Lecture 8b

EE-215 Electronic Devices and Circuits

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Discrete-Circuit MOS Amplifiers

- Thus any of the above biasing methods can be utilized to implement a MOSFET amplifier
    - A MOSFET amplifier can be a
        - Common Source Amplifier
            - Common Gate Amplifier
            - or a Source Follower
        - here we will utilize the constant-current biasing scheme,
            - to implement the three basic configurations of MOS amplifiers

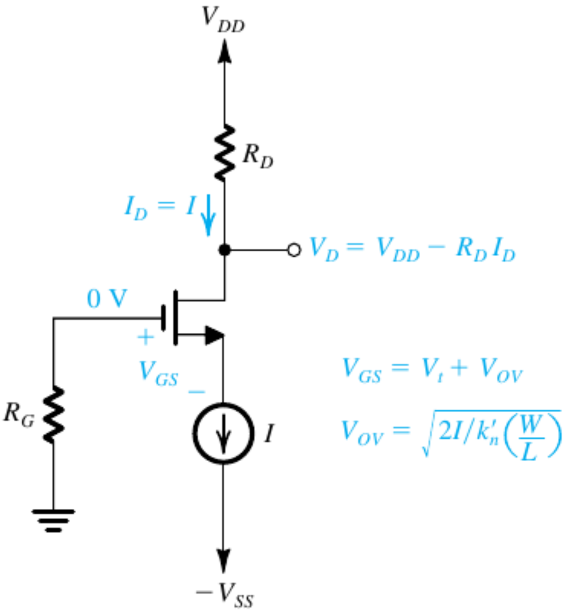
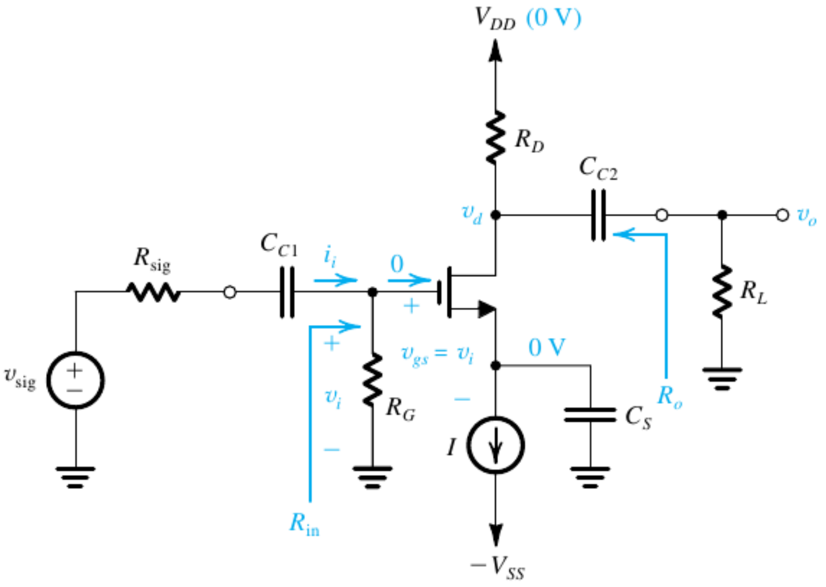


Figure 5.56 Basic structure of the circuit used to realize single-stage, discrete-circuit MOS amplifier configurations.

The Common-Source (CS) Amplifier

- A common-source amplifier realized using the constant-current biasing is shown here
    - here a signal ground (or ac ground) at the source is
        - realized by connecting a capacitor C_S between the source and ground
        - the value of C_S should be large enough so as to provide a very low impedance at the desired frequenies

(i.e. $\frac{1}{j\omega C_S}$ should be very small)



(a)

- this capacitor C_S thus acts as a short circuit for the ac signal frequencies
    - the signal current passes through C_S to ground and thus bypass the output resistance of current source I
    - C_S is therefore called a bypass capacitor
        - C_{C1} is used to couple the ac signal source to the gate of MOSFET
            - this capacitor blocks dc and acts as a short circuit at ac and is called a coupling capacitor
- C_{C2} is also a coupling capacitor which is utilized to connect the load to the drain terminal
    - As a consequence of the coupling and bypass capacitors,
        - the dc equivalent circuit stays the same as the basic constant-current source biasing circuit
- As a consequence of the coupling and bypass capacitors,
    - the dc equivalent circuit stays the same as the basic constant-current source biasing circuit

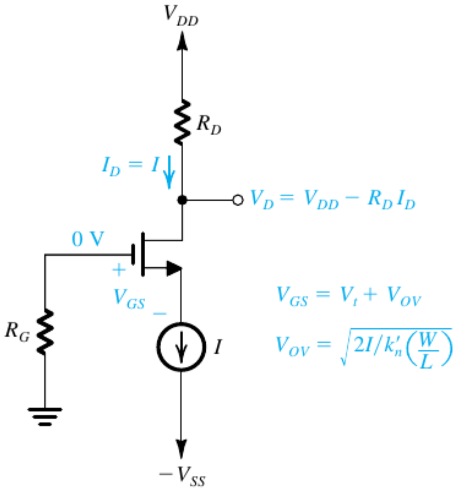


Figure 5.56 Basic structure of the circuit used to realize single-stage, discrete-circuit MOS amplifier configurations.

- Now to determine the terminal characteristics of the CS amplifier (i.e. R_{in}, R_o, A_v , G_v),
  - we replace the CS amplifier by its equivalent small-signal circuit
  - i.e. we replace the MOSFET by its small-signal model
    - suppress the dc sources
    - replace capacitors by short-circuits (if $\frac{1}{j\omega C} \to 0$)

