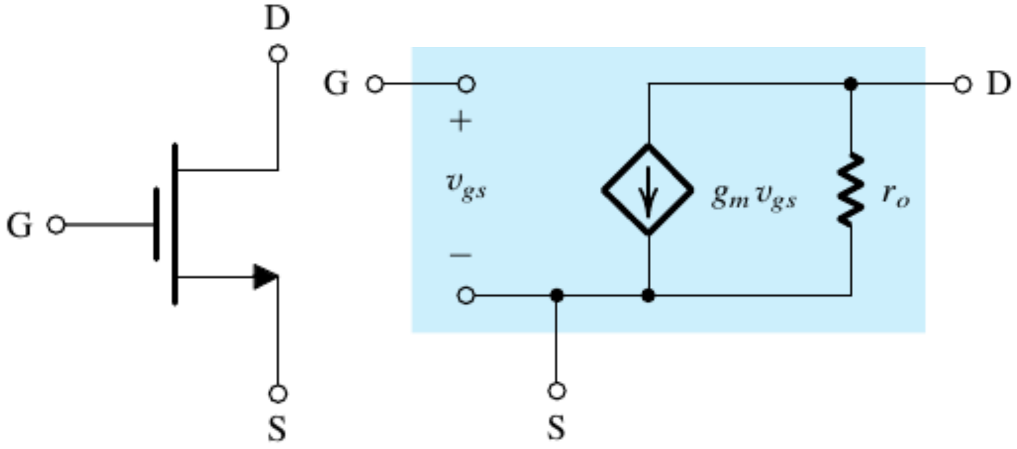
Lecture 7a

EE-215 Electronic Devices and Circuits

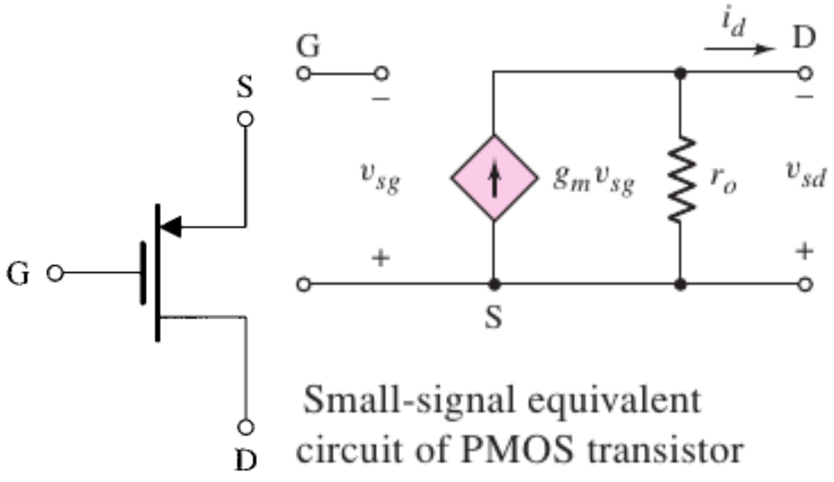
Asst Prof Muhammad Anis Chaudhary

Small-Signal Equivalent Circuit Models

- we had already seen the small-signal equivalent circuit model (hybrid-π model) for an NMOS transistor

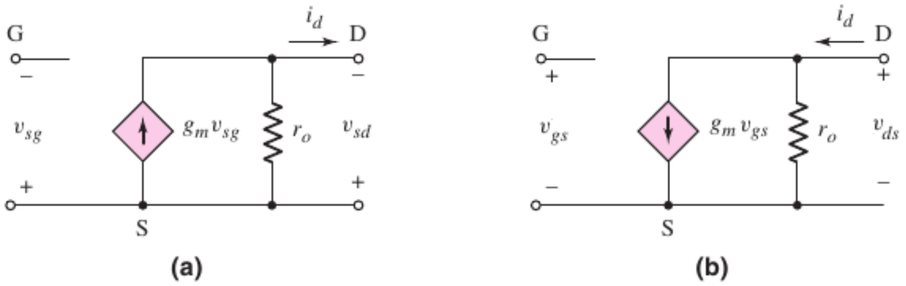


- also for PMOS transistor, the MOSFET acts as a voltage controlled current source.
    - thus the small-signal model for the p-channel MOSFET can be given as



Small-signal equivalent circuit of PMOS transistor

- In the small-signal model of PMOS transistor,
    - if we substitute, $v_{sg} = -v_{gs}$
        - $= \Rightarrow g_m v_{sg} = -g_m v_{gs}$
        - i.e. if the control voltage polarity is reversed, then the dependent current direction is also reversed.
    - also $v_{sd} = -v_{ds}$

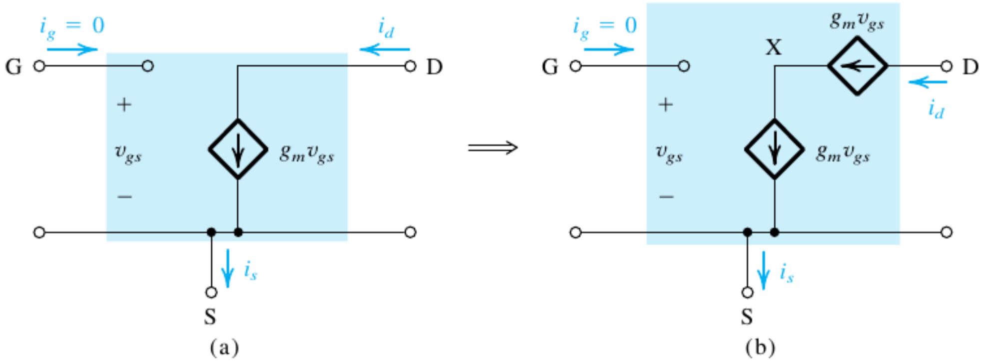


Small signal equivalent circuit of a p-channel MOSFET showing (a) the conventional voltage polarities and current directions and (b) the case when the voltage polarities and current directions are reversed.

