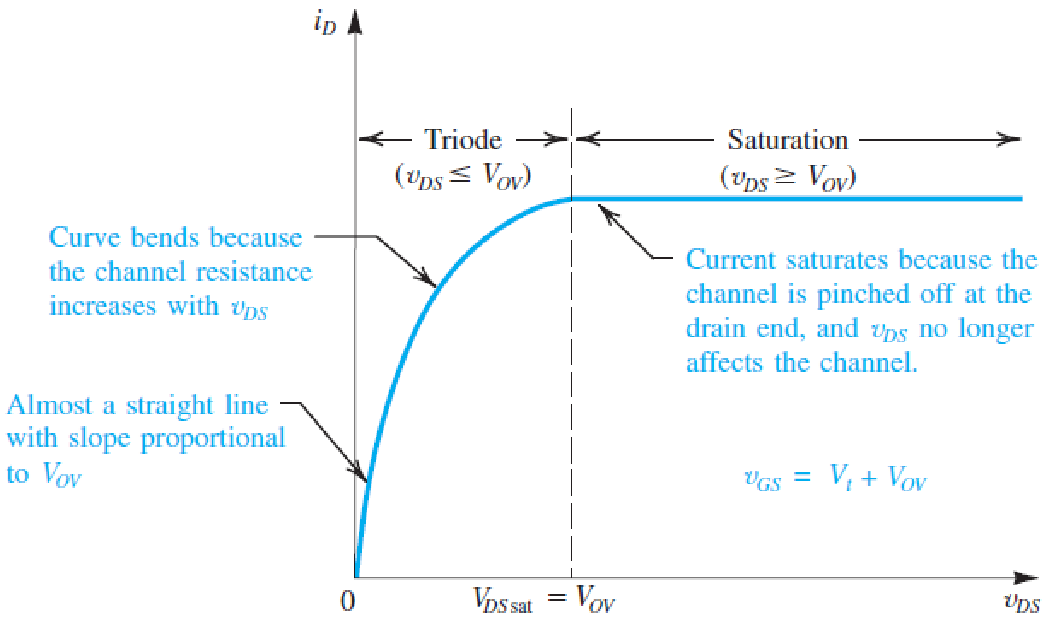
- The channel is controlled by the effective voltage or overdrive voltage:

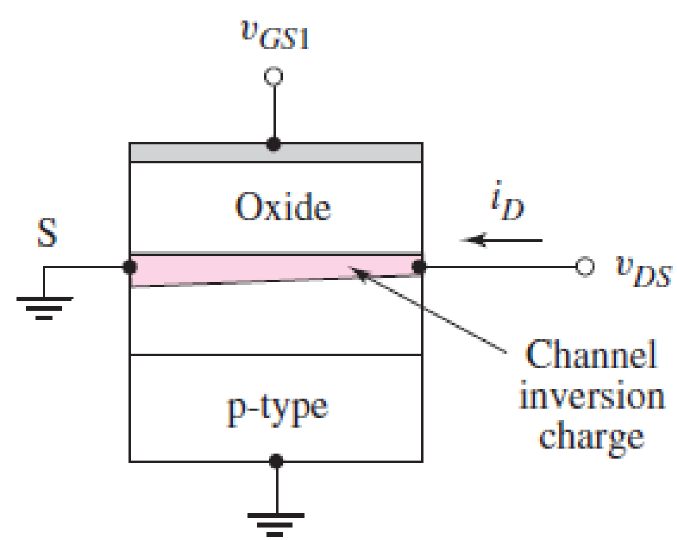
$$V_{OV} = V_{GS} - V_t$$

MOSFET – Increasing v_{DS}

- As v_{DS} is increased, the channel becomes more tapered and its resistance increases correspondingly.
- At the point $v_{DSsat} = v_{GS} - V_t$, the channel is pinched off at the drain side.
- Triode region: $v_{DS} < v_{DSsat}$
- Saturation region: $v_{DS} \geq v_{DSsat}$







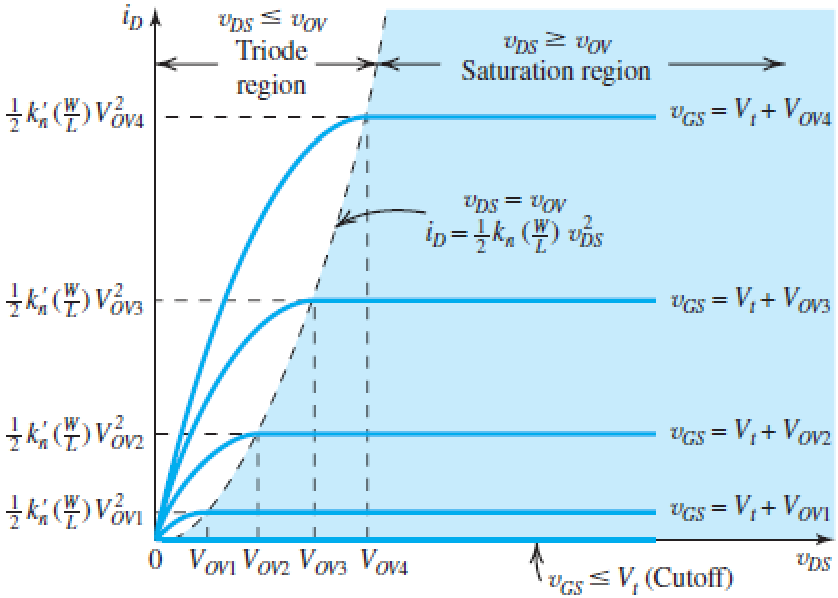
MOSFET – IV Relationship

- Triode region: $i_D = k_n\left[(v_{GS} - V_t)v_{DS} - \frac{1}{2}v_{DS}^2\right]$
- Saturation region: $i_{Dsat} = \frac{1}{2}k_n(v_{GS} - V_t)^2$
- Channel resistance: $r_{DS} = \frac{1}{k_n(v_{GS} - V_t)}$
- Transconductance parameter: $k_n = \mu_n C_{ox}\frac{W}{L} = k'_n\frac{W}{L}$ where:

C_{ox}: oxide capacitance per unit area.

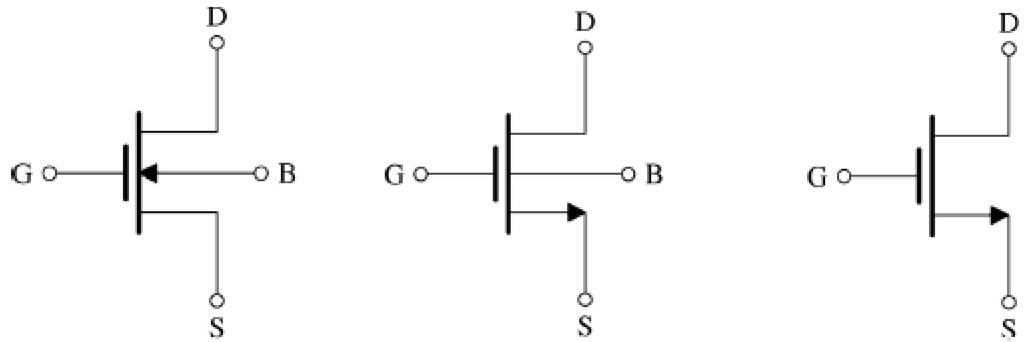
μ_n: mobility of electron in the inversion layer.

W and L: channel width and length.

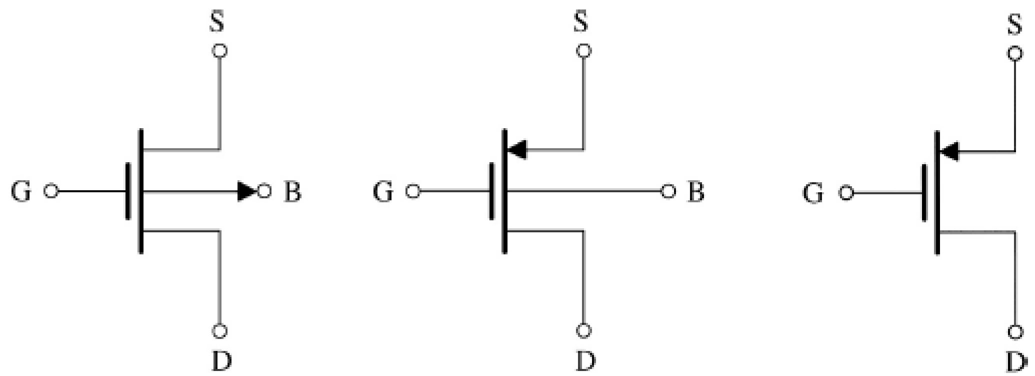


MOSFET – Circuit Symbols

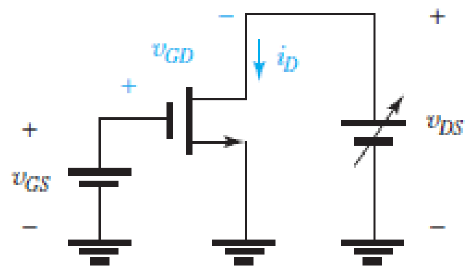
- ***n-channel enhancement-mode MOSFET:***

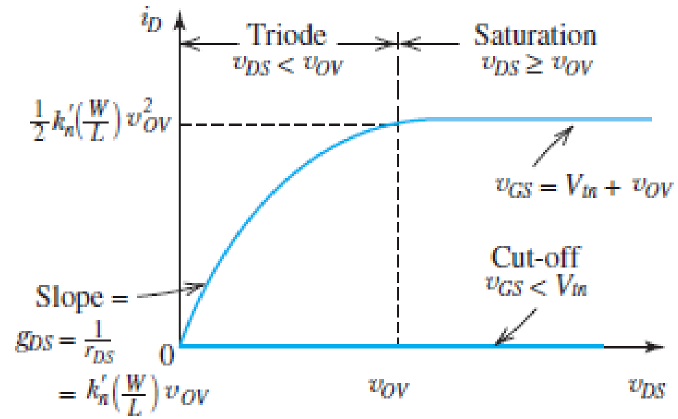


- ***p-channel enhancement-mode MOSFET:***



NMOS – Current Voltage Characteristics





- $v_{GS} < V_{tn}$: no channel; transistor in cut-off; $i_D = 0$
- $v_{GS} = V_{tn} + v_{OV}$: a channel is induced; transistor operates in the triode region or the saturation region depending on whether the channel is continuous or pinched-off at the drain end;

Triode Region

Continuous channel, obtained by:

$$v_{GD} > V_{tn}$$

or equivalently:

$$v_{DS} < v_{OV}$$

Then,

$$i_D = k_n'\left(\frac{W}{L}\right)\left[(v_{GS} - V_{tn})v_{DS} - \frac{1}{2}v_{DS}^2\right]$$

or equivalently,

$$i_D = k_n'\left(\frac{W}{L}\right)\left(v_{OV} - \frac{1}{2}v_{DS}\right)v_{DS}$$

Saturation Region

Pinched-off channel, obtained by:

$$v_{GD} \leqslant V_{tn}$$

or equivalently:

$$v_{DS} \geqslant v_{OV}$$

Then

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

or equivalently,

$$i_D = \frac{1}{2}k_n'\left(\frac{W}{L}\right)v_{OV}^2$$

MOSFET - Current Voltage Characteristics

Example 1: Consider an NMOS transistor fabricated in a $\mathrm{L} = 0.18\mu m$ process with $\mathrm{L} = 0.18\mu m$ and $\mathrm{W} = 2\mu m$. The process technology is specified to have $C_{ox} = 8.6\ \mathrm{fF}/\mathrm{\mu}m^2$, $\mu_n = 450\ cm^2/Vs$ and $V_{tn} = 0.5V$.

a. Find V_{GS} and V_{DS} that result in the MOSFET operating at the edge of saturation with $I_D = 100\mu A$.

b. If V_{GS} is kept constant, find V_{DS} that results in $I_D = 50\mu A$.