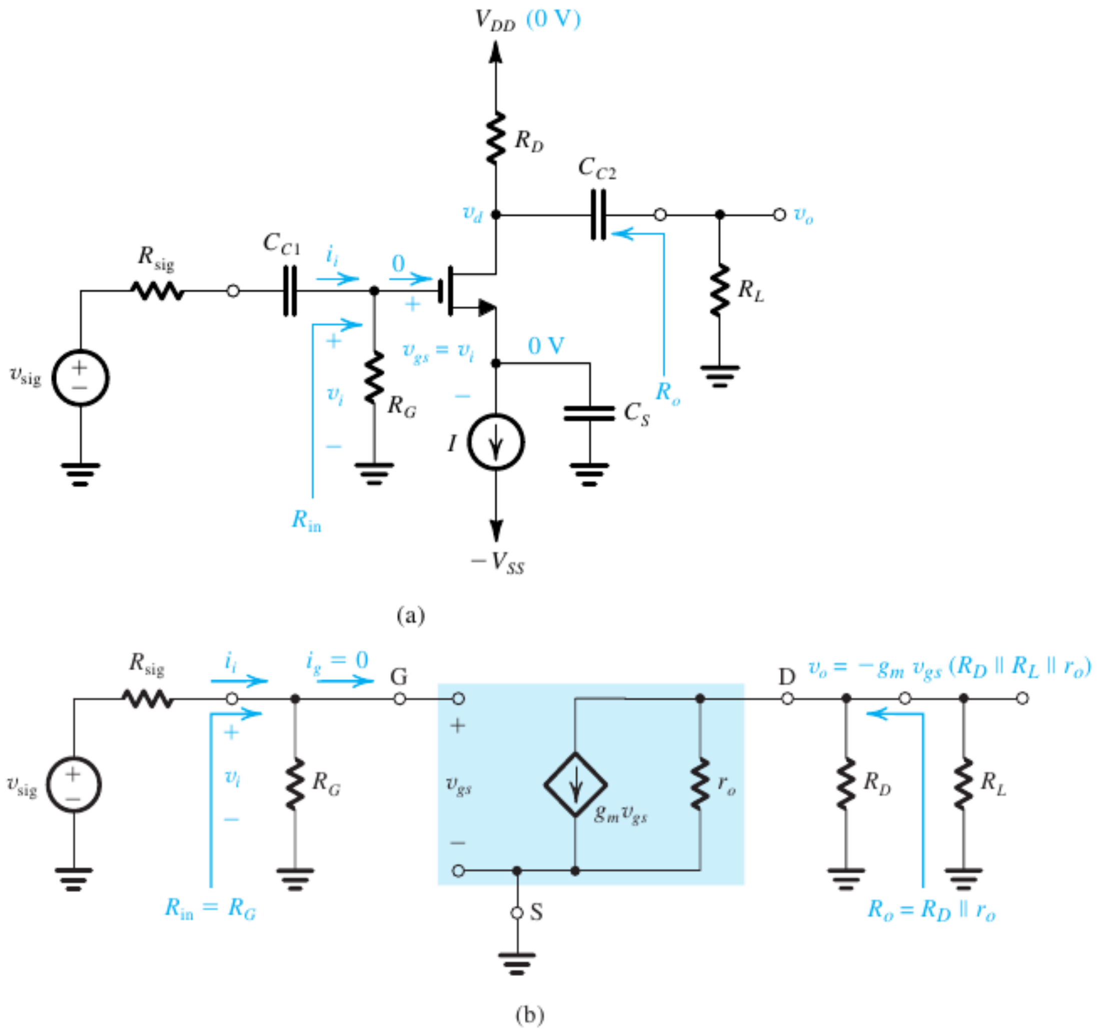
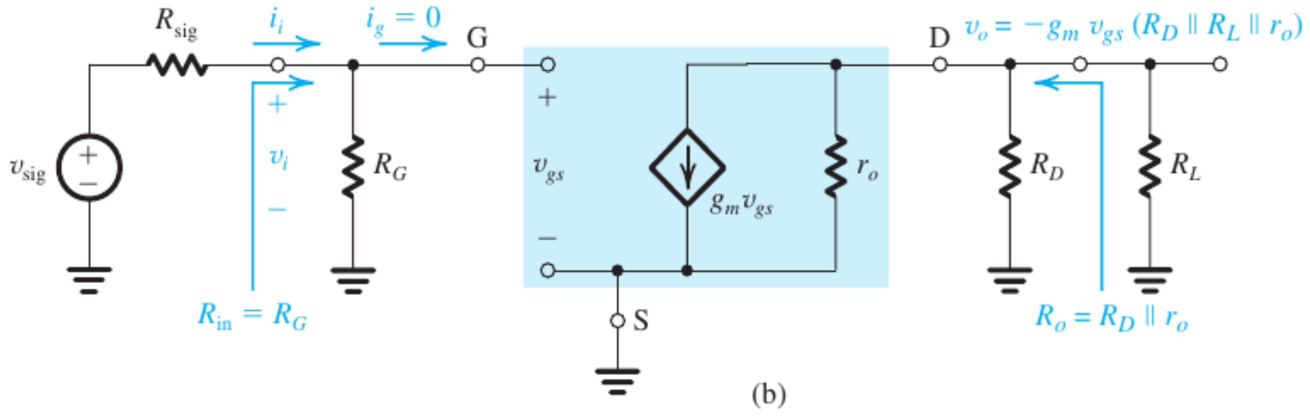
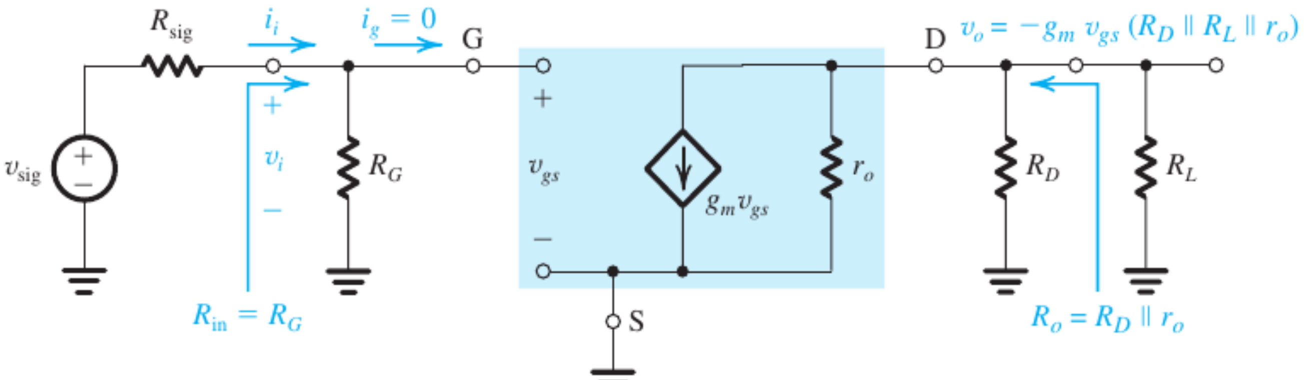


Figure 5.57 **(a)** Common-source amplifier based on the circuit of Fig. 5.56. **(b)** Equivalent circuit of the amplifier for small-signal analysis.

- here the input resistance , $R_{in} = R_G$
  - to determine R_o
    - we apply a test source at the output, suppress the independent sources i.e. $v_i = 0$
    - $v_{gs} = v_i$
    - $v_i = 0 = \Rightarrow v_{gs} = 0 = \Rightarrow g_m v_{gs} = 0$
    - $= \Rightarrow R_o = R_D \parallel r_o$



- $A_v = \frac{v_o}{v_i}$
    - as r_o, R_D and R_L are in parallel
        - $= \Rightarrow -g_m v_{gs} = \frac{v_o}{r_o \| R_D \| R_L}$
        - or $-g_m \left(r_o \parallel R_D \parallel R_L \right) = \frac{v_o}{v_{gs}}$
    - As $v_{gs} = v_i = \Rightarrow A_v = \frac{v_o}{v_i} = -g_m \left(r_o \parallel R_D \parallel R_L \right)$
    - and $A_{vo} = . \left. \frac{v_o}{v_i} \right|_{R_L \to \infty} = -g_m \left(r_o \parallel R_D \right)$

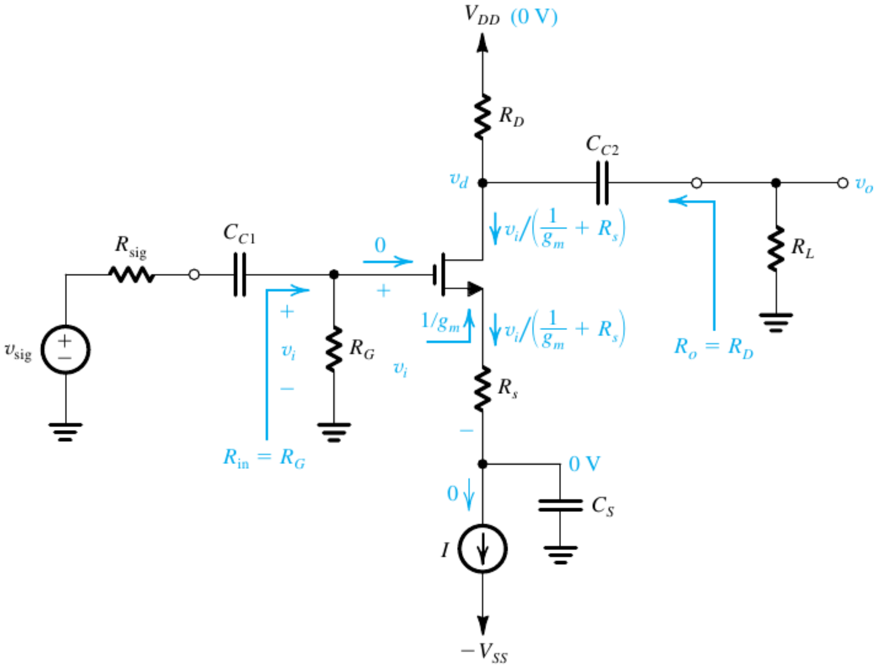


(b)