- thus the resultant equivalent circuit (fig b) for the PMOS transistor is exactly the same as that of the NMOS transistor
    - we conclude that the small-signal equivalent circuit model (hybrid-π model) is
        - exactly the same for both the NMOS and the PMOS transistors

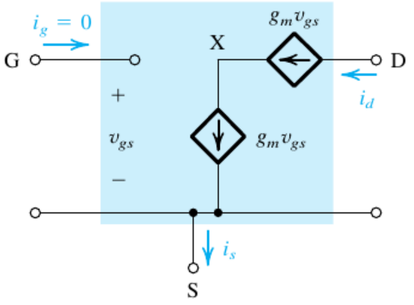
The T Equivalent-Circuit Model

- A simple circuit transformation can lead to an alternative
    - equivalent circuit model for a MOSFET
    - we start with the hybrid-π model



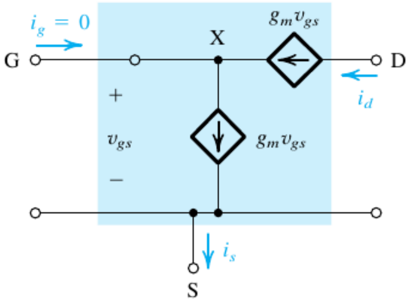
- here we have placed a 2nd $g_m v_{gs}$ current source in series with the original controlled source.
- Note that, this new current source doesnot change the terminal currents and is thus allowed

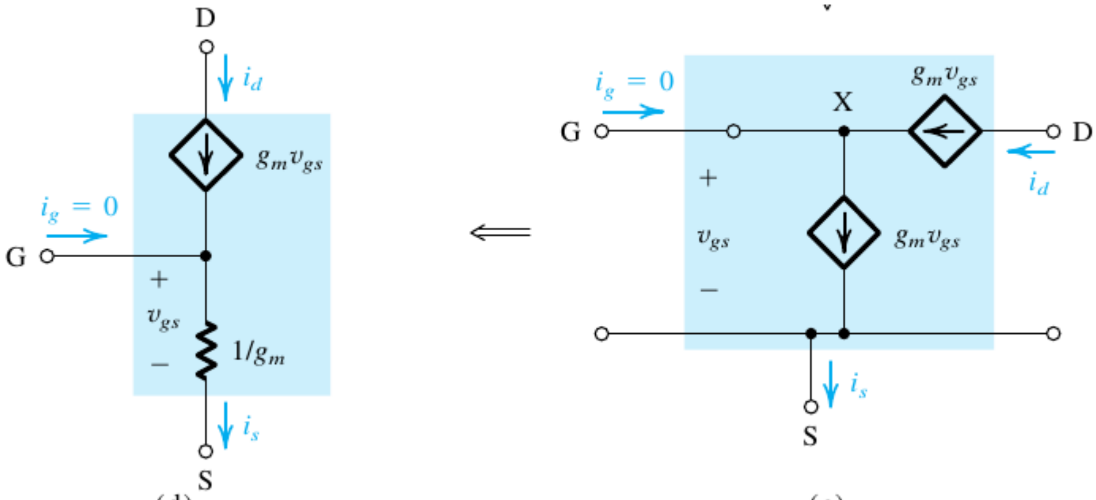
- the new node X, can be connected to the gate.
    - As because of KCL, still the gate current $i_g = 0$.
        - so the gate current is still zero (i.e. this connection doesnot change the terminal characteristics)



(b)

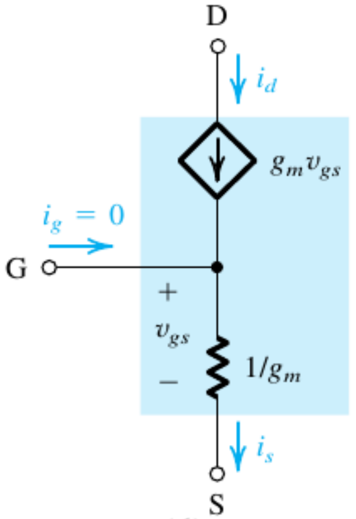
$\Downarrow$





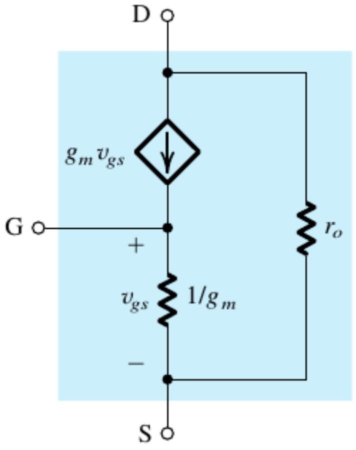
(d) (c)

- Note that, here we have a controlled current source $g_m v_{gs}$
    - whose current is controlled by the control voltage v_{gs}
        - where v_{gs} is across itself
    - $= \Rightarrow$ this current source can be replaced by a resistor of value $\frac{v_{gs}}{g_m v_{gs}} = \frac{1}{g_m}$
- Note that the resistance between the gate and the source,
    - looking in to the source terminal is $1/g_m$
        - and looking in to the gate terminal is infinite