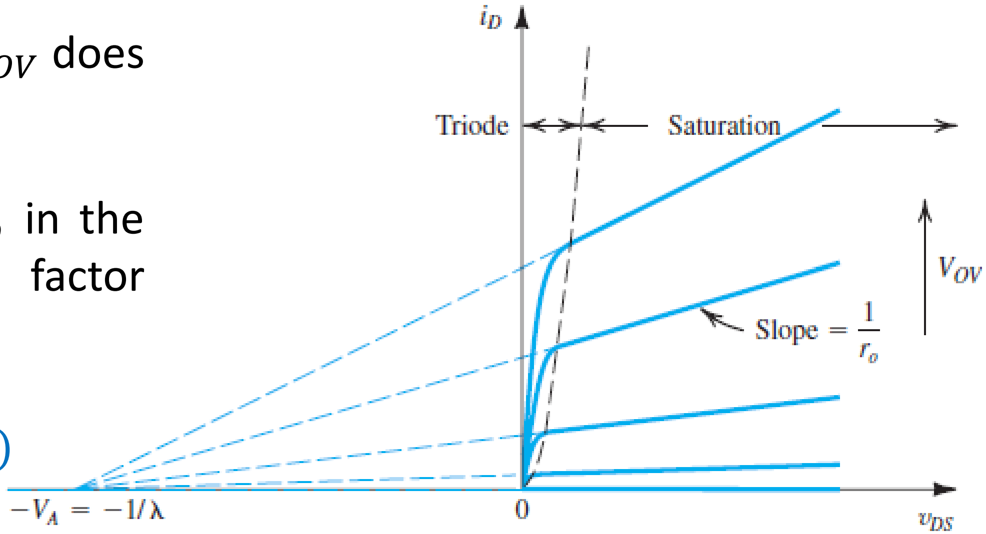
c. To investigate the use of the MOSFET as a linear amplifier, let it be operating in saturation with $V_{DS} = 0.3V$. Find the change in i_D resulting from V_{GS} changing from $0.7V$ by $+0.01V$ and by $-0.01V$.

MOSFET – Finite Output Resistance

- In practice, increasing v_{DS} beyond v_{OV} does affect the channel somewhat.

- This effect can be accounted for i_D in the expression for by including a factor $(1 + \lambda v_{DS})$:

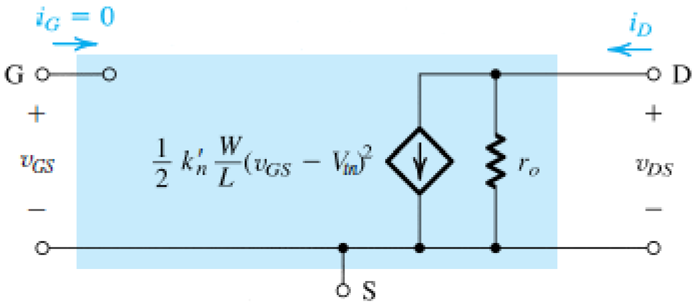
$$i_{Dsat} = \frac{1}{2} k_n (v_{GS} - V_t)^2 (1 + \lambda v_{DS})$$



- Defining the output resistance r_o as

$$r_o \equiv \left[\frac{\partial v_{DS}}{\partial i_D}\right]\Bigg|_{v_{GS}=const} = \frac{V_A}{I_D}$$

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

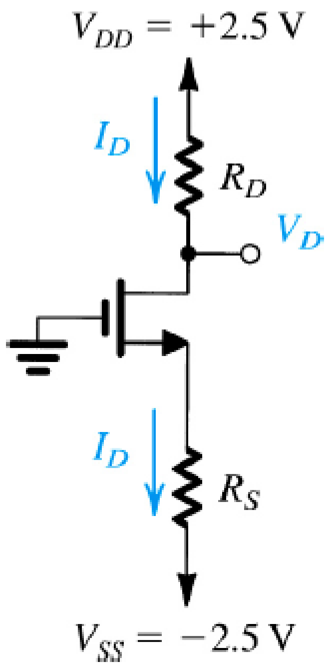


MOSFET Circuits at DC

❖ DC analysis for MOSFET circuits:

- Assume the operation mode and solve the dc bias utilizing the corresponding current equation.
- Verify the assumption with terminal voltages (cutoff, triode and saturation).
- If the solution is invalid, change the assumption of operation mode and analyze again.

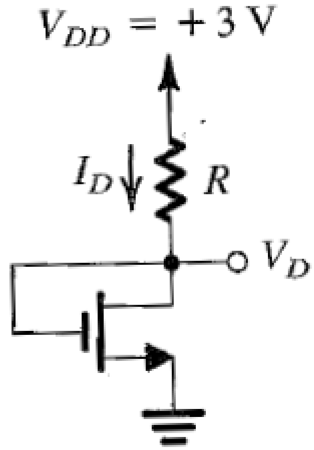
Example 2: The NMOS transistor in the following circuit has $V_t = 0.7V$, $\mu_n C_{ox} = 100\mu A/V^2$, $L = 1\mu m$ and $W = 32\mu m$. Design the circuit so that the transistor operates at $I_D = 0.4mA$ and $V_D = 0.5V$.



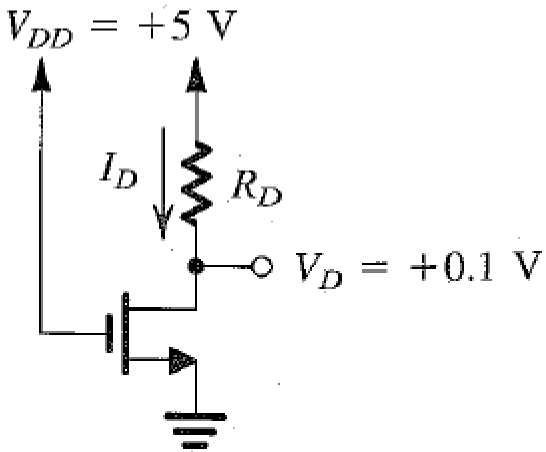
MOSFET Circuits at DC

Example 3: The NMOS transistor in the following circuit has $V_t = 0.6V$, $\mu_n C_{ox} = 200\mu A/V^2$, $L = 0.8\mu m$ and $W = 4\mu m$. Design the circuit so that the transistor operates at $I_D = 80\ \mu A$. Find the DC voltage V_D.

Example 4: Design the circuit so that the transistor operates at $V_D = 0.1V$. Let $V_t = 1V$, $k_n = 1mA/V^2$. Find the effective resistance between drain and source at this operating point.



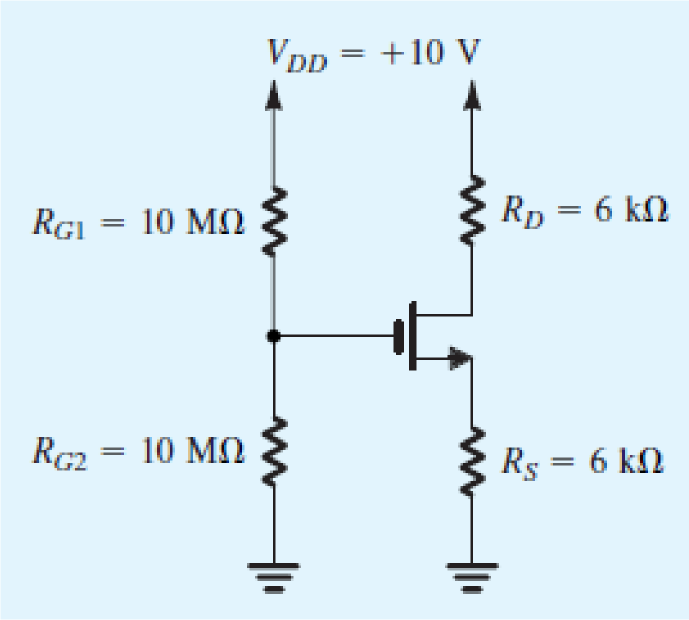
Example 3

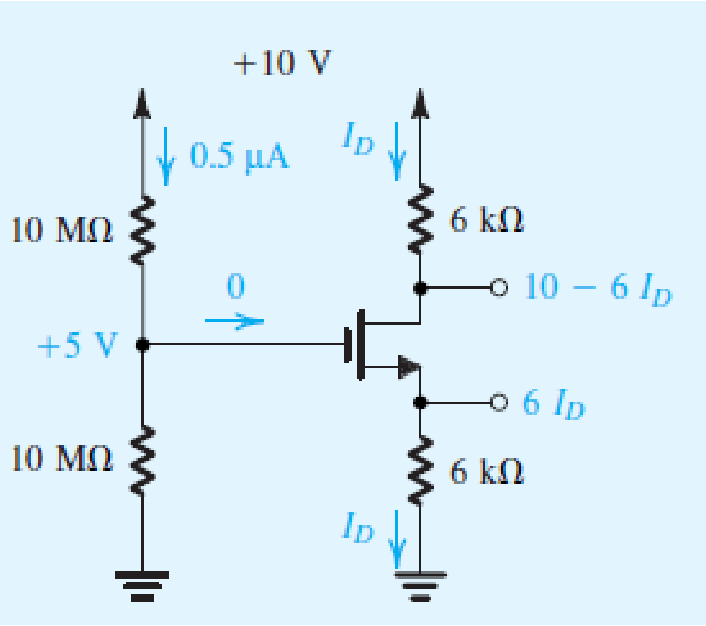


Example 4

MOSFET Circuits at DC

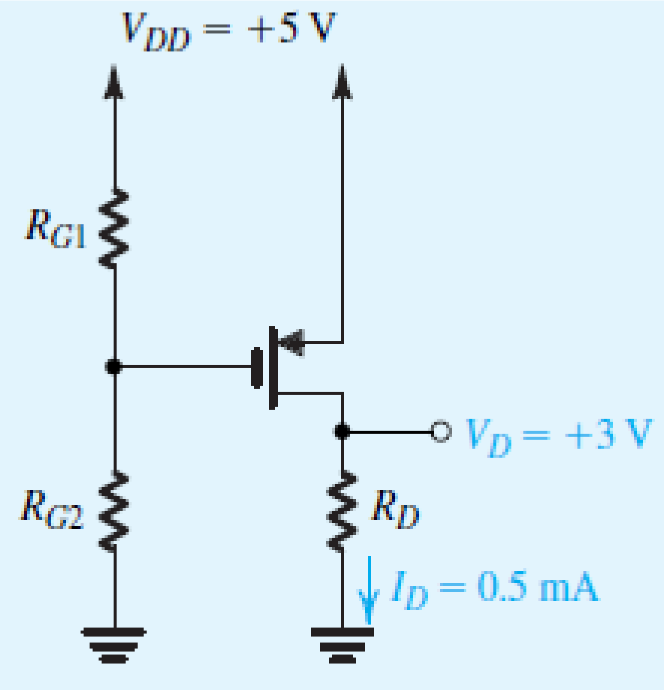
Example 5: Determine the voltage and the current of all nodes and branches? $V_t = 1V,\ k_n = 1mA/V^2$.