- $G_v = \frac{v_o}{v_{sig}} = \frac{v_i}{v_{sig}} \frac{v_o}{v_i} = \frac{v_i}{v_{sig}} A_v$
    - by voltage divider $v_i = \frac{R_G}{R_G + R_{sig}} v_{sig}$
    - $= \Rightarrow G_v = \frac{v_i}{v_{sig}} A_v = \frac{R_G}{R_G + R_{sig}} A_v$
    - As $A_v = -g_m (r_o \parallel R_D \parallel R_L)$
    - $= \Rightarrow G_v = \left(\frac{R_G}{R_G + R_{sig}} \right) \left[-g_m (r_o \parallel R_D \parallel R_L) \right]$

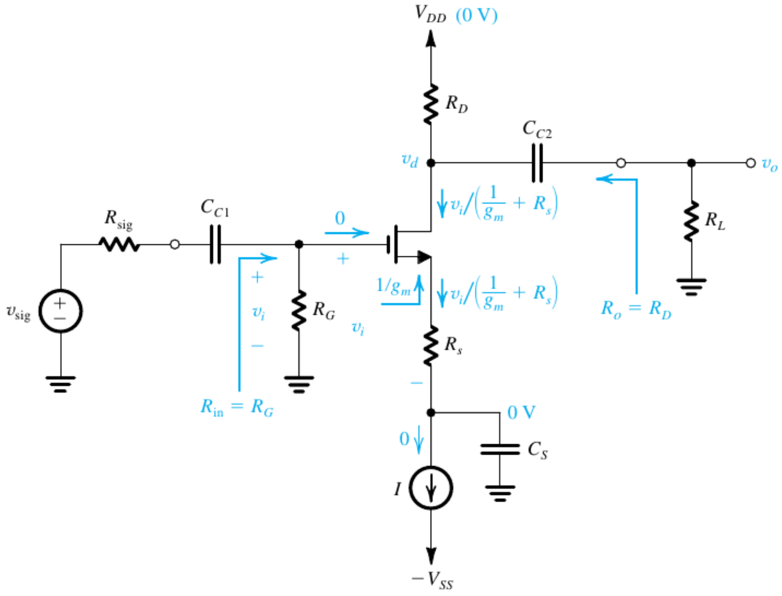
The Common-Source Amplifier with a Source Resistance

- the Common-source amplifier with a source resistance, utilizing the constant-current biasing scheme is shown in figure

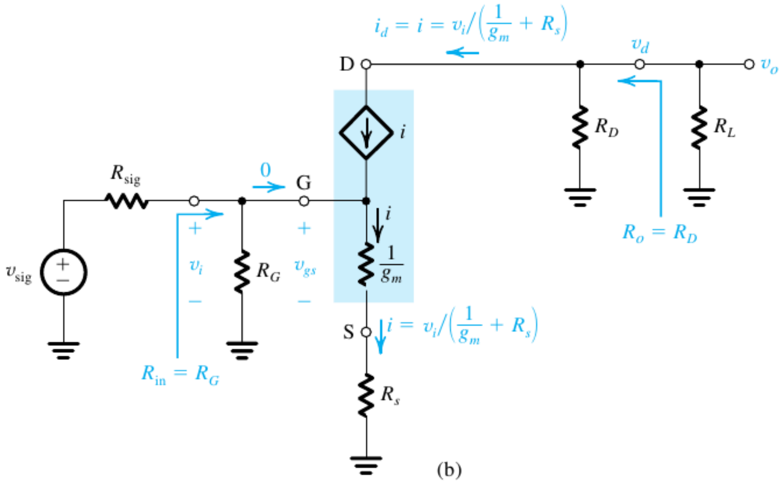


(a)

- small signal equivalent circuit for fig a, can be given as

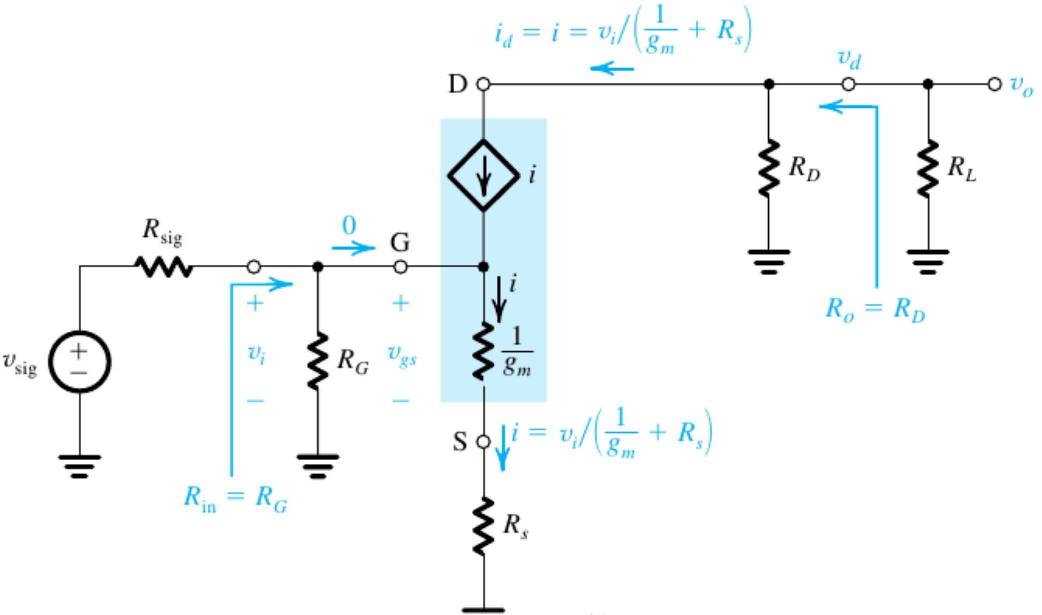


(a)



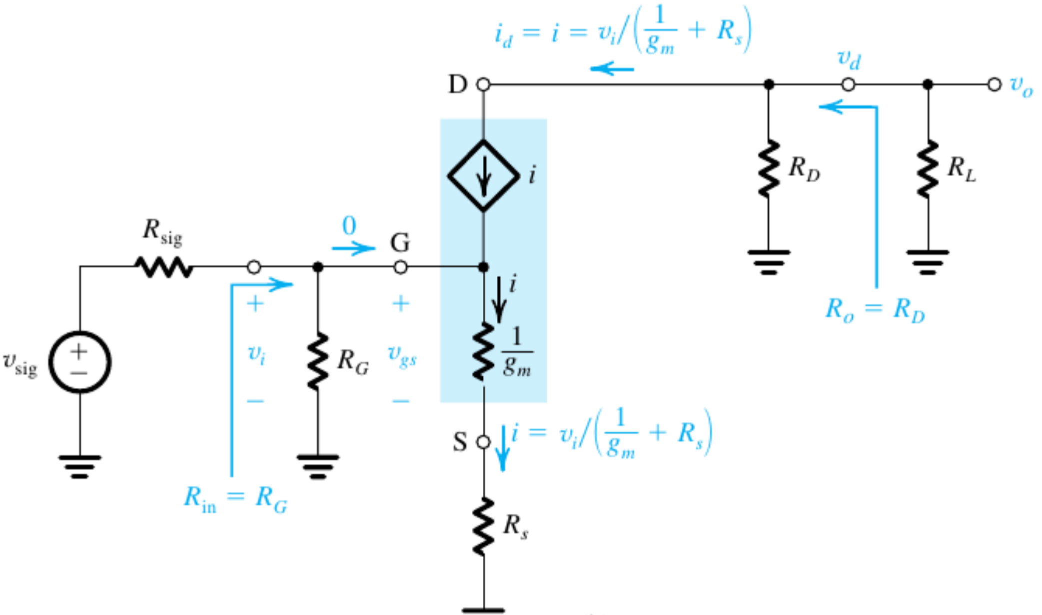
(b)