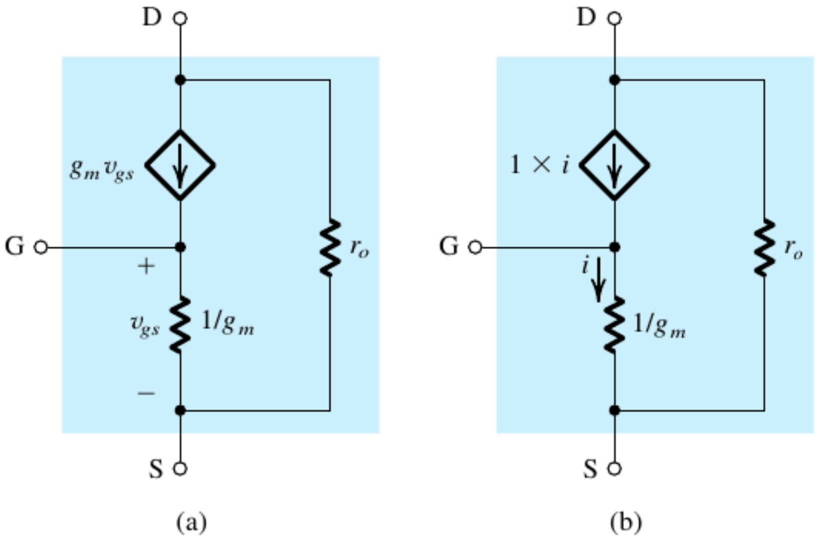
(d)

- if the channel-length modulation effect cannot be ignored,
    - we can include r_o in the T-model between the drain and the source terminal



(a)

- Also we can have an alternative representation of the T model,
    - where we can replace the voltage-controlled current source by
        - a current controlled current source



(a) (b)

Figure 5.41 **(a)** The T model of the MOSFET augmented with the drain-to-source resistance r_o. **(b)** An alternative representation of the T model.