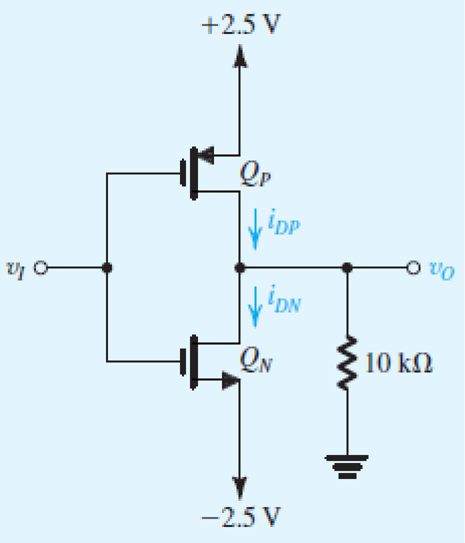
MOSFET Circuits at DC

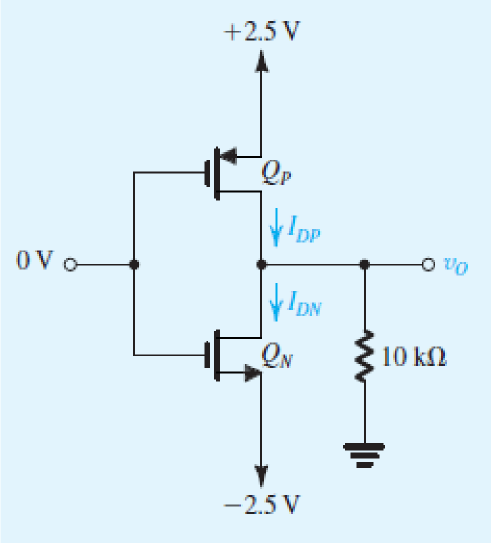
Example 6: Design the following circuit so that the transistor operates in saturation with $I_D = 0.5mA$ and $V_D = 3V$. Let the enhancement-type PMOS transistor have $V_{tp} = -1V$ and $k'_p \frac{W}{L} = 1mA/V^2$. Assume $\lambda = 0$. What is the largest value that R_D can have while maintaining saturation-region operation?

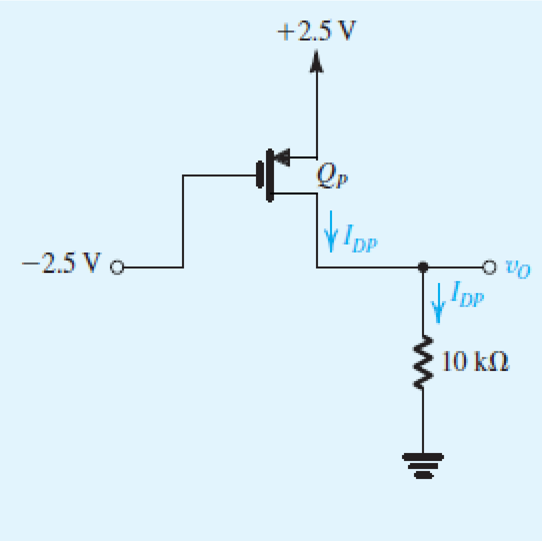


MOSFET Circuits at DC

Example 7: The NMOS and PMOS transistors in the following circuit are matched, with $k_n' \frac{W}{L} = k_p' \frac{W}{L} = 1mA/V^2$ and $V_{tn} = -V_{tp} = 1V$. Assume $\lambda = 0$ for both devices, find the drain currents i_{DN} and i_{DP} as well as the voltage v_o for $v_I = 0V, 2.5V\ and\ -2.5V$.

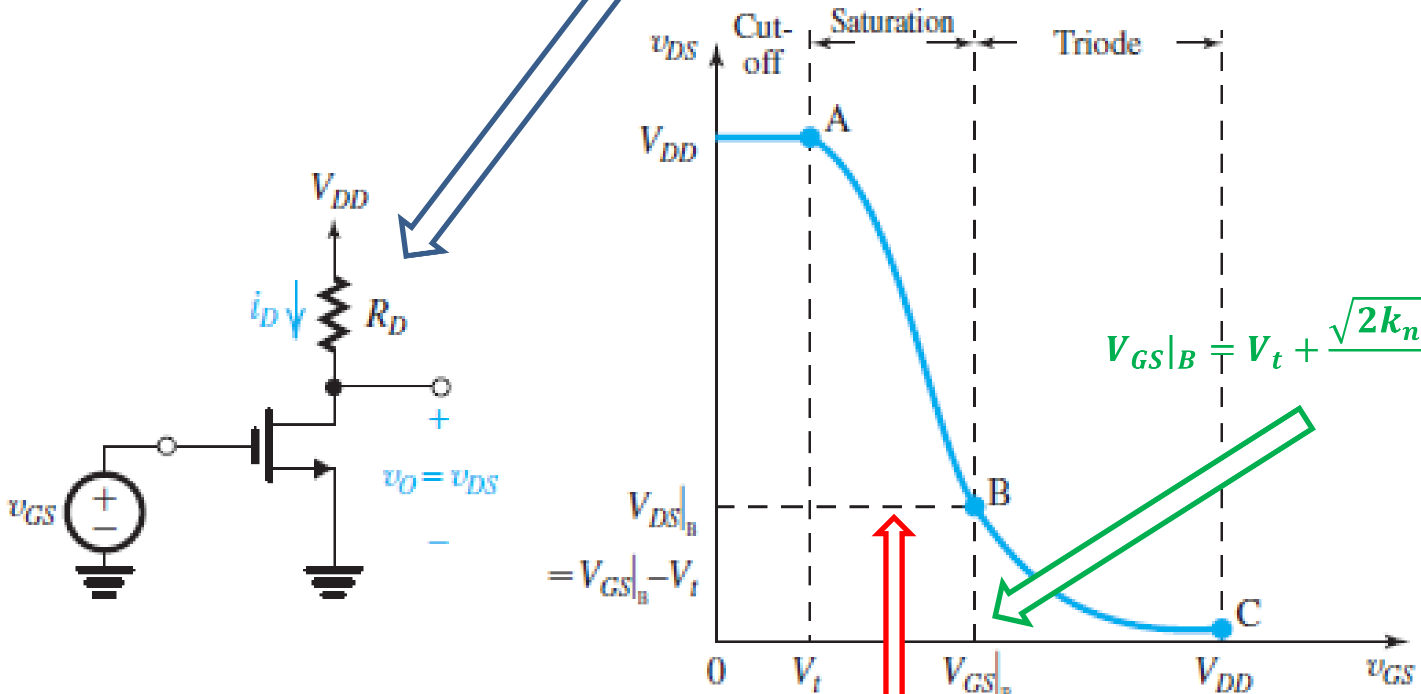






MOSFET in Amplifier Design

$$i_D = \frac{1}{2} k_n (v_{GS} - V_t)^2$$



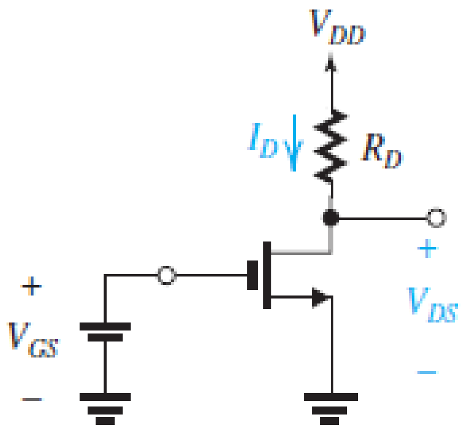
$$V_{GS}|_B = V_t + \frac{\sqrt{2k_n R_D V_{DD} + 1} - 1}{k_n R_D}$$

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

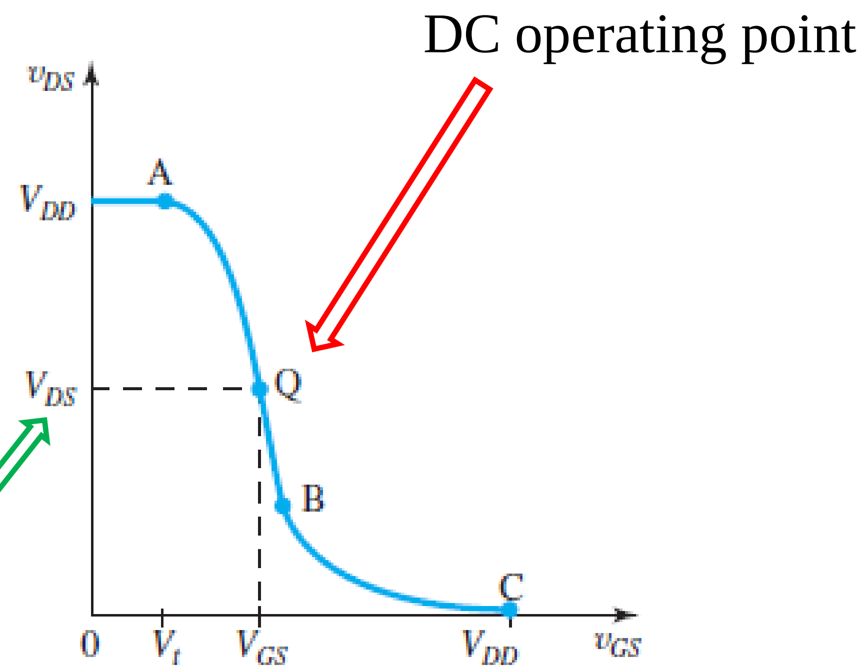
$$v_{DS} = V_{DD} - \frac{1}{2} k_n R_D (v_{GS} - V_t)^2$$

❖ *Input voltage increase → drain current increase → output voltage decrease.*

MOSFET in Amplifier Design



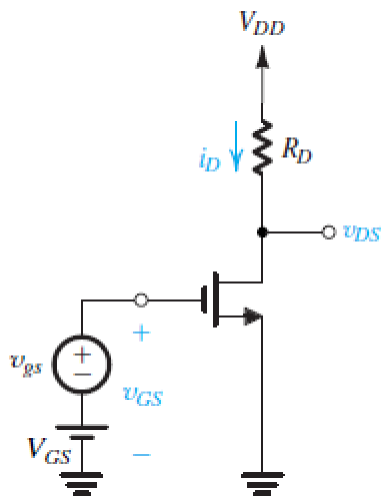
$$v_{DS} = V_{DD} - \frac{1}{2} k_n R_D (v_{GS} - V_t)^2$$



❖ The signal to be amplified, $v_{gs}(t)$, a function of time t, is superimposed on the bias voltage. Thus the total instantaneous value of becomes:

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

MOSFET in Amplifier Design



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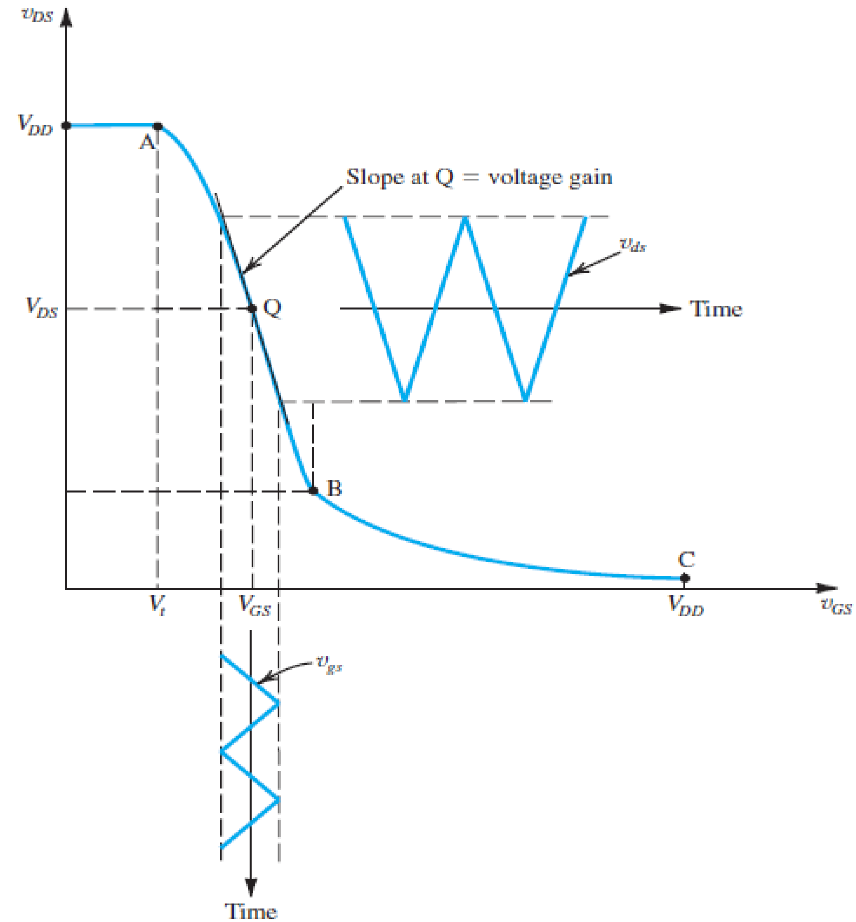


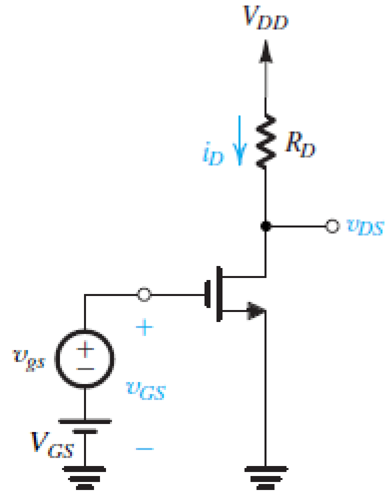
$$A_v \equiv \frac{\partial v_{DS}}{\partial v_{GS}}\Big|_{v_{GS}=V_{GS}} = -k_n(V_{GS} - V_t)R_D$$

MOSFET in Amplifier Design

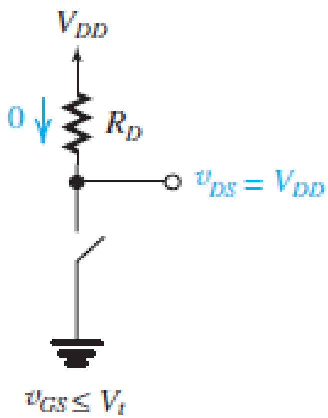
Example 8: The transistor is specified to have $V_t = 0.4V, k_n' = 0.4mA/V^2, W/L = 10, V_{DD} = 1.8V, R_D = 17.5k\Omega, V_{GS} = 0.6V$.

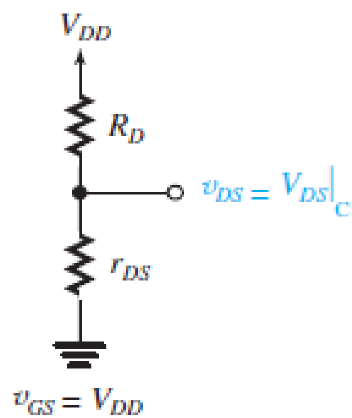
a. For $v_{gs} = 0$, find V_{OV}, I_D, V_{DS} and A_v.

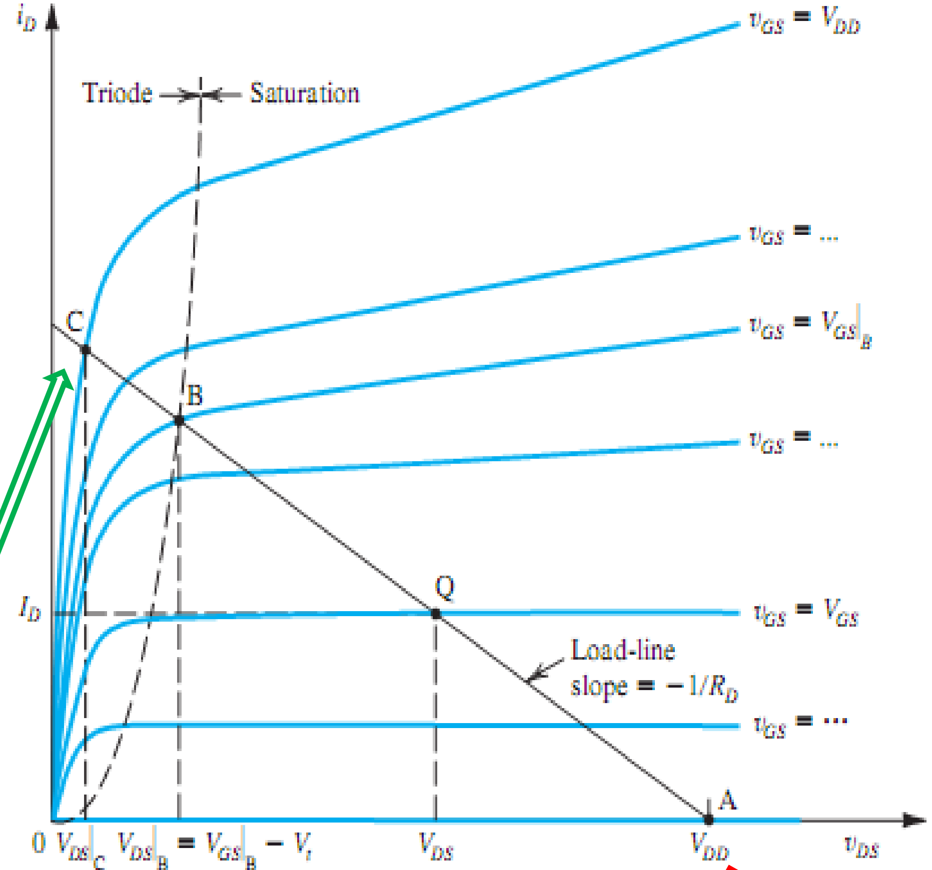
b. What is the maximum symmetrical signal swing allowed at the drain? Hence find the maximum allowable amplitude of a sinusoidal v_{GS}.



MOSFET in Amplifier Design





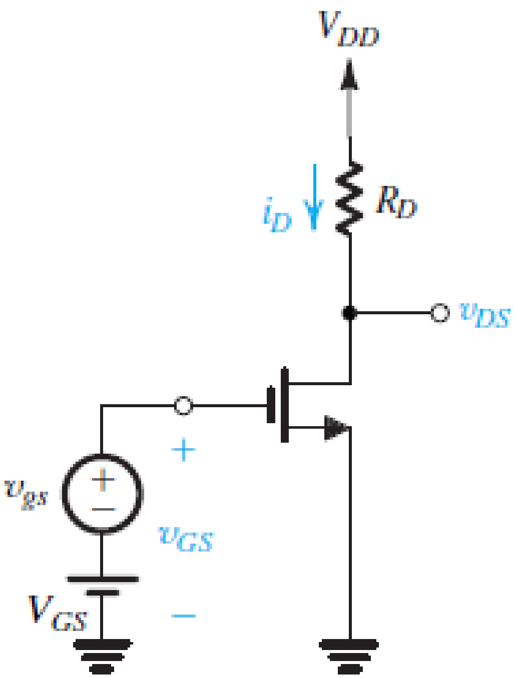


$v_{DS} \approx 0$

$I_D = 0$
$v_{DS} = V_{DD}$

Transistor as a switch

Small Signal Operation and Models



- The DC bias point:

$$I_D = \frac{1}{2} k_n (V_{GS} - V_t)^2 = \frac{1}{2} k_n V_{OV}^2$$

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

- When the input signal v_{gs} applied

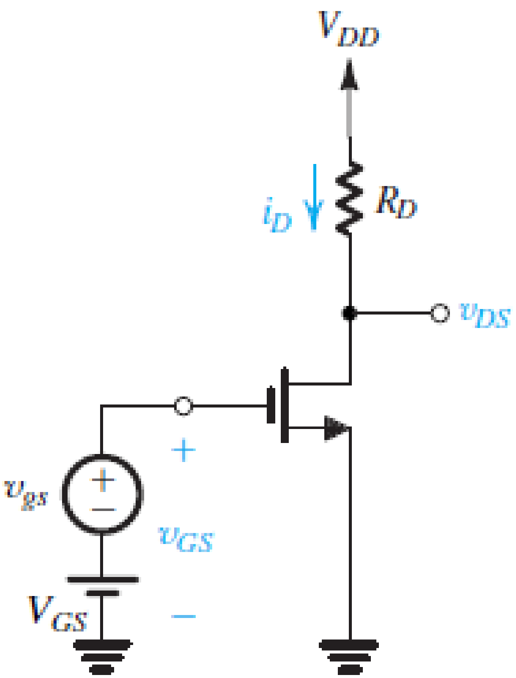
$$i_D = \frac{1}{2} k_n \left(V_{GS} + v_{gs} - V_t \right)^2$$

$$= \frac{1}{2} k_n (V_{GS} - V_t)^2 + k_n (V_{GS} - V_t) v_{gs} + \frac{1}{2} k_n v_{gs}^2$$

- In order to reduce the non-linear distortion: $\frac{1}{2} k_n v_{gs}^2 \ll k_n (V_{GS} - V_t) v_{gs}$

$$\leftrightarrow v_{gs} \ll 2(V_{GS} - V_t)$$

Small Signal Operation and Models



$$A_v \equiv \frac{v_{ds}}{v_{gs}} = -g_m R_D$$

- If the small signal condition is satisfied:

$$i_D = \frac{1}{2}k_n(V_{GS} - V_t)^2 + k_n(V_{GS} - V_t)v_{gs} = I_D + i_d$$

- The MOSFET **transconductance** g_m:

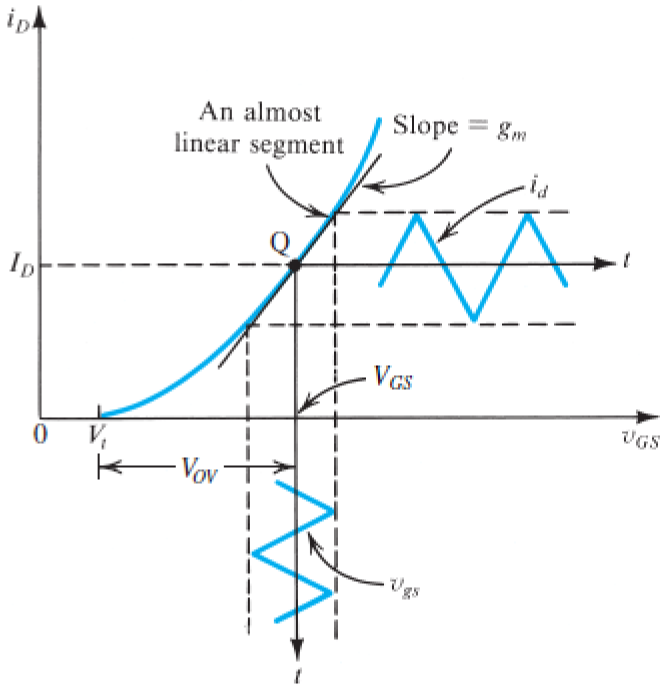
$$g_m \equiv \frac{i_d}{v_{gs}} = k_n(V_{GS} - V_t)$$

