small sign

$I_D =$

$I_D + \Delta I_D = f(V_{gs} + \underset{small}{\Delta V_{gs}},\ V_{DS} + \underset{small}{\Delta V_{DS}})$ only 1st order because of small signal chang

taylors explantion partial differenti

$I_D + \Delta I_D = f(V_{gs} + V_{DS}) + \frac{\partial I_D}{\partial V_{GS}} \Delta V_{GS} + \frac{\partial I_D}{\partial V_{DS}} \Delta V_{DS}$

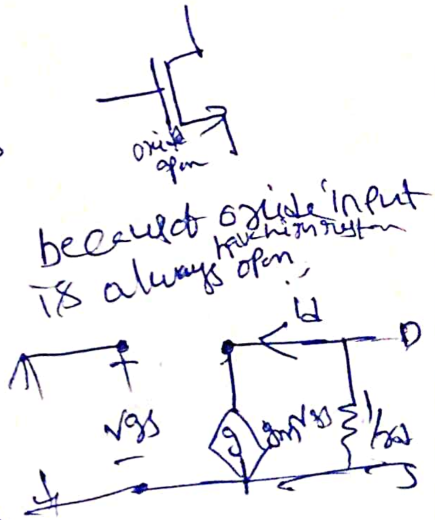
oxide open

because oxide input is always open

$\Delta V_{GS} = V_{gs}$

$\Delta V_{DS} = V_{ds}$

$\Delta I_D = i_d$



$I_D + i_d =$

$i_d = \underbrace{\frac{\partial I_D}{\partial V_{GS}}\Big|_{V_{DS}}}_{g_m} V_{gs} + \underbrace{\frac{\partial I_D}{\partial V_{DS}}\Big|_{V_{gs}}}_{g_d = 1/r_d} V_{ds}$ drain

$i_d = \underbrace{g_m V_{gs}}_{VCCS\ source} + \frac{1}{r_d} \cdot V_{ds}$

4.1.2 Small-Signal Equivalent Circuit

Now that we have the ac equivalent circuit for the NMOS amplifier circuit, (Figure 4.4), we must develop a small-signal equivalent circuit for the transistor.

Initially, we assume that the signal frequency is sufficiently low so that any capacitance at the gate terminal can be neglected. The input to the gate thus appears as an open circuit, or an infinite resistance. Equation (4.14) relates the small-signal drain current to the small-signal input voltage, and Equation (4.7) shows that the transconductance g_m is a function of the Q-point. The resulting simplified small-signal equivalent circuit for the NMOS device is shown in Figure 4.5. (The phasor components are in parentheses.)

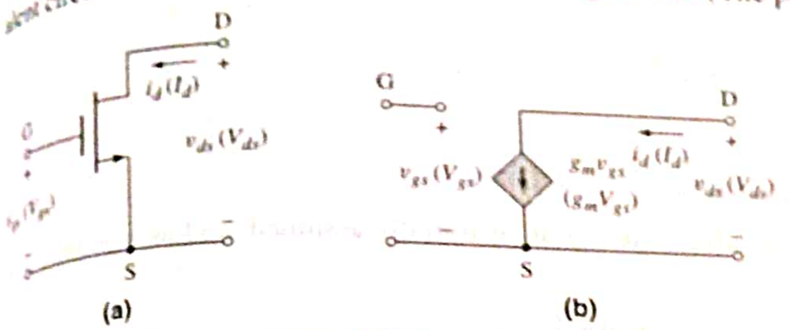


Figure 4.5 (a) Common-source NMOS transistor with small-signal parameters and (b) simplified small-signal equivalent circuit for NMOS transistor

This small-signal equivalent circuit can also be expanded to take into account the finite output resistance of a MOSFET biased in the saturation region. This effect, discussed in the last chapter, is a result of the nonzero slope in the i_D versus v_{DS} curve.