Small-Signal Operation and Models

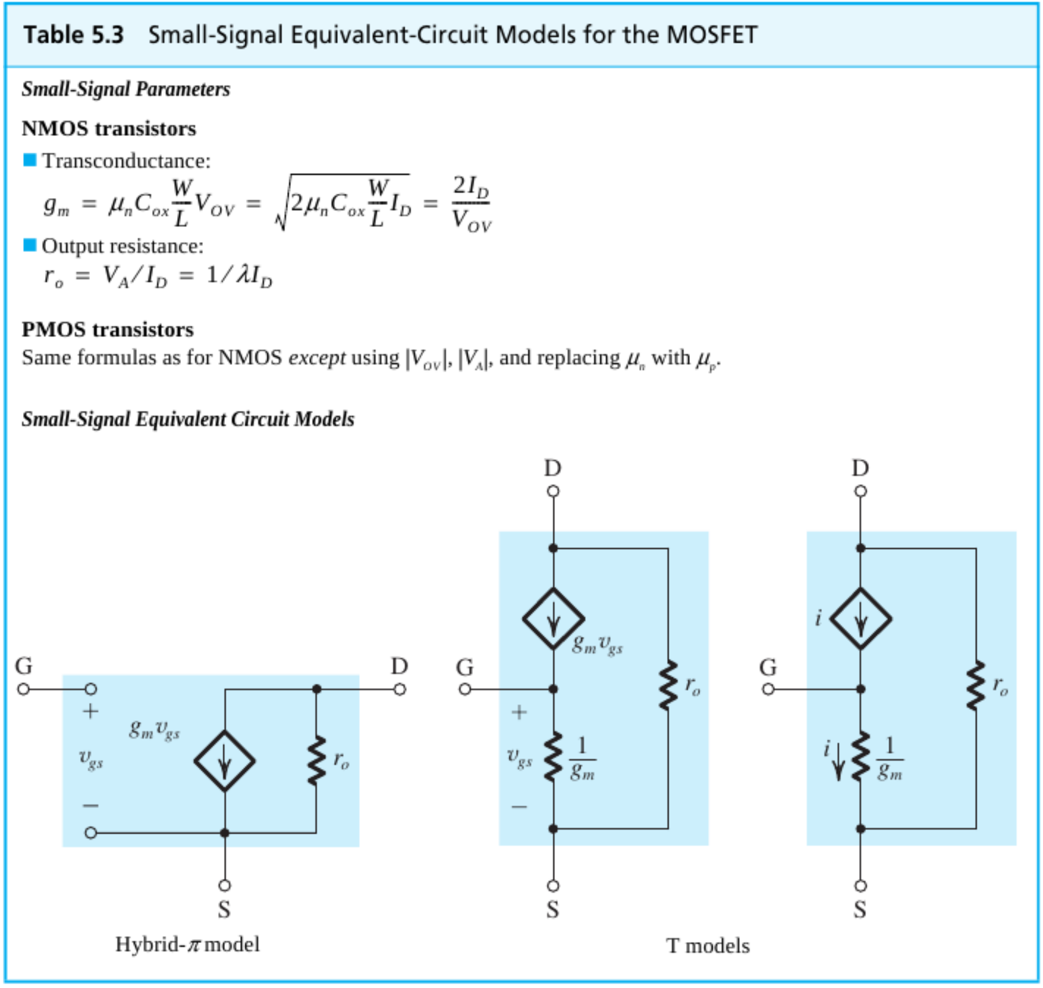


Table 5.3 Small-Signal Equivalent-Circuit Models for the MOSFET

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

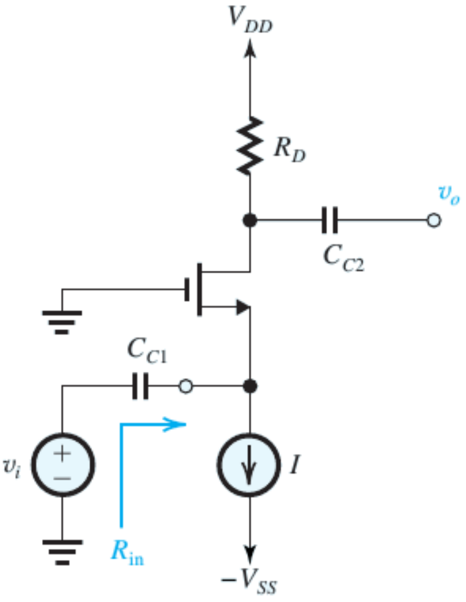
Hybrid-π model

T models

Example 5.11

- Figure 5.42(a) shows a MOSFET amplifier biased by a constant-current source I. Assume that the values of I and R_D are such that the MOSFET operates in the saturation region. The input signal v_i is coupled to the source terminal by utilizing a large capacitor C_{C1}.

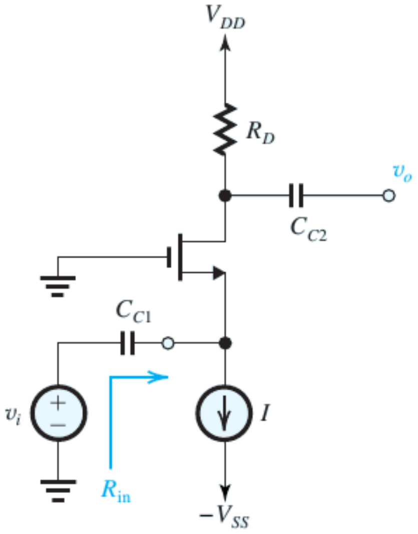
Similarly, the output signal at the drain is taken through a large coupling capacitor C_{C2}. Find the input resistance R_{in} and the voltage gain $v_o \,/\, v_i$. Neglect channel-length modulation.



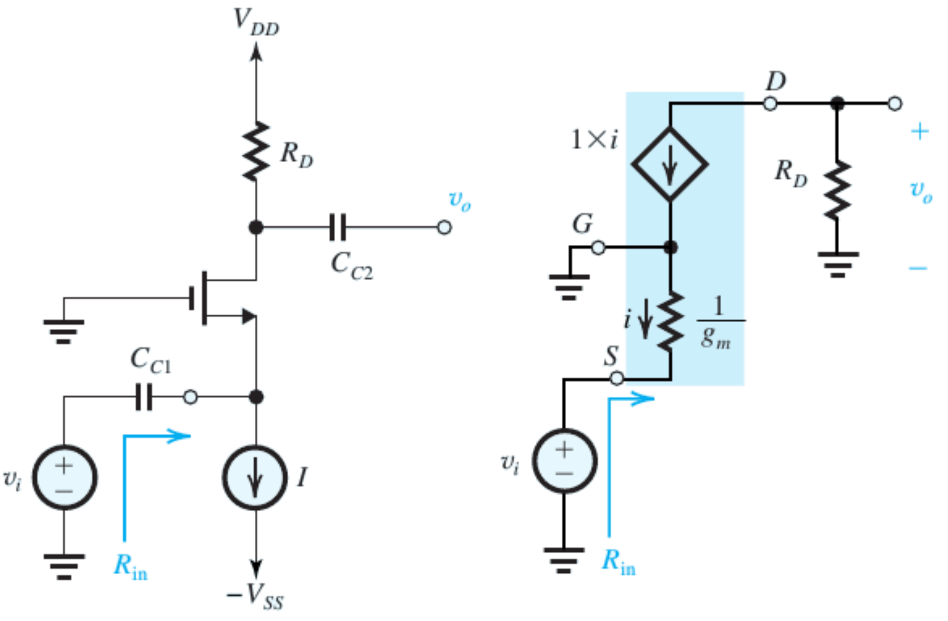
(a)

Solution:

- here $\lambda = 0$, R_{in} =? , $A_v = \frac{v_o}{v_i}$ =?
    - as an ac source is connected at the source terminal of the MOSFET, it is more convenient to use T-model.
        - thus for ac analysis,
        - suppress dc sources i.e. V_{DD} is replaced by short circuit
            - and I is replaced by an open circuit
        - C_{C1} , C_{C2} are replaced by short circuits
        - MOSFET is replaced by its T-model



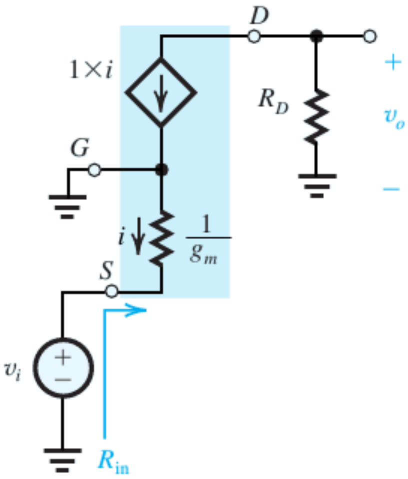
(a)



(a) (b)

Figure 5.42 (**a**) Amplifier circuit for Example 5.11; (**b**) Small-signal equivalent circuit of the amplifier in (a).