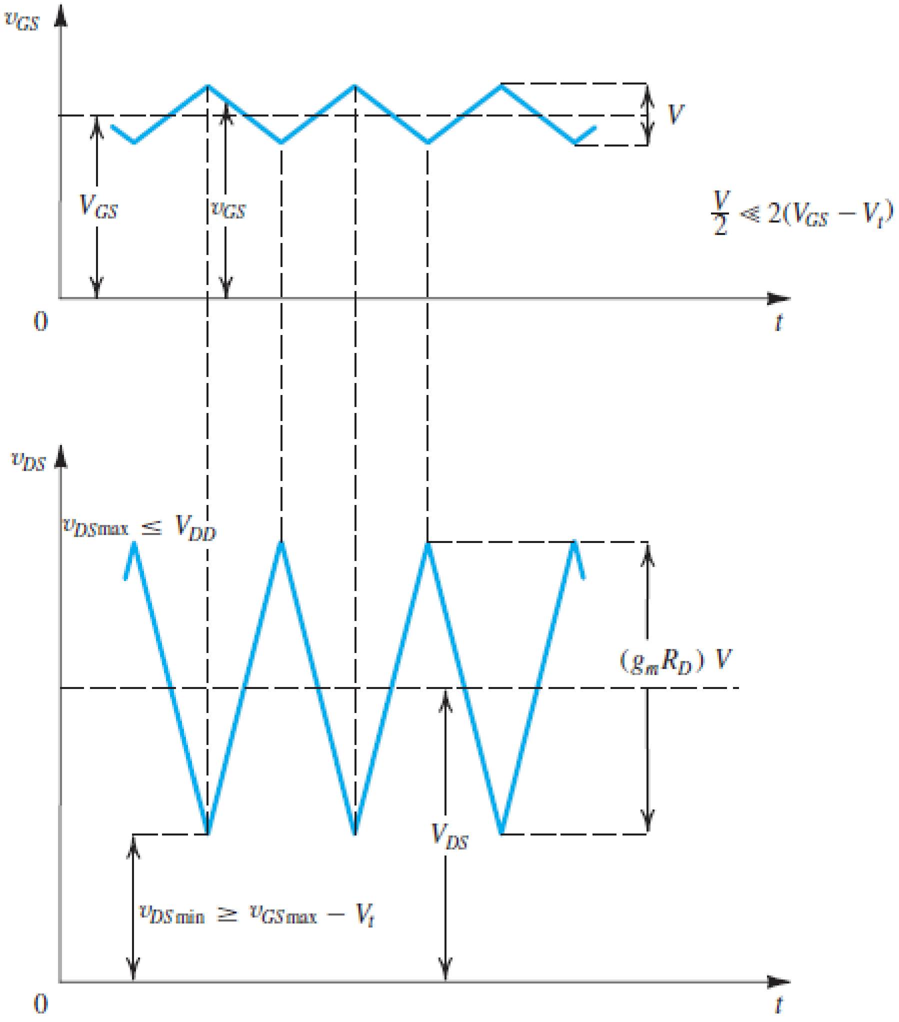
- Voltage gain:

$$v_{DS} = V_{DD} - i_D R_D = V_{DD} - (I_D + i_d)R_D$$

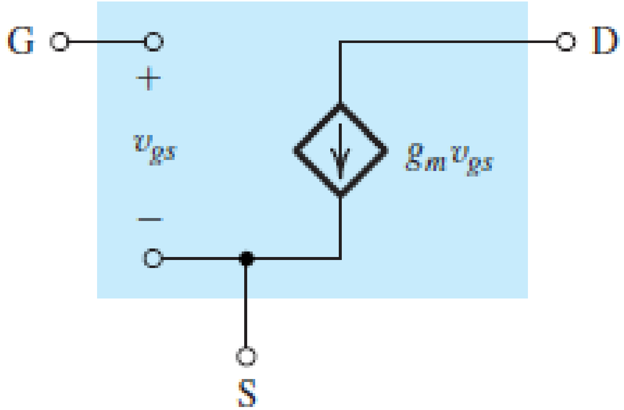
$$= V_{DS} - i_d R_D$$

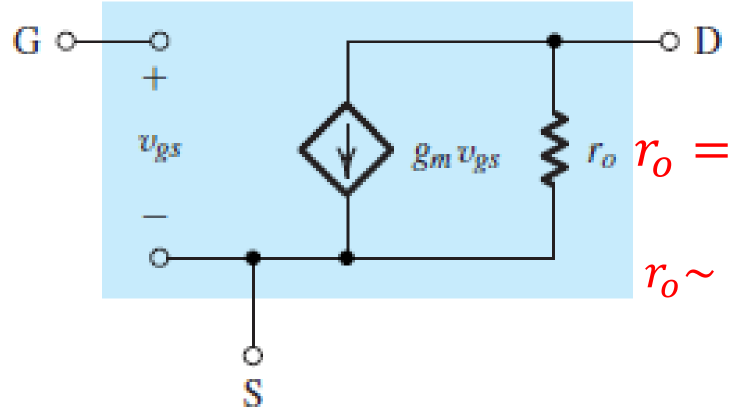
Small Signal Operation and Models





Small Signal Model



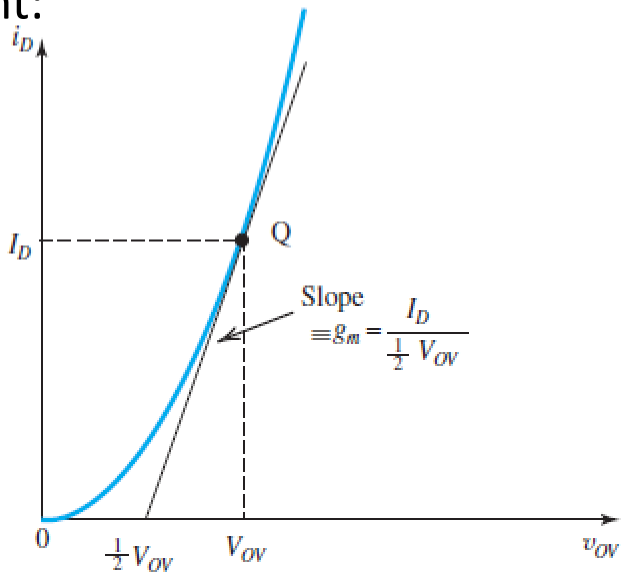


$$r_o = \frac{V_A}{I_D}$$

$$r_o \sim 10k\Omega - 100k\Omega$$

❖ The current I_D is the value of the dc drain current:

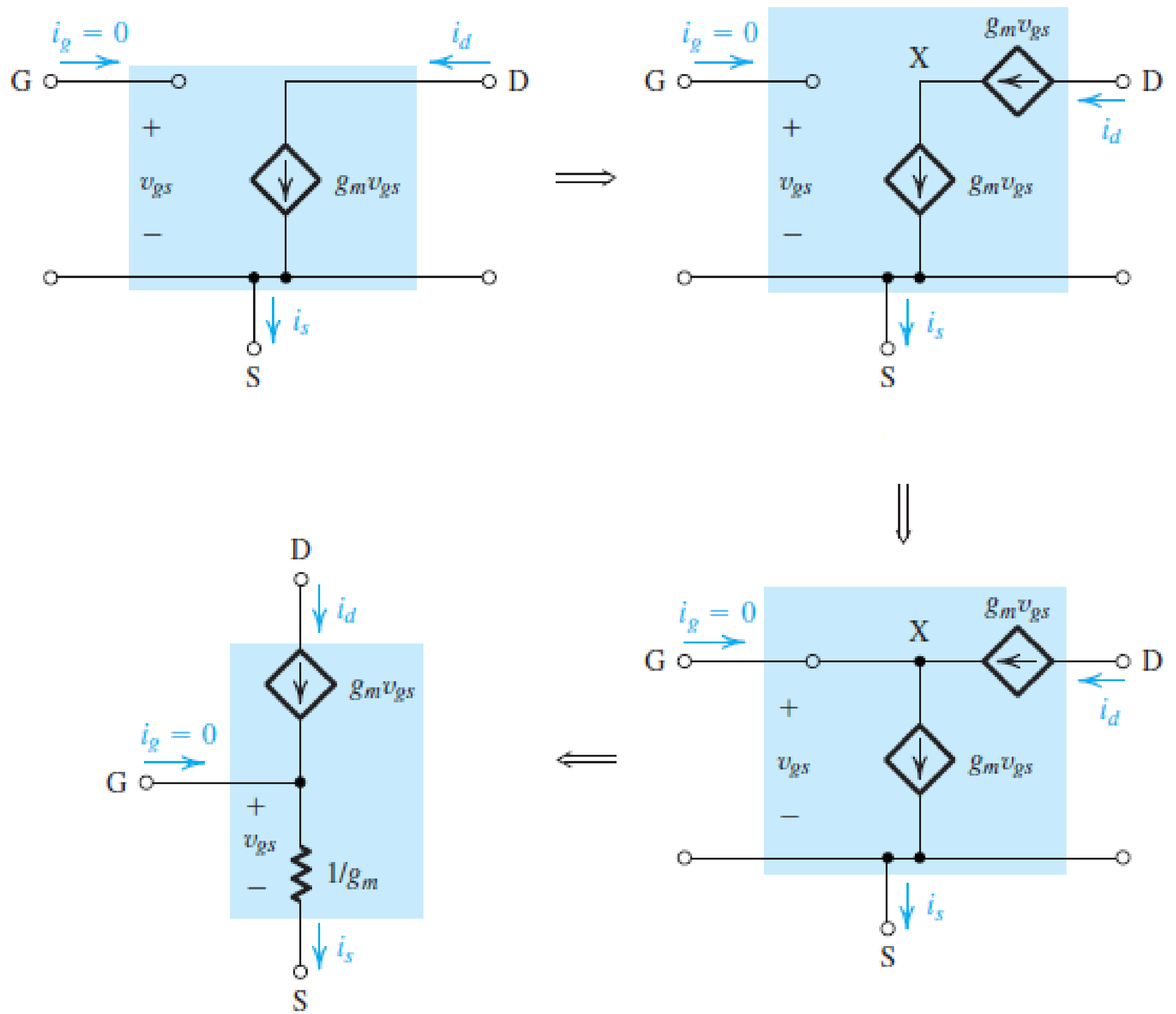
$$I_D = \frac{1}{2}k_n(V_{GS} - V_t)^2 = \frac{1}{2}k_n V_{OV}^2$$



❖ The trans-conductance g_m:

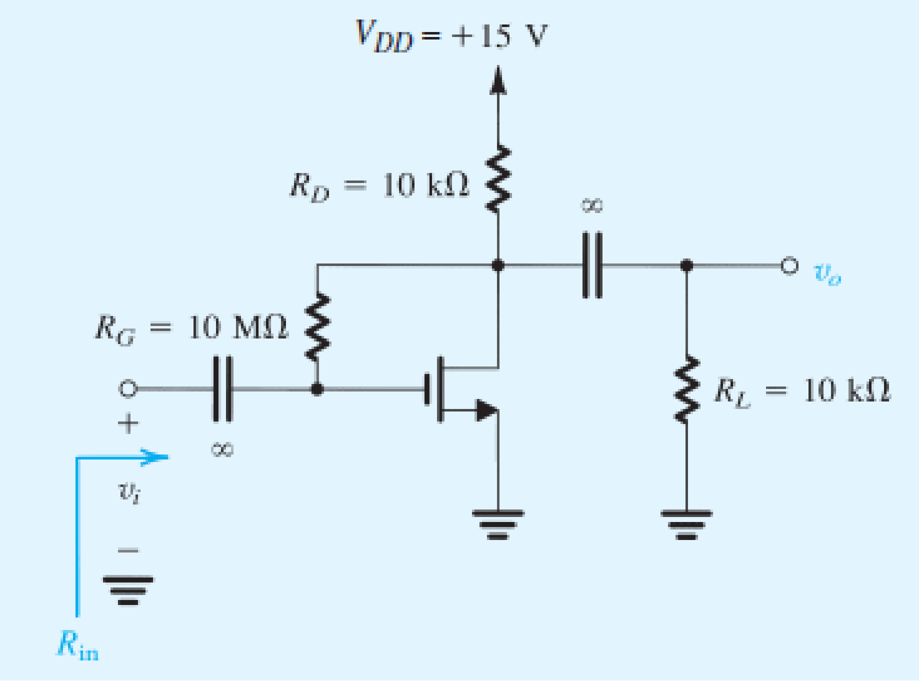
$$g_m = k_n V_{OV} = k_n'(W/L)V_{OV} = \frac{2I_D}{V_{OV}}$$

Small Signal Model – T model



Small Signal Model

Example 9: A discrete common-source MOSFET amplifier utilizing a drain-to-gate resistance R_G for biasing purposes. The transistor has $V_t = 1.5\,V, k_n'W/L = 0.25mA/V^2$ and $V_A = 50V$. Determine its small-signal voltage gain and its input resistance.