- here $R_{in} = R_G$



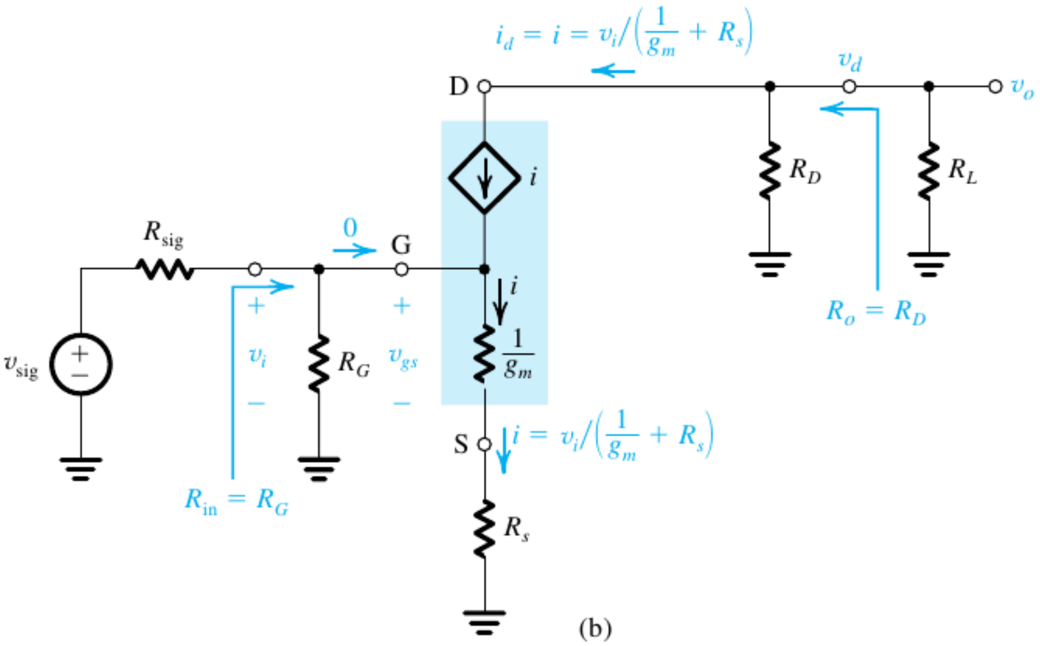
(b)

- here $v_{gs} = \frac{\frac{1}{g_m}}{\frac{1}{g_m}+R_S} v_i$, $v_i = \frac{R_G}{R_G+R_{sig}} v_{sig}$
  - $= \Rightarrow v_{gs} = \frac{\frac{1}{g_m}}{\frac{1}{g_m}+R_S} \frac{R_G}{R_G+R_{sig}} v_{sig} = \Rightarrow$ if $v_{sig} = 0$ then $v_{gs} = 0$
- to determine R_o, we set $v_i = 0 = \Rightarrow v_{gs} = 0 = \Rightarrow g_m v_{gs} = 0$ or $i = 0$
  - $= \Rightarrow R_o = R_D$



(b)

- $i = \frac{v_i}{\frac{1}{g_m}+R_S} = -\frac{v_o}{R_D \| R_L}$
  - $= \Rightarrow \frac{v_o}{v_i} = \frac{-R_D \| R_L}{\frac{1}{g_m}+R_S} = A_v = \Rightarrow A_{vo} = .\ A_v|_{R_L \to \infty} = \frac{-R_D}{\frac{1}{g_m}+R_S}$

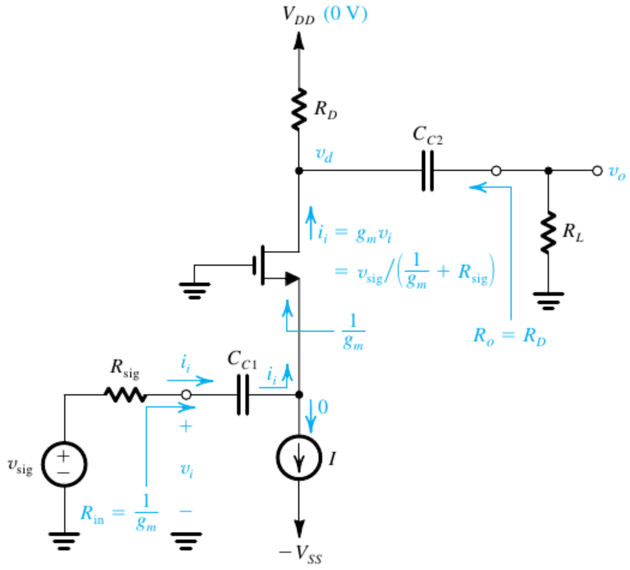


(b)

- $G_v = \frac{v_o}{v_{sig}} = \frac{v_i}{v_{sig}}\frac{v_o}{v_i} = \frac{R_G}{R_G+R_{sig}}\frac{v_o}{v_i} \because v_i = \frac{R_G}{R_G+R_{sig}}v_{sig}$
    - $G_v = \frac{R_G}{R_G+R_{sig}}A_v = \frac{R_G}{R_G+R_{sig}}\left(\frac{-R_D\|R_L}{\frac{1}{g_m}+R_S}\right)$

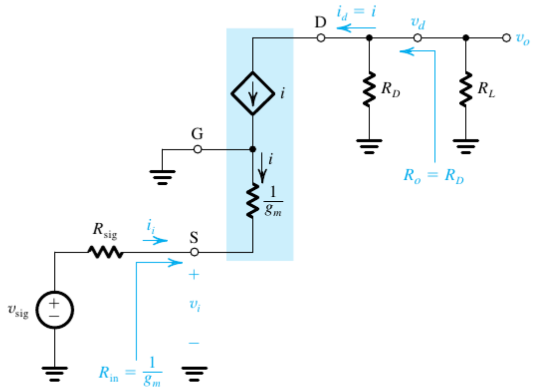
The Common-Gate (CG) Amplifier

- here both the dc and ac voltages at the gate are to be zero,
    - thus the gate is directly connected to the ground



(a)

- the small-signal equivalent circuit can be given as



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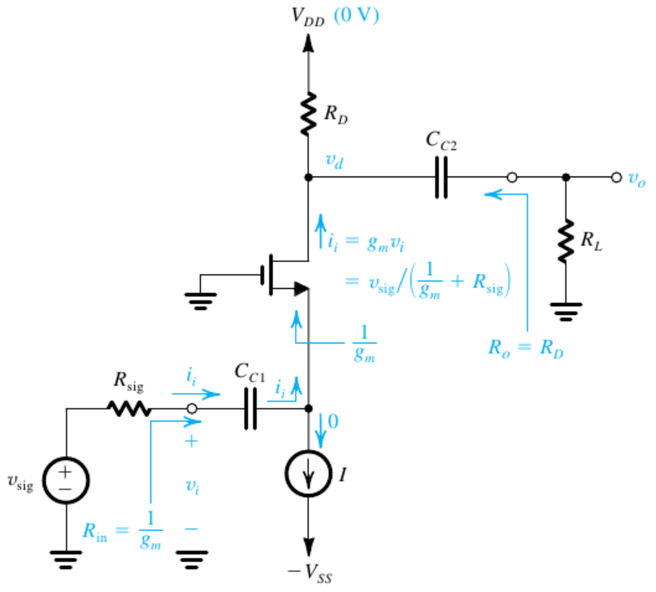
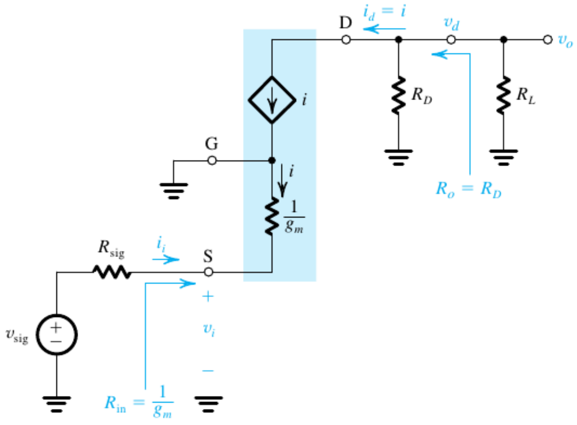


(a)