- as $\frac{v_{gs}}{i}=\frac{1}{g_m}$ and $v_{gs}=-v_i$
  - $==\Rightarrow \frac{-v_i}{i}=\frac{1}{g_m}$
    - and $R_{in}=\frac{v_i}{i_i}=\frac{v_i}{-i}=\frac{-v_i}{i}=\frac{1}{g_m}$
    - by ohm's law at R_D
      - $v_o=(-i)R_D$
      - As $i=\frac{v_{gs}}{1/g_m}=g_m v_{gs}$
    - $==\Rightarrow v_o=-g_m v_{gs} R_D$
    - or $v_o=-g_m(-v_i)R_D \because v_{gs}=-v_i$
    - $v_o=g_m v_i R_D ==\Rightarrow A_v=\frac{v_o}{v_i}=g_m R_D$



(b)

Basic MOSFET Amplifier Configurations

Basic MOSFET Amplifier Configurations

- we have already determined that
    - almost-linear amplification can be obtained by
        - biasing the MOSFET at a suitable point Q in
        - its saturation region of operation
        - and by keeping the signal v_{gs} small

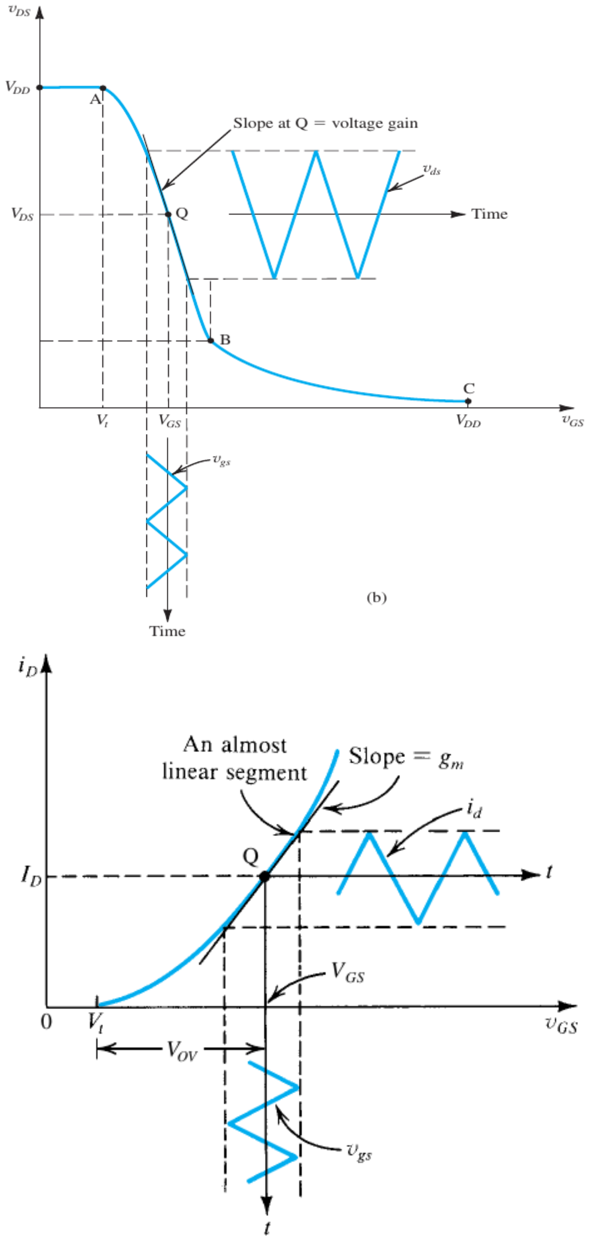


Figure 5.35 Small-signal operation of the MOSFET amplifier.