Summary

Small-Signal Parameters

NMOS transistors

- Transconductance:

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

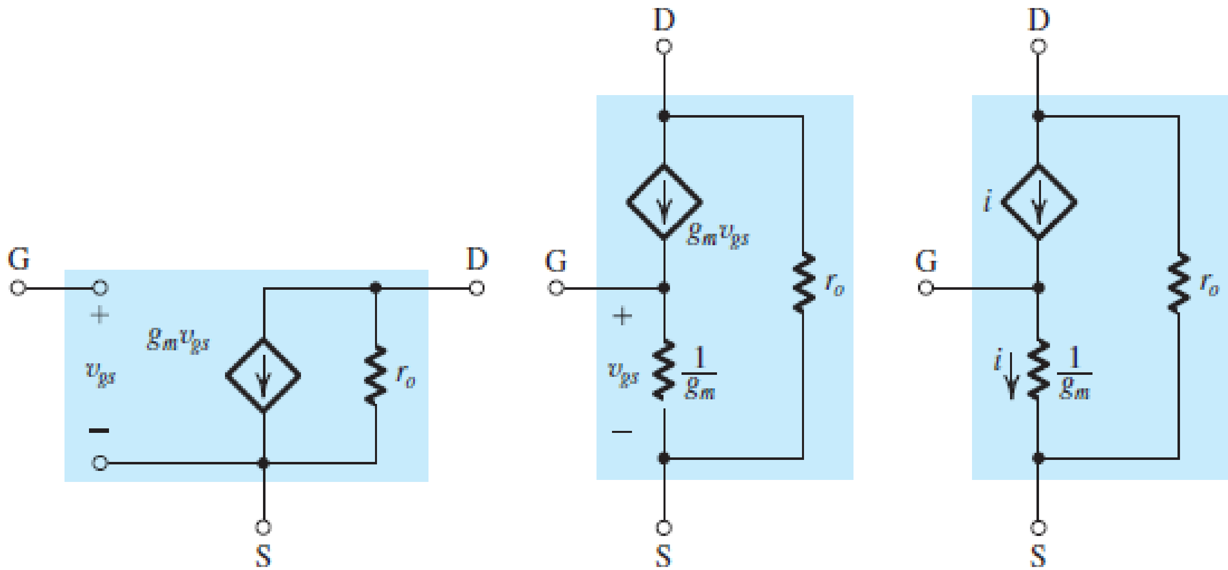
- Output resistance:

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

PMOS transistors

Same formulas as for NMOS *except* using $|V_{OV}|$, $|V_A|$, and replacing μ_n with μ_p.

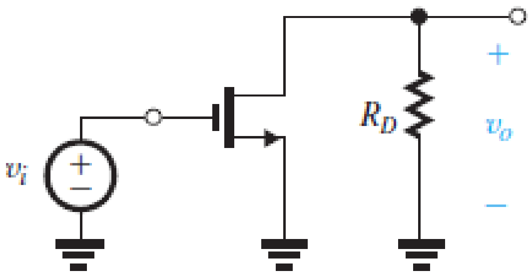
Small-Signal Equivalent Circuit Models



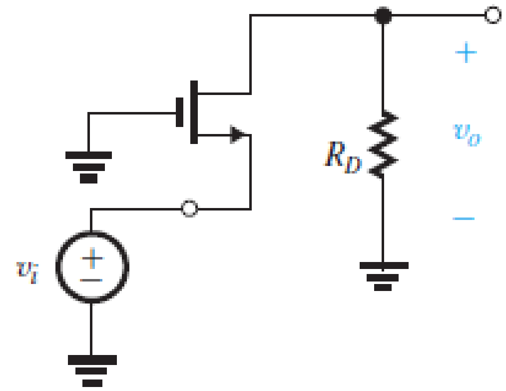
Hybrid-π model

T models

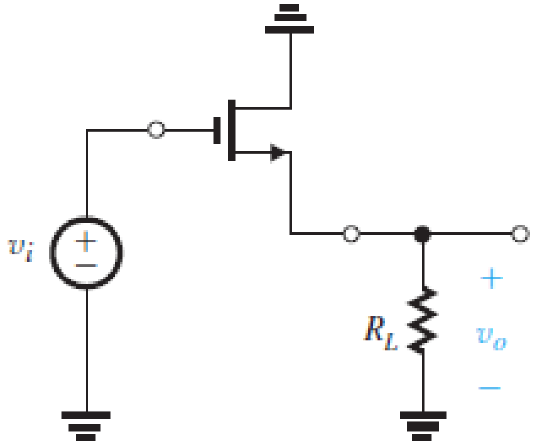
The Three Basic Configurations



(a) Common Source (CS)



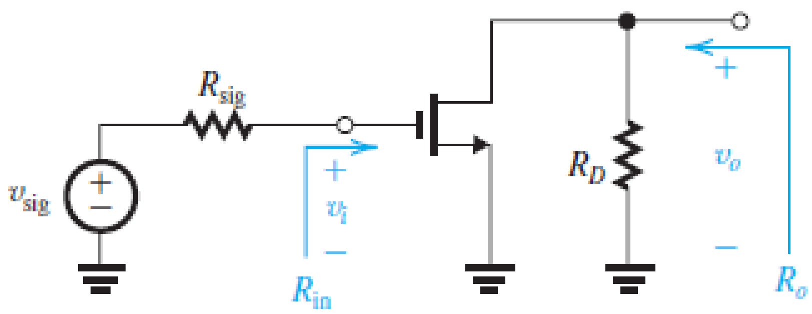
(b) Common Gate (CG)

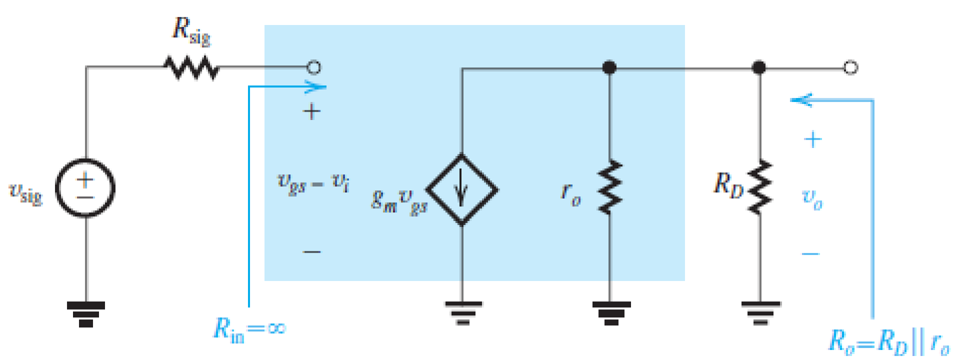


(c) Common Drain (CD)

Common Source Amplifier

- ❖ The common source is the most widely used.
- ❖ The bulk of the voltage gain is obtained by using one or more Common Source stages in the cascade.





Characteristic Parameters of the CS Amplifier:

- Open circuit voltage gain:

$$A_{v0} = -g_m(R_D \parallel r_o) \approx -g_m R_D$$

- Overall voltage gain:

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

- Input resistance:

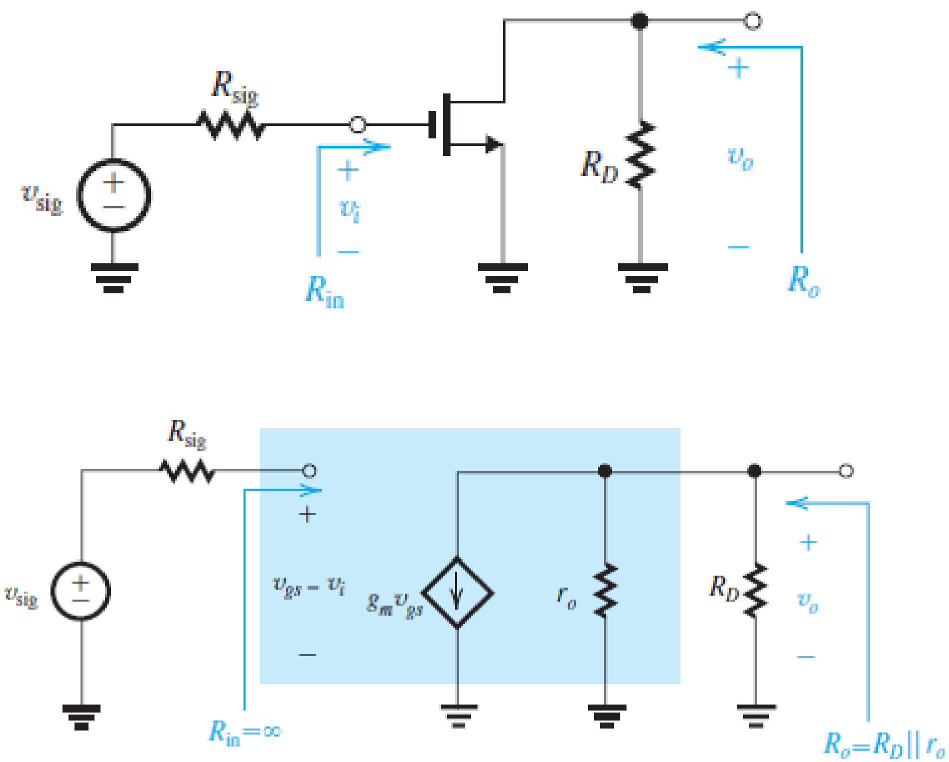
$$R_{in} = \infty$$

- Output resistance:

$$R_{out} = R_D \parallel r_o \approx R_D$$

Common Source Amplifier

- The common source is the most widely used.
- The bulk of the voltage gain is obtained by using one or more Common Source stages in the cascade.