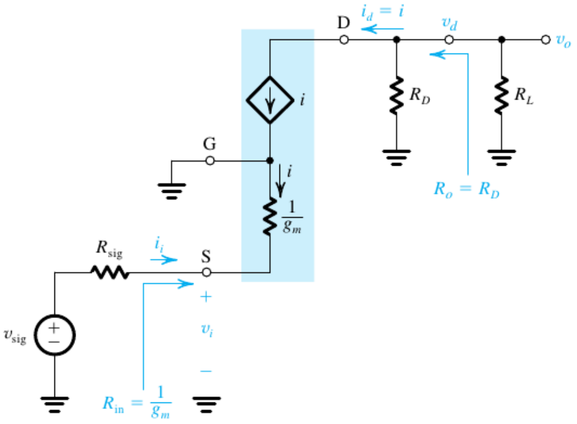
- here $R_{in} = \frac{v_i}{i_i} = \frac{v_i}{-i} = \frac{-v_{gs}}{-i} \because v_i = -v_{gs}$
  - $R_{in} = \frac{-v_{gs}}{-i} = \frac{-v_{gs}}{-g_m v_{gs}} = \frac{1}{g_m}$



(b)

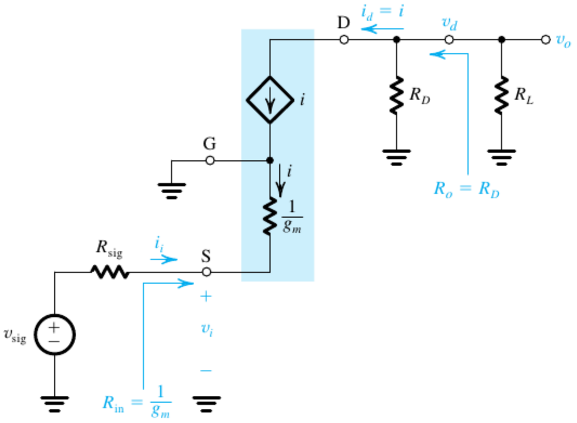
- by voltage divider
  - $v_i = \frac{R_{in}}{R_{in}+R_{sig}} v_{sig} = \frac{\frac{1}{g_m}}{\frac{1}{g_m}+R_{sig}} v_{sig}$
    - and $v_i = -v_{gs}$

        - to determine R_o, we apply test source at the output and set $v_i = 0$
        - $v_i = 0 = \Rightarrow v_{gs} = -v_i = 0 = \Rightarrow g_m v_{gs} = 0$ or $i = 0$
        - $= \Rightarrow R_o = R_D$



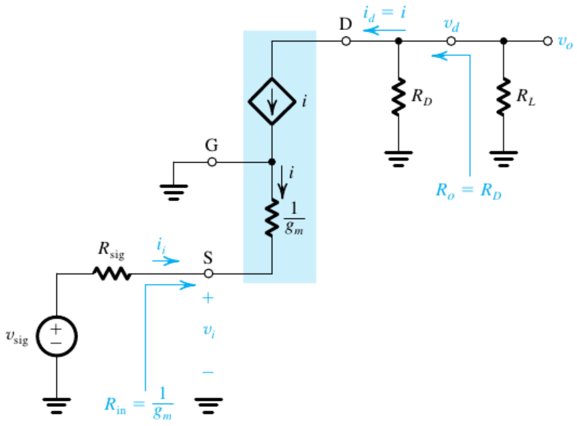
(b)

- $i = g_m v_{gs} = \frac{-v_o}{R_D \| R_L}$
    - as $v_{gs} = -v_i$
        - $= \Rightarrow i = -g_m v_i = \frac{-v_o}{R_D \| R_L}$
            - or $v_o = g_m(R_D \parallel R_L)v_i$
        - $= \Rightarrow A_v = \frac{v_o}{v_i} = g_m\left(R_D \parallel R_L\right)$
        - and $A_{vo} = .\ A_v|_{R_L \to \infty} = g_m R_D$



(b)

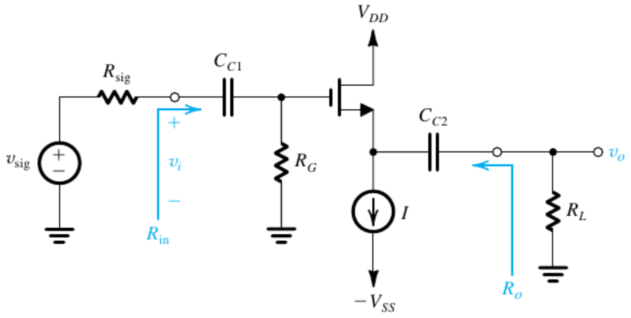
- $A_v = \frac{v_o}{v_i} = g_m\left(R_D \parallel R_L\right)$
    - $G_v = \frac{v_o}{v_{sig}} = \frac{v_i}{v_{sig}}\frac{v_o}{v_i} = \frac{v_i}{v_{sig}}A_v$
        - $= \Rightarrow G_v = \frac{\frac{1}{g_m}}{\frac{1}{g_m} + R_{sig}}A_v = \frac{\frac{1}{g_m}}{\frac{1}{g_m} + R_{sig}}g_m\left(R_D \parallel R_L\right)$
        - or $G_v = \frac{R_D \| R_L}{\frac{1}{g_m} + R_{sig}}$



(b)

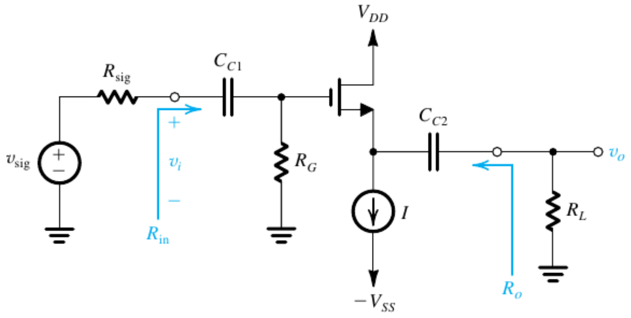
The Source Follower

- In this common drain amplifier,
    - As the drain is to function as a signal ground, there is no need for resistor R_D
    - therefor R_D has been eliminated
        - the input signal is applied via C_{C1} to the MOSFET gate
        - the output signal is taken at the MOSFET source and is coupled to the load R_L via C_{C2}

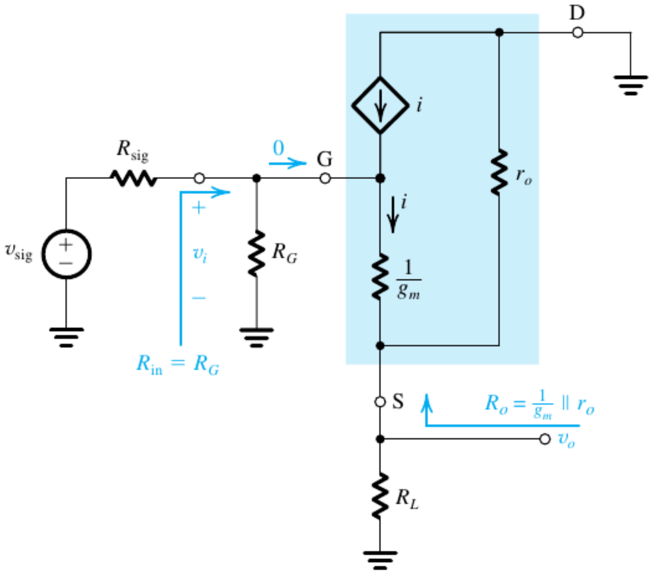


(a)

- Small signal equivalent circuit for this ampifier can be obtained
    - by replacing MOSFET with its T-model,
        - by suppressing dc sources
        - and by replacing capacitors by short circuits (as $\frac{1}{j\omega C}$ is very small at the frequency of interest)