Basic MOSFET Amplifier Configurations

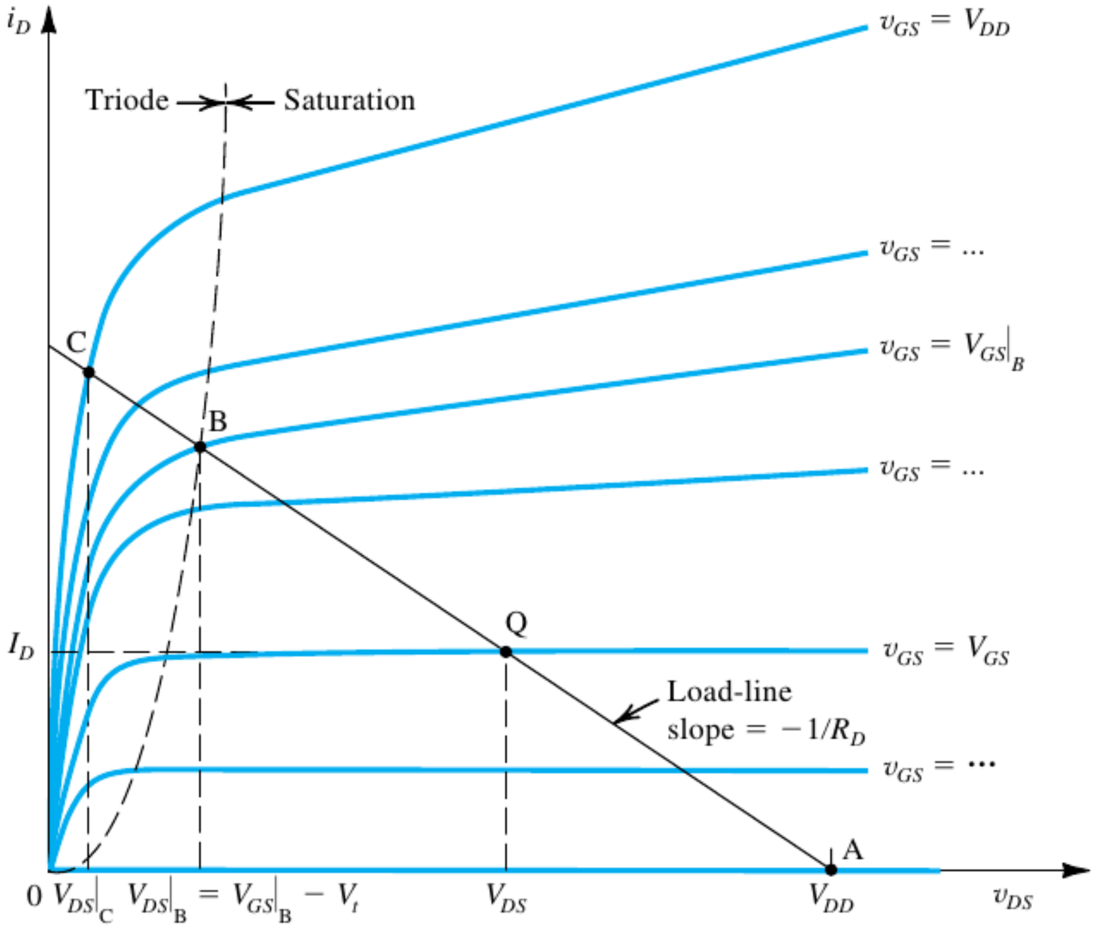
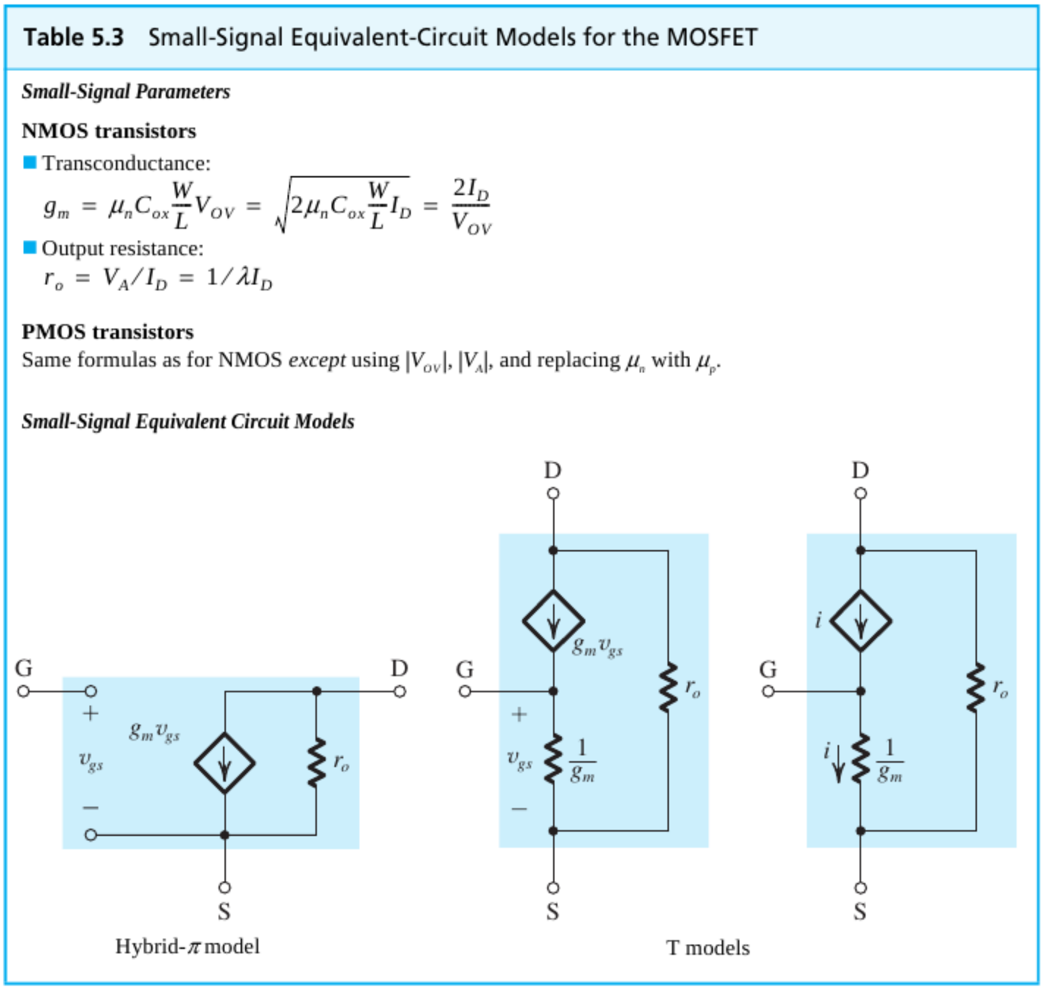


Figure 5.31 Graphical construction to determine the voltage transfer characteristic of the amplifier in Fig. 5.29(a).