We know that

$$i_D = K_n[(v_{GS} - V_{TN})^2(1 + \lambda v_{DS})] \tag{4.16}$$

where λ is the channel-length modulation parameter and is a positive quantity. The small-signal output resistance, as previously defined, is

$$r_o = \left(\frac{\partial i_D}{\partial v_{DS}}\right)^{-1}\Bigg|_{v_{GS}=V_{GSQ}=\text{const.}} \tag{4.17}$$

or

$$r_o = [\lambda K_n(V_{GSQ} - V_{TN})^2]^{-1} \cong [\lambda I_{DQ}]^{-1} \tag{4.18}$$

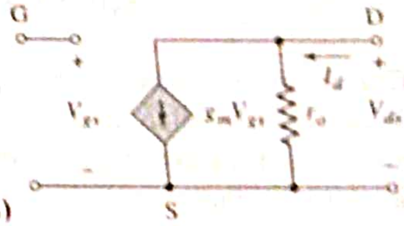


Figure 4.6 Expanded small-signal equivalent circuit, including output resistance, for NMOS transistor

This small-signal output resistance is also a function of the Q-point parameters.

The expanded small-signal equivalent circuit of the n-channel MOSFET is shown in Figure 4.6 in phasor notation. Note that this equivalent circuit is a transconductance amplifier in that the input signal is a voltage and the output signal is a current. This equivalent circuit can now be inserted into the amplifier ac equivalent circuit in Figure 4.4 to produce the circuit in Figure 4.7.

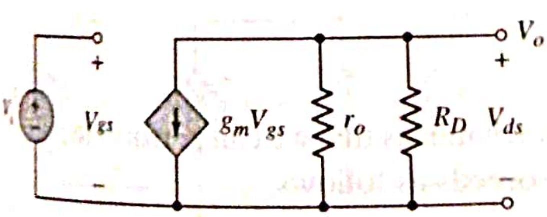


Figure 4.7 Small-signal equivalent circuit of common-source circuit with NMOS transistor model

EXAMPLE 4.2

Objective: Determine the small-signal voltage gain of a MOSFET circuit.

For the circuit in Figure 4.1, assume parameters are: $V_{GSQ} = 2.12$ V, $V_{DD} = 5$ V, and $R_D = 2.5$ kΩ. Assume transistor parameters are: $V_{TN} = 1$ V, $K_n = 0.80$ mA/V^2, and $\lambda = 0.02$ V^{-1}. Assume the transistor is biased in the saturation region.

Solution: The quiescent values are

$$I_{DQ} \cong K_n(V_{GSQ} - V_{TN})^2 = (0.8)(2.12 - 1)^2 = 1.0 \text{ mA}$$

and

$$V_{DSQ} = V_{DD} - I_{DQ}R_D = 5 - (1)(2.5) = 2.5 \text{ V}$$

Therefore,

$$V_{DSQ} = 2.5 \text{ V} > V_{DS}(\text{sat}) = V_{GS} - V_{TN} = 1.82 - 1 = 0.82 \text{ V}$$

which means that the transistor is biased in the saturation region, as initially assumed, and as required for a linear amplifier. The transconductance is

$$g_m = 2K_n(V_{GSQ} - V_{TN}) = 2(0.8)(2.12 - 1) = 1.79 \text{ mA/V}$$

and the output resistance is

$$r_o = [\lambda I_{DQ}]^{-1} = [(0.02)(1)]^{-1} = 50 \text{ k}\Omega$$

From Figure 4.7, the output voltage is

$$V_o = -g_m V_{gs}(r_o \| R_D)$$

Since $V_{gs} = V_i$, the small-signal voltage gain is

$$A_v = \frac{V_o}{V_i} = -g_m(r_o \| R_d) = -(1.79)(50 \| 2.5) = -4.26$$

Comment: Because of the relatively low value of transconductance, MOSFET circuits tend to have a relatively low value of small-signal voltage gain. Note that the small-signal voltage gain contains a minus sign, which means that the sinusoidal output