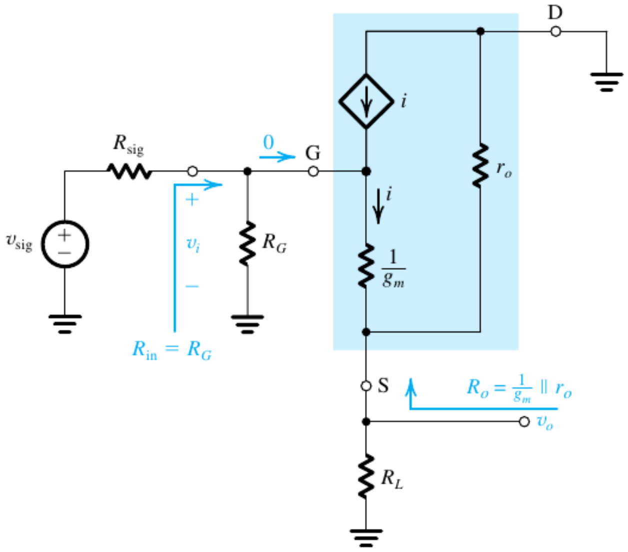


(a)



(b)

- here $R_{in} = R_G$
- R_o:
  - to determine R_o , we set $v_i = 0$
  - Remove R_L and apply a test source
    - $v_i = 0 = \Rightarrow v_g = 0$



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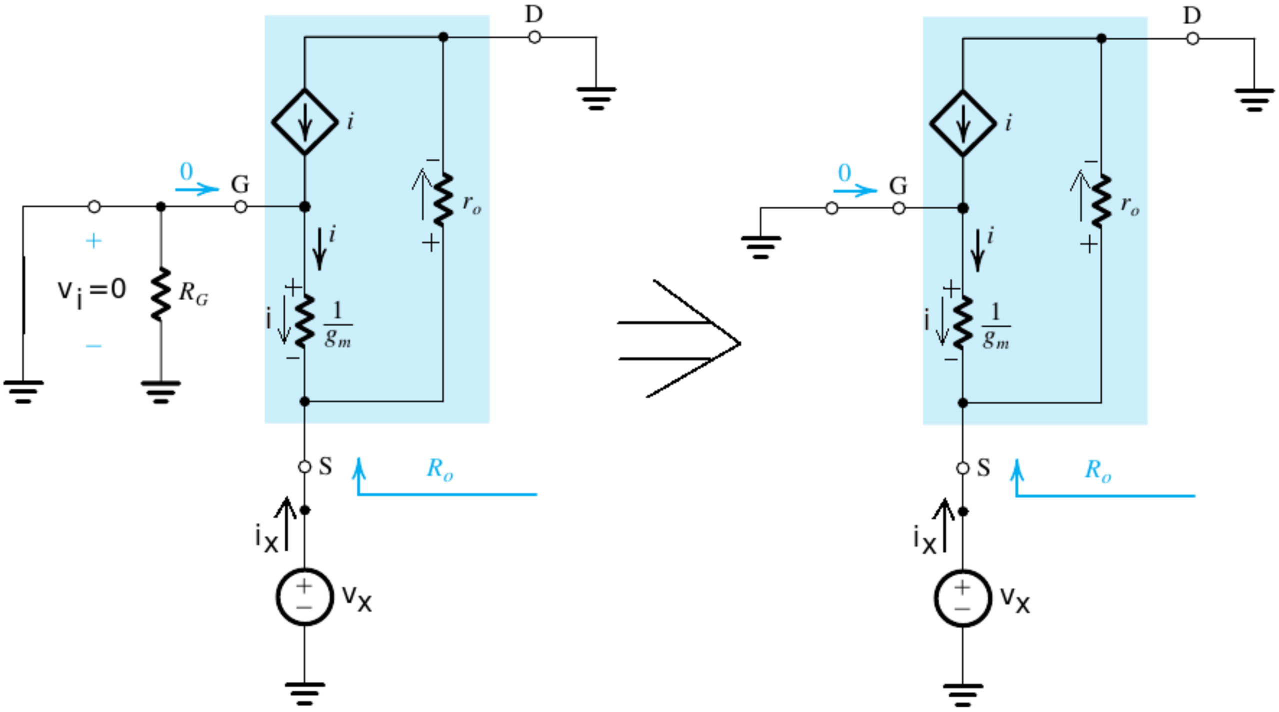
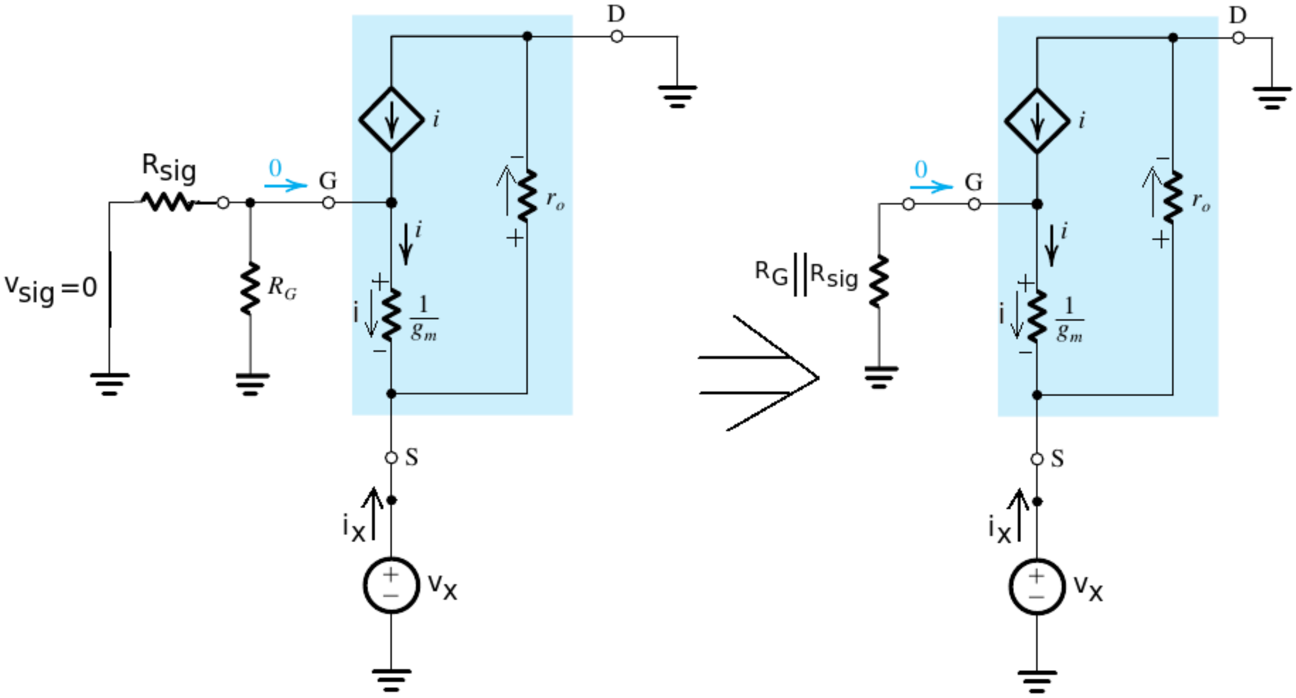


- KCL at MOSFET Source terminal
  - $= \Rightarrow i_x + i = \frac{v_x - 0}{r_o} = \Rightarrow i_x = \frac{v_x}{r_o} - i$
  - Ohm's Law across resistor $\frac{1}{g_m}$
    - $= \Rightarrow v_g - v_s = \frac{1}{g_m} i$
      $= \Rightarrow i = g_m (v_g - v_s) = g_m (0 - v_x) = -g_m v_x$
  - eliminating i from above 2 equations
    - $= \Rightarrow i_x = \frac{v_x}{r_o} - i = \frac{v_x}{r_o} - \left(-g_m v_x\right)$
    - $i_x = \frac{v_x}{r_o} + g_m v_x = v_x \left(\frac{1}{r_o} + g_m\right)$
    - $\frac{i_x}{v_x} = \frac{1}{r_o} + g_m$
    - $= \Rightarrow R_o = \frac{v_x}{i_x} = \frac{1}{\frac{1}{ro} + g_m} = \frac{1}{\frac{1}{ro} + \frac{1}{1/g_m}} = r_o \parallel \left(\frac{1}{g_m}\right)$

R_{out}:

- to determine R_{out}, we set $v_{sig} = 0$, disconnect R_L and apply a test source at the source terminal of MOSFET