- Also when v_{gs} is small, the MOSFET can be replaced by its small-signal circuit model (either hybrid-π model or the T-model)
    - the resultant ac circuit can be used to determine the amplifier parameters like
        - the voltage gain,
        - the input resistance
        - and the output resistance



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PMOS transistors

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

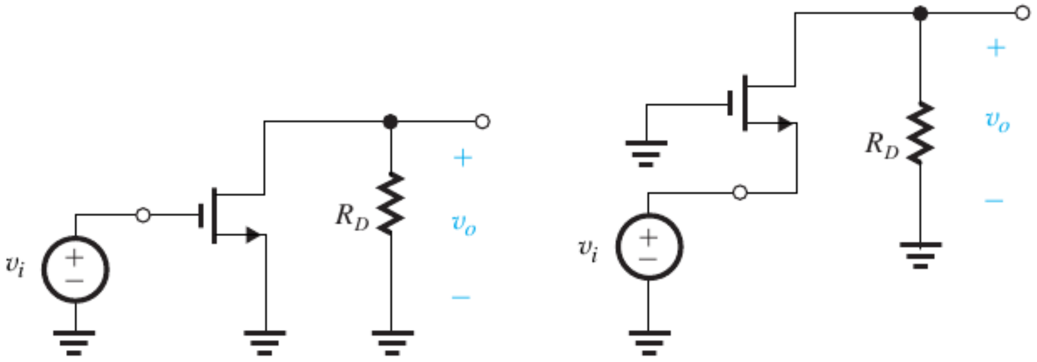
Small-Signal Equivalent Circuit Models

Hybrid-π model

T models

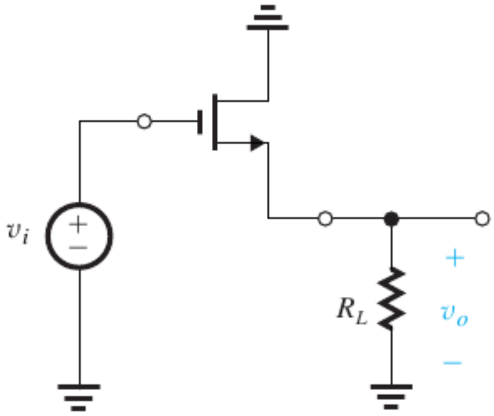
The Three Basic Configurations

- There are three basic configurations for connecting the MOSFET as an amplifier, namely
    - the Common Source (CS) Amplifier
        - the Common Gate (CG) Amplifier
        - The Common Drain (CD) Amplifier (also called Source Follower)
    - Each of these configurations is obtained by
        - connecting one of the three MOSFET terminals to ground
        - thus creating a two-port network with the grounded terminal
        - being common to the input and output ports
    - The resulting three configurations with biasing arrangement ommited are shown in fig



(a) Common Source (CS)

(b) Common Gate (CG)

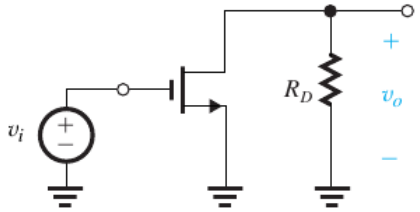


(c) Common Drain (CD)

Figure 5.43 The three basic MOSFET amplifier configurations.

Common Source Amplifier

- here the source terminal is connected to ground,
  - the input voltage is applied at the gate (w.r.t ground),
    - the output voltage is taken at the drain (w.r.t ground)



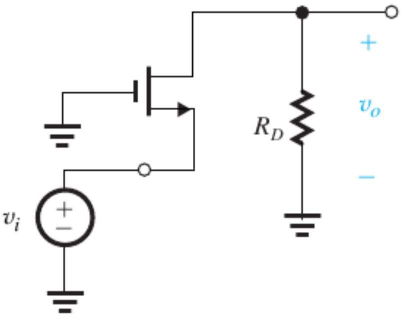
(a) Common Source (CS)

  - this configuration is called the grounded source or the common source (CS) amplifier
  - Note that dc biasing circuit is not shown in figure

Common Gate Amplifier

- The common gate (CG) or grounded gate amplifier is obtained
  - by connecting the gate to ground,
    - applying the input between the source and ground

            - taking the output v_o between the drain and ground

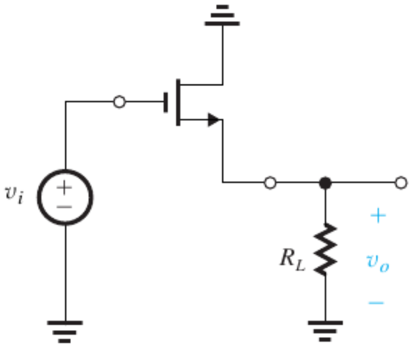


(b) Common Gate (CG)

    - Note that dc biasing circuit is not shown in figure

Common Drain Amplifier

- The common drain (CD) or grounded drain amplifier is obtained
    - by connecting the drain terminal to ground,
        - applying the input between the gate and ground
            - taking the output v_o between the source and ground

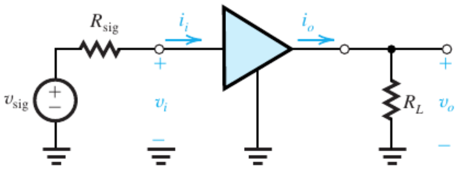


(c) Common Drain (CD)

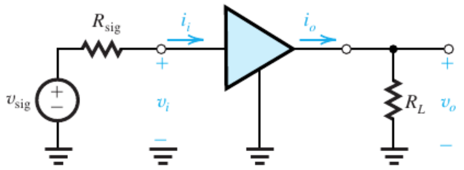
    - Note that dc biasing circuit is not shown in figure
    - the Common Drain amplifier is also called Source Follower