Characteristic Parameters of the CS Amplifier:

- Open circuit voltage gain:

$$A_v = -g_m(R_D \parallel r_o) \approx -g_m R_D$$

- Overall voltage gain:

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

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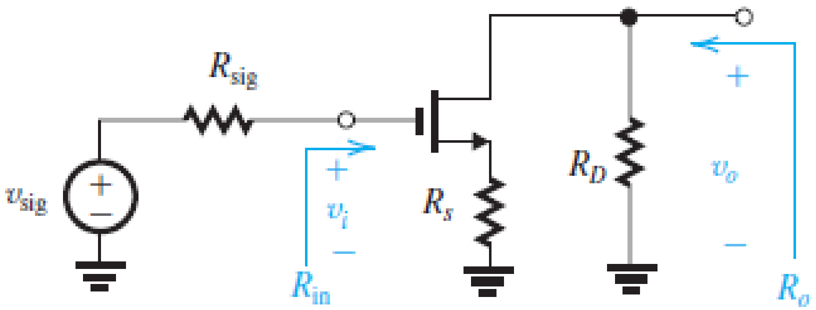
$$R_{in} = \infty$$

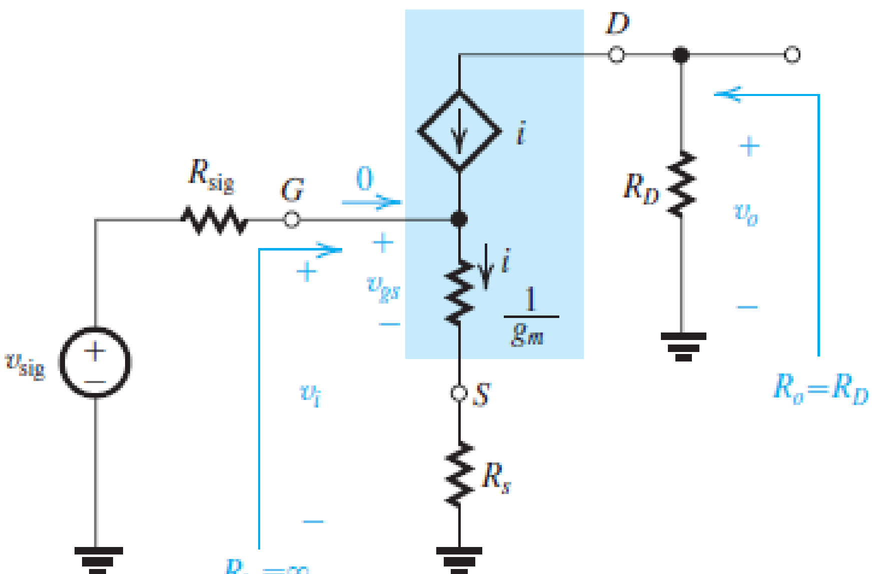
- Output resistance:

$$R_{out} = R_D \parallel r_o \approx R_D$$

Common Source Amplifier



CS amplifier with source resistance



Characteristic Parameters of the CS Amplifier (with source resistance):

$$i = \frac{v_i}{1/g_m + R_s} = \frac{g_m}{1 + g_m R} v_i$$

$$v_o = -iR_D$$

- Open circuit voltage gain:

$$A_v = \frac{v_o}{v_i} = -\frac{g_m R_D}{1 + g_m R_S}$$

- Input resistance:

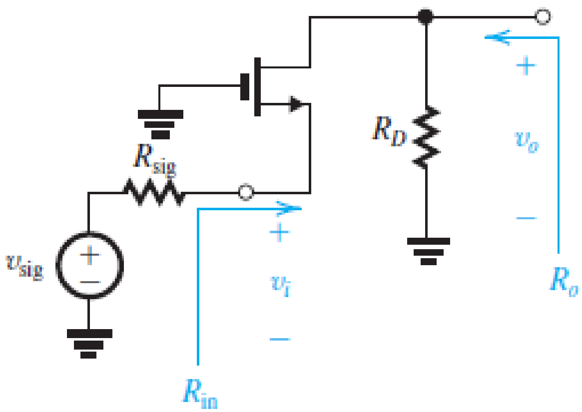
$$R_{in} = \infty$$

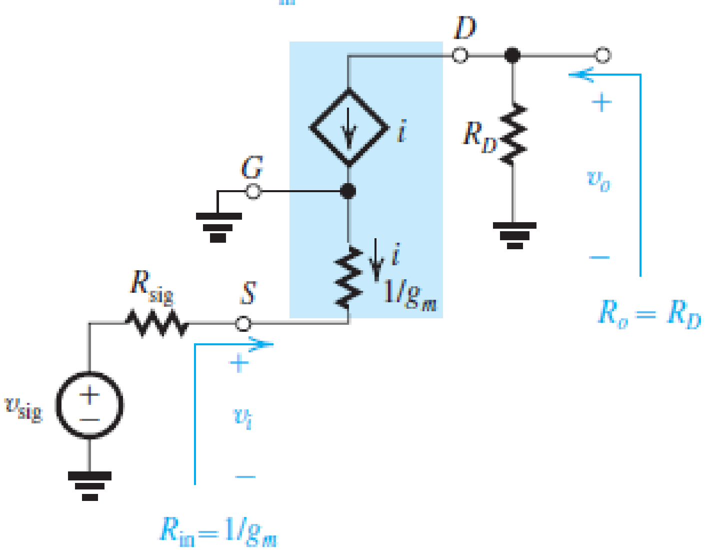
- Output resistance:

$$R_{out} = R_D \parallel r_o \approx R_D$$

Common Gate Amplifier

❖ Common Gate amplifier is used to obtain wide bandwidth.





Characteristic Parameters of the CS Amplifier:

- Open circuit voltage gain:

$$A_v = g_m R_D$$

- Overall voltage gain:

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

- Input resistance:

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

Disadvantage!!!

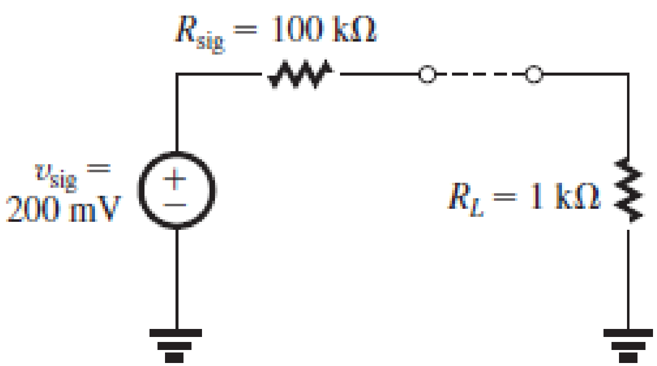
- Output resistance:

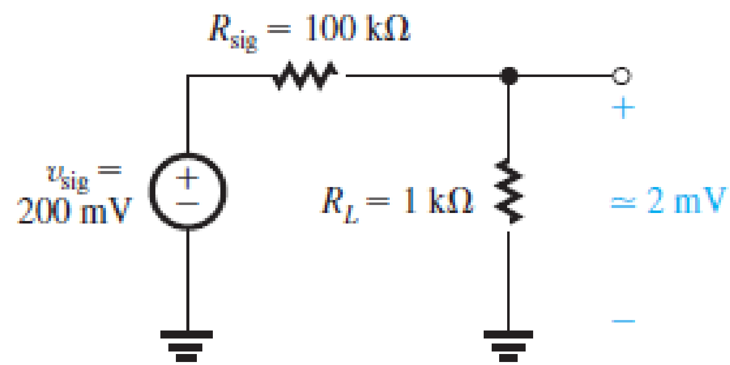
$$R_{out} = R_D$$

Common Drain Amplifier (Source Follower)

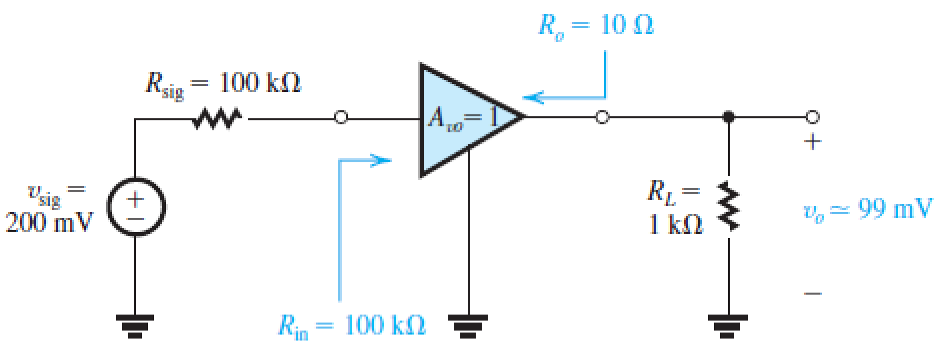
The need for voltage buffers: the amplifier has

- **High input resistance.**
- **Low output resistance.**



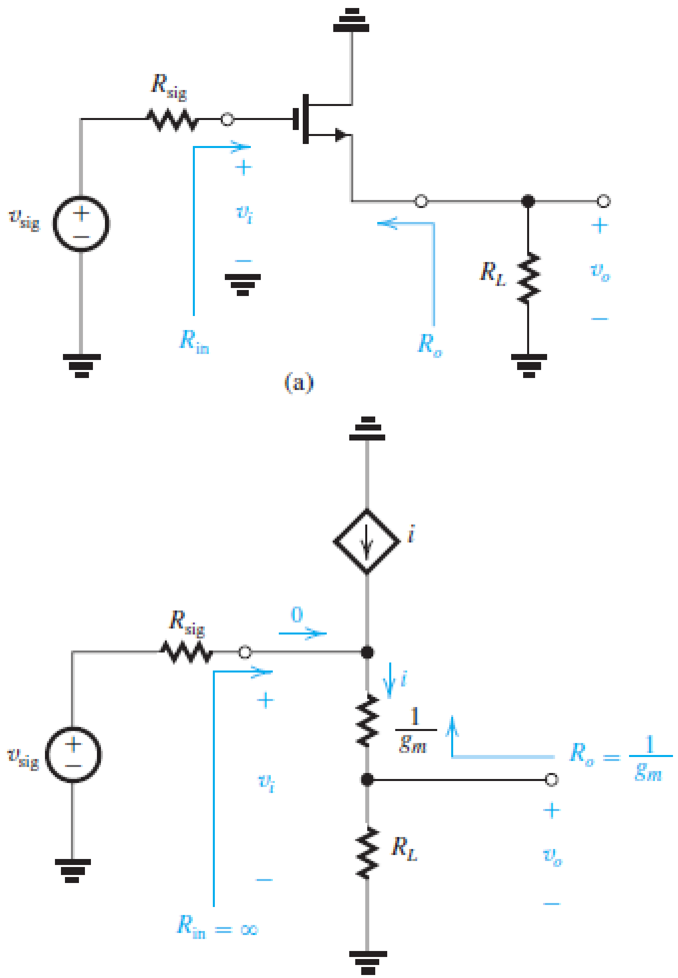


(b)



Common Drain Amplifier (Source Follower)

❖ Common Drain amplifier is usually used as a voltage buffer.