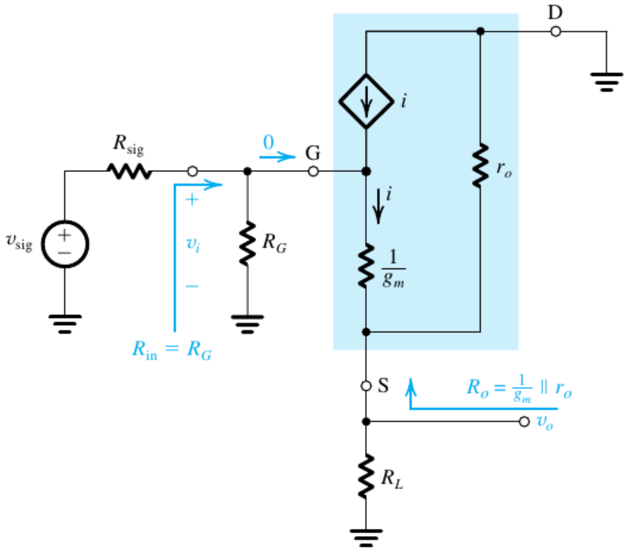


- KCL at MOSFET Source terminal
  - $= \Rightarrow i_x + i = \frac{v_x - 0}{r_o} = \Rightarrow i_x = \frac{v_x}{r_o} - i$
  - Ohm's Law across resistor $\frac{1}{g_m}$
    - $= \Rightarrow v_g - v_s = \frac{1}{g_m} i = \Rightarrow i = g_m(v_g - v_s)$
    - $= \Rightarrow i = g_m(0 - v_x) = -g_m v_x \because i_g = 0 = \Rightarrow v_g = 0$
  - eliminating i from above 2 equations
    - $= \Rightarrow i_x = \frac{v_x}{r_o} - i = \frac{v_x}{r_o} - \left(-g_m v_x\right)$
    - $i_x = \frac{v_x}{r_o} + g_m v_x = v_x\left(\frac{1}{r_o} + g_m\right)$
    - $\frac{i_x}{v_x} = \frac{1}{r_o} + g_m$
    - $= \Rightarrow R_{out} = \frac{v_x}{i_x} = \frac{1}{\frac{1}{ro} + g_m} = \frac{1}{\frac{1}{ro} + \frac{1}{(1/g_m)}} = r_o \parallel \left(\frac{1}{g_m}\right)$

A_v:

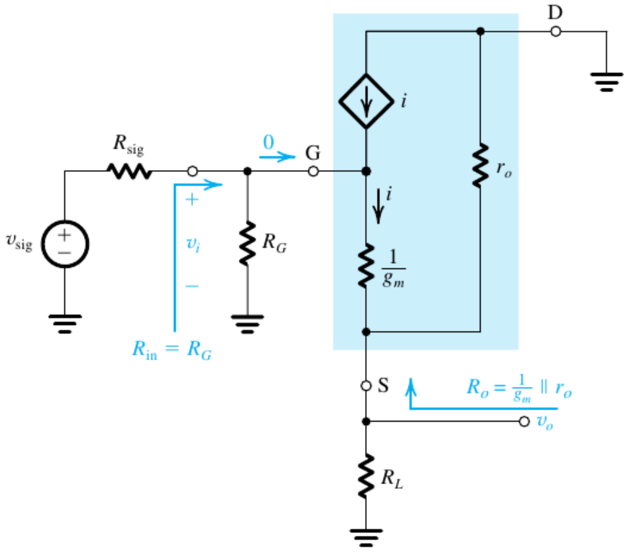
- By KVL
  - $v_i = v_{gs} + v_o = \left(\frac{1}{g_m}\right) i + v_o$
    - but $i = \frac{v_o}{R_L \| r_o}$
      - $= \Rightarrow v_i = \frac{1}{g_m}\left(\frac{v_o}{R_L \| r_o}\right) + v_o$
      - $v_i = v_o\left(\frac{1}{g_m(R_L \| r_o)} + 1\right)$
      - $v_i = v_o\left(\frac{1 + g_m(R_L \| r_o)}{g_m(R_L \| r_o)}\right)$

        - $A_v = \frac{v_o}{v_i} = \frac{g_m(R_L \| r_o)}{1+g_m(R_L \| r_o)}$
        - $A_{vo} = .\ A_v|_{R_L \to \infty} = \frac{g_m r_o}{1+g_m r_o}$



(b)

- $A_v = \frac{v_o}{v_i} = \frac{g_m(R_L \| r_o)}{1+g_m(R_L \| r_o)}$
- $G_v = \frac{v_o}{v_{sig}} = \frac{v_i}{v_{sig}} \frac{v_o}{v_i} = \frac{v_i}{v_{sig}} A_v = \frac{v_i}{v_{sig}} \frac{g_m(R_L \| r_o)}{1+g_m(R_L \| r_o)}$
    - by voltage divider $v_i = \frac{R_G}{R_G+R_{sig}} v_{sig}$
        - $= \Rightarrow G_v = \frac{R_G}{R_G+R_{sig}} \frac{g_m(R_L \| r_o)}{1+g_m(R_L \| r_o)}$
        - or $G_v = \frac{R_G}{R_G+R_{sig}} \left(\frac{R_L \| r_o}{\frac{1}{g_m}+R_L \| r_o} \right)$



(b)

The Amplifier Frequency Response

- Uptill now, we have considered the gain of MOSFET to be constant,

  - and independent of the frequency of the input signal, which is not true
  - A MOSFET has a finite bandwidth (i.e. the gain of MOSFET is dependents upon the frequency of the input signal)
  - fig shows the frequency response of a CS amplifier (i.e. gain is plotted versus frequency)

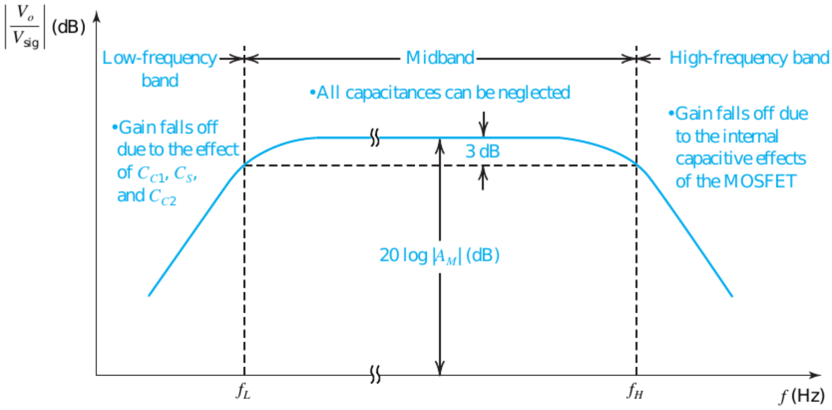
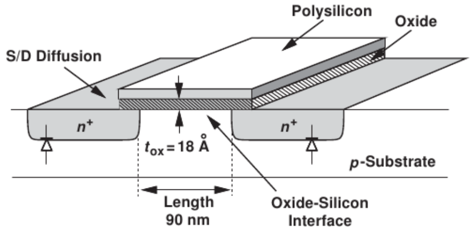


Figure 5.61 A sketch of the frequency response of a CS amplifier delineating the three frequency bands of interest.