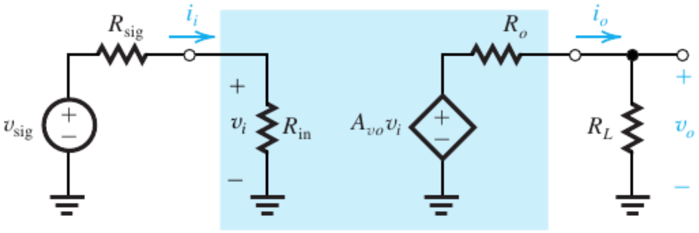
Characterizing Amplifiers

- lets take a look at how to characterize the performance of an amplifier as a circuit building block
    - here an amplifier is fed with a signal source
        - having an open-circuit voltage v_{sig} and an internal resistance R_{sig}



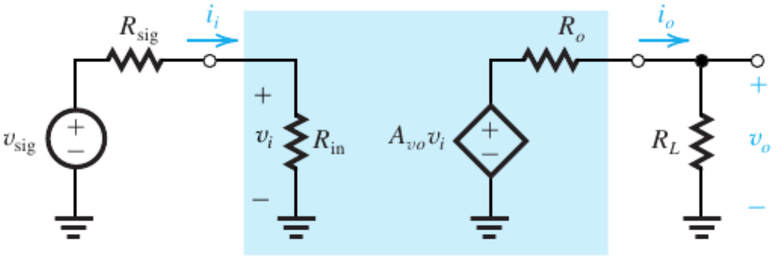
    - this voltage source (v_{sig}, R_{sig}) can be an actual signal source
        - or in a cascade amplifier, it can be the Thevenin equivalent of the output circuit of the preceeding amplifier.
    - the load resistor R_L is connected at the output terminal of the amplifier
        - this R_L can be an actual load resistor
        - or the input resistance of a succeeding amplifier stage in a cascade amplifier
- The amplfier block can be replaced by its equivalent circuit model





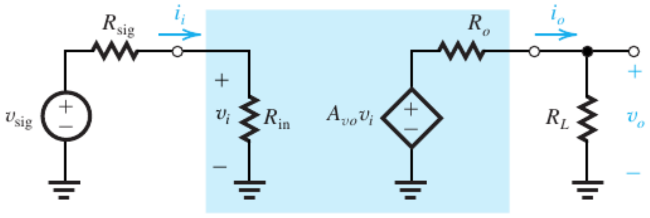
(b)

    - the input resistance R_{in}
        - indicate the loading effect of the amplifier input on the signal source
        - and is given as $R_{in} = \frac{v_i}{i_i}$
    - by voltage divider rule
        - $v_i = \frac{R_{in}}{R_{in}+R_{sig}} v_{sig}$



(b)

- $v_i = \frac{R_{in}}{R_{in}+R_{sig}} v_{sig}$
    - A_{vo} is the open-circuit voltage gain and is defined as
        - $A_{vo} = . \frac{v_o}{v_i}\Big|_{R_L=\infty}$



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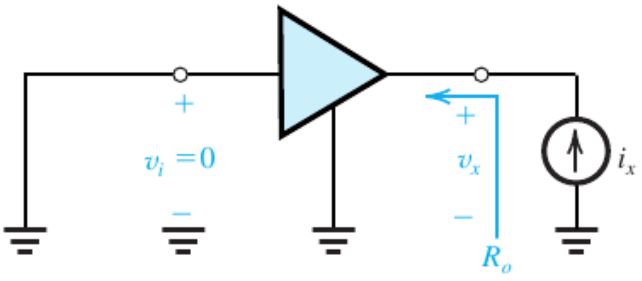
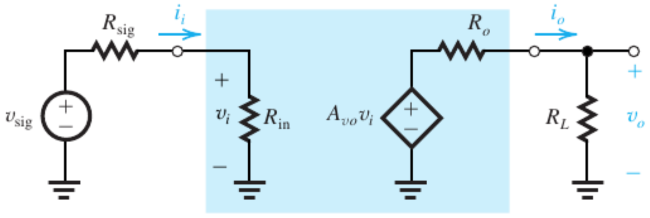


(c)

- the 3rd parameter that is essential to characterize an amplifier is the output resistance R_o
    - R_o is the resistance seen looking back into the amplfier output terminal with v_i set to zero
        - $= \Rightarrow R_o = \frac{v_x}{i_x}$
    - Note that the controlled source $A_{vo}v_i$ and the output resistance R_o
        - represent the Thevenin equivalent of the amplifier output circuit.



(b)

- by voltage divider
    - the output voltage v_o can be given as
        - $v_o = \frac{R_L}{R_L+R_o}\left(A_{vo}v_i\right) = \Rightarrow \frac{v_o}{v_i} = A_{vo}\frac{R_L}{R_L+R_o}$
    - thus the voltage gain of the amplifier is
        - $A_v = \frac{v_o}{v_i} = A_{vo}\frac{R_L}{R_L+R_o}$
    - the overall voltage gain is
        - $G_v = \frac{v_o}{v_{sig}} = A_{vo}\frac{R_L}{R_L+R_o}\frac{v_i}{v_{sig}}$
        - $G_v = A_{vo}\frac{R_L}{R_L+R_o}\frac{R_{in}}{R_{in}+R_{sig}} \because v_i = \frac{R_{in}}{R_{in}+R_{sig}}v_{sig}$