Characteristic Parameters of the CS Amplifier:

- Open circuit voltage gain:

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

- Overall voltage gain:

$$G_v = \frac{R_L}{R_L + 1/g_m} \approx 1$$

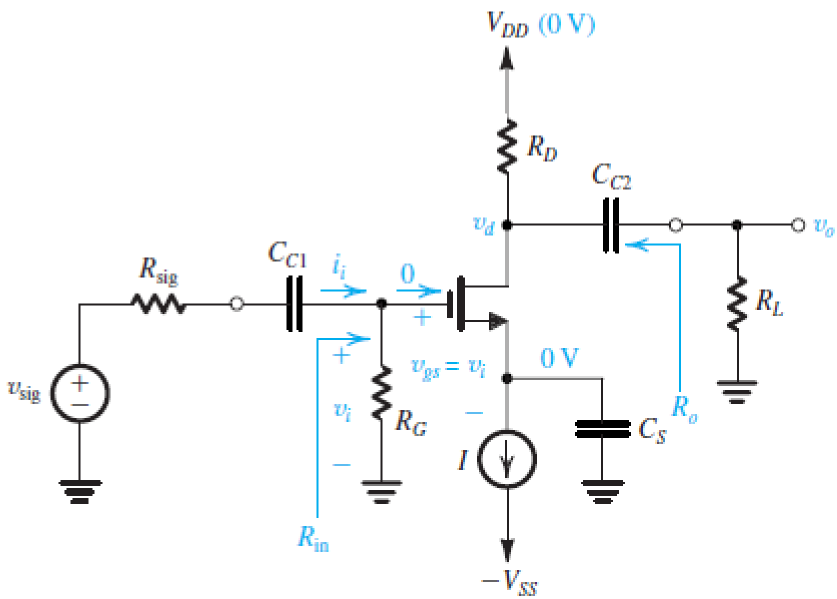
- Input resistance:

$$R_{in} = \infty$$

- Output resistance:

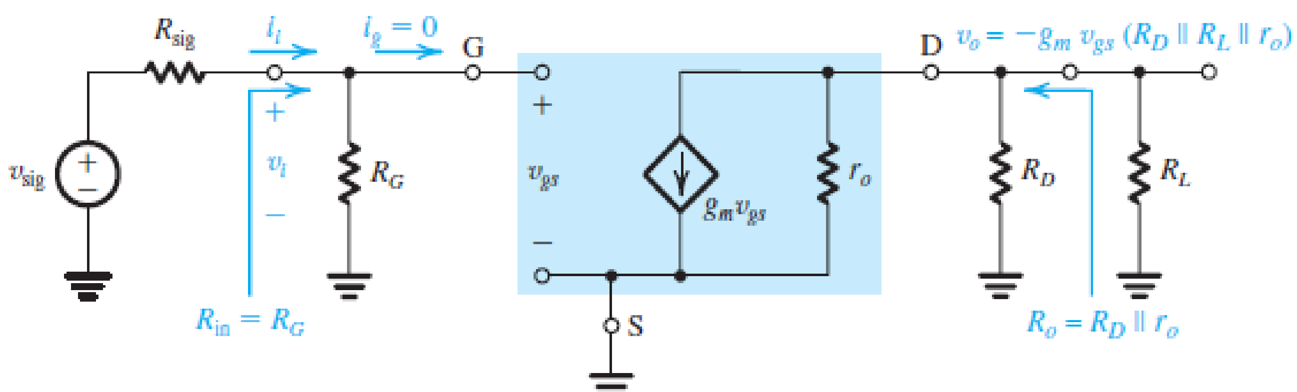
$$R_{out} = {}^{1}/_{g_m}$$

Discrete Circuit MOS Amplifiers

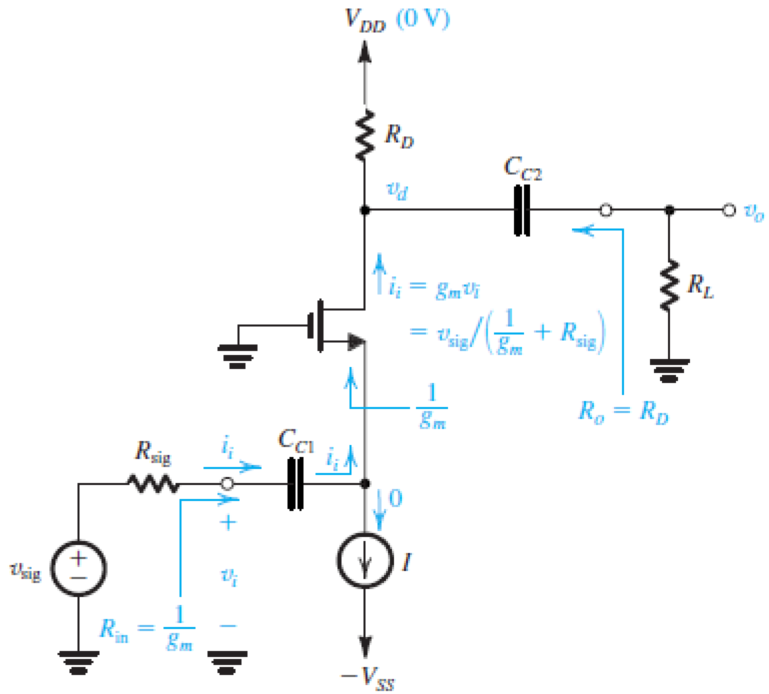


Example 9: Given $V_{DD} = V_{SS} = 10V$, $k_n = 1mA/V^2$, $I = 0.5mA$, $R_D = 15k\Omega$, $R_G = 4.7M\Omega$ $V_t = 1.5V$, $V_A = 75V$.

Calculate input, output resistance and overall voltage gain. $R_{sig} = 100k\Omega$, $R_L = 15k\Omega$.

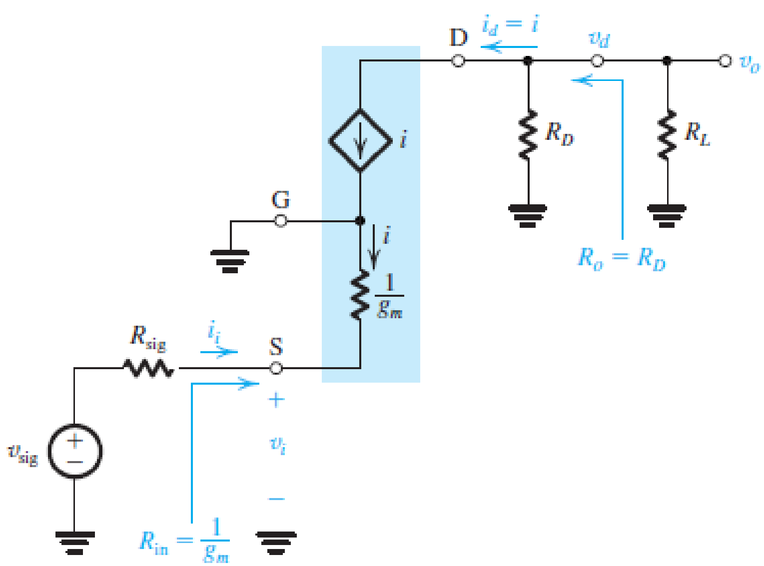


Discrete Circuit MOS Amplifiers

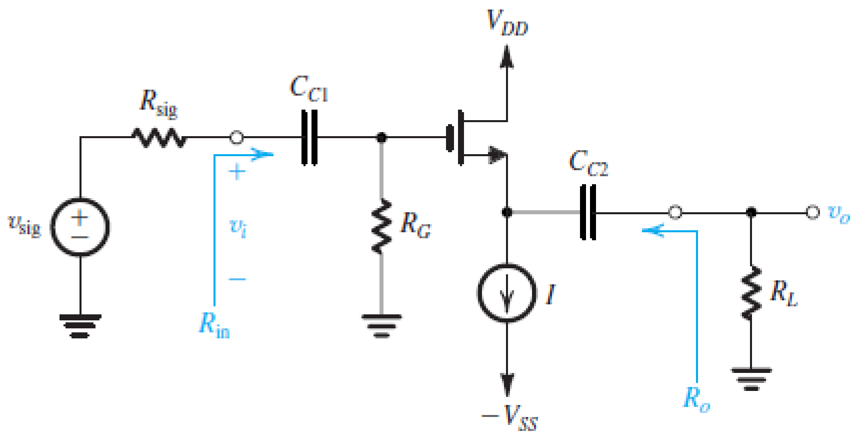


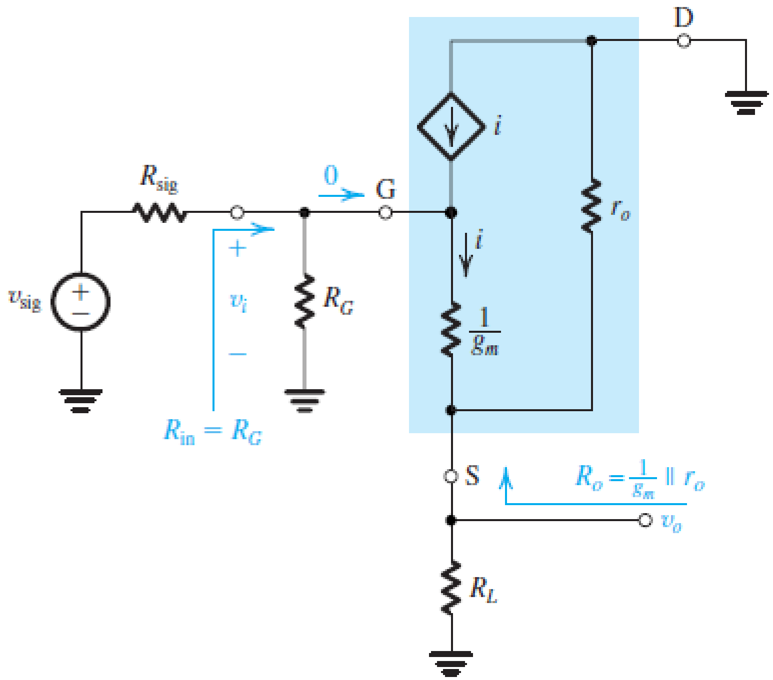
Example 10: Given $V_{DD} = V_{SS} = 10V$, $k_n = 1mA/V^2$, $I = 0.5mA$, $R_D = 15k\Omega$, $R_G = 4.7M\Omega$ $V_t = 1.5V$, $g_m = 1mA/V$.

Calculate input, output resistance and overall voltage gain. $R_{sig} = 50\Omega$, $R_L = 15k\Omega$.



Discrete Circuit MOS Amplifiers





Example 11: Given $V_{DD} = V_{SS} = 10V$, $k_n = 1mA/V^2$, $I = 0.5mA$, $R_D = 15k\Omega$, $R_G = 4.7M\Omega$ $V_t = 1.5V$, $g_m = 1mA/V$.

Calculate input, output resistance and overall voltage gain. $R_{sig} = 1M\Omega$, $R_L = 15k\Omega$.

Summary

Amplifier type	R_{in}	A_{vo}	R_o	A_v	G_v
	Characteristics[a, b]				
Common source	∞	$-g_m R_D$	R_D	$-g_m(R_D \parallel R_L)$	$-g_m(R_D \parallel R_L)$
Common source with R_s	∞	$-\dfrac{g_m R_D}{1+g_m R_s}$	R_D	$\dfrac{-g_m(R_D \parallel R_L)}{1+g_m R_s}$ $-\dfrac{R_D \parallel R_L}{1/g_m + R_s}$	$-\dfrac{g_m(R_D \parallel R_L)}{1+g_m R_s}$ $-\dfrac{R_D \parallel R_L}{1/g_m + R_s}$
Common gate	$\dfrac{1}{g_m}$	$g_m R_D$	R_D	$g_m(R_D \parallel R_L)$	$\dfrac{R_D \parallel R_L}{R_{sig} + 1/g_m}$
Source follower	∞	1	$\dfrac{1}{g_m}$	$\dfrac{R_L}{R_L + 1/g_m}$	$\dfrac{R_L}{R_L + 1/g_m}$

Q&A