- Note that there is a wide frequency range over which the gain remains almost constant
  - this is the useful frequency range (called the midband) of operation for a particular amplifier
- At lower frequencies, the magnitude of amplifier gain falls off
  - because the coupling capacitors, no longer have low impedances
    - i.e. $\frac{1}{j\omega C}$ is large at low frequencies
- At higher frequencies, the gain falls off because of the internal capacitive effects in the MOSFET
  - thus for every MOS amplifier, there is a finite band over which the gain is almost constant.
  - the boundaries of this useful frequency band (called midband), are the two frequencies f_L and f_H
- Note that at f_L and f_H, the gain drops by 3dB below its value at midband
  - thus the amplifier 3dB bandwidth can be defined as
    - $BW = f_H - f_L$
  - as $f_L < f_H = \Rightarrow BW \approx f_H$
- A figure of merit for the amplifier is its gain-bandwidth product i.e. $GB = |A_M| BW$
  - where $|A_M|$ is the magnitude of the amplifier gain in the midband
    - this relation $= \Rightarrow$in amplifier design, it should be possible to trade off gain for bandwidth

The Role of the Substrate-The Body Effect

- Thus far, it has been assumed that the source and body terminals are connected$= \Rightarrow V_{SB} = 0$
    - with $V_{SB} = 0$, the MOSFET behaves as if it were a three terminal device
    - However, in integrated circuits, the substrate is common to many MOS transistors.
    - In order to maintain the cutoff condition for all the substrate to drain/source junctions,
    - the substrate is connected to the most negative power supply in an NMOS circuit (the most +ve power supply for PMOS devices)
        - $= \Rightarrow V_{SB} \searrow = 0$

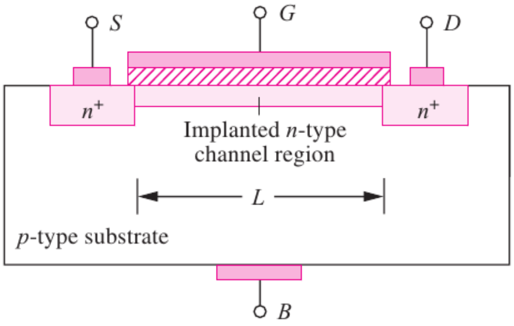


- $V_{SB} \searrow = 0$
    - this non-zero value of V_{SB} affects the i-v characteristics of the MOSFET, by changing its threshold voltage.
    - this effect is called the body effect and can be modeled as (for an NMOS)
        - $V_t = V_{t0} + \gamma\left[\sqrt{2\varphi_f + V_{SB}} - \sqrt{2\varphi_f}\right]$
        - where V_{t0} is the threshold voltage for $V_{SB} = 0$
        - φ_f is a physical parameter (with $2\varphi_f$ typically 0.6V)
    - γ is a fabrication parameter given by
        - $\gamma = \frac{\sqrt{2qN_A\varepsilon_S}}{C_{ox}}$, where q is the electron charge
        - N_A is the doping concentration of the p-type substrate
        - ε_S is the permitivity of silicon$= 11.7\varepsilon_o$
    - the parameter γ has the dimension of $\sqrt{V}$ and is typically $0.4V^{1/2}$
- for a PMOS transistor
    - $V_{tp} = V_{t0} + \gamma\left[\sqrt{2\varphi_f + V_{BS}} - \sqrt{2\varphi_f}\right]$
        - here γ is -ve and is given as $\gamma = -\frac{\sqrt{2qN_D\varepsilon_S}}{C_{ox}}$
        - where N_D is the doping concentration of the n-well in which PMOS is formed
    - for PMOS transistor

    - $2\varphi_f$ is typically 0.75V
    - γ is typically $-0.5V^{\frac{1}{2}}$

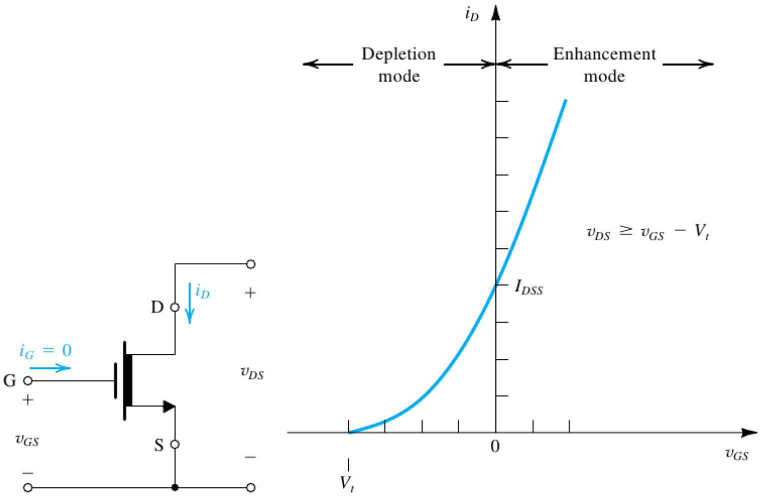
The Depletion-Type MOSFET

- The structure of depletion-type MOSFET is similar to the
  - enhancement-type MOSFET with one important difference
  - The depletion MOSFET has a physically implanted channel



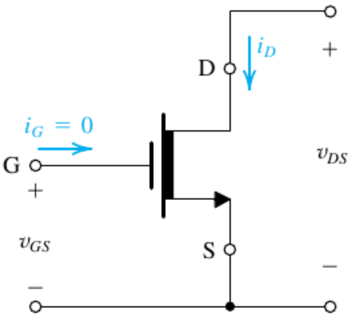
  - (b)
  - thus an n-channel depletion-type MOSFET has a built-in n-type channel
    - in the device so that the n^+ drain and n^+ source regions are
    - connected through this channel even when $v_{GS} = 0$
  - $= \Rightarrow$if a voltage v_{DS} is applied between the drain and source, a current i_D flows for $v_{GS} = 0$
  - A negative voltage must be applied to the gate, v_{GS} to deplete the n-type channel region
    - and eliminate the current path between the source and drain
    - (hence the name depletion-type MOSFET)
- thus for depletion-type MOSFET, applying a +ve v_{GS} enhances
  - the channel by attracting more electrons into it
  - and by applying a -ve v_{GS}, electrons can be repelled from
    - the channel and thus the channel will become shallower
  - i.e. the -ve v_{GS} deplete the channel of its charge carriers
    - and this mode of operation (-ve v_{GS}) is called depletion mode
  - As v_{GS} is made more -ve, a value is reached at which
    - the channel is completely depleted of charge carriers $= \Rightarrow i_D = 0$
  - and this value of v_{GS} is the threshold voltage of the n-channel depletion type MOSFET
- thus the depletion-type MOSFET can be operated
  - in the enhancement mode by applying a +ve v_{GS}

- and in the depletion mode by applying a -ve v_{GS}



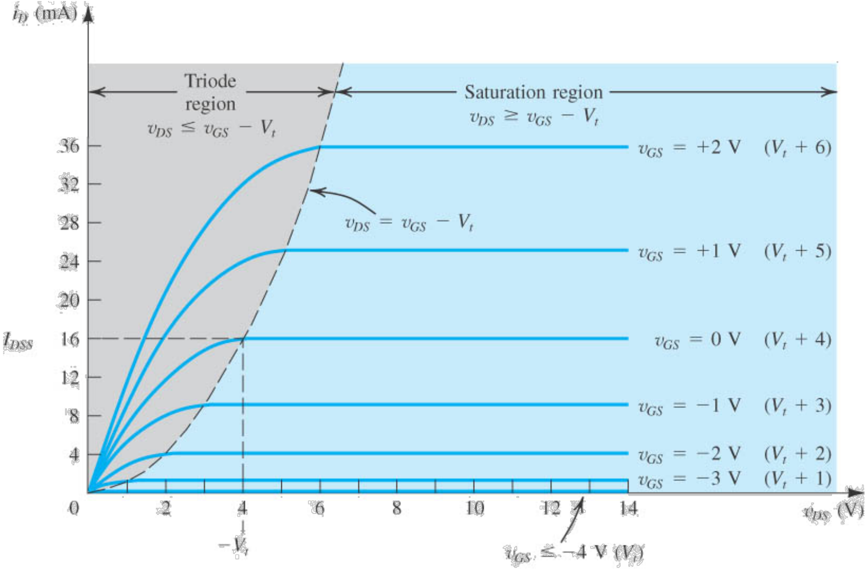
(a) (b)

Figure 5.63 The circuit symbol **(a)** and the i_D–v_{GS} characteristic in saturation; **(b)** for an *n*-channel depletion-type MOSFET.



(a)

- Note that the device symbol denotes the existing channel
  - via the shaded area next to the vertical line
- the $i_D - v_{DS}$ characteristics for this device are the same as those for the enhancement type MOSFET
  - except for the negative V_{tn}



(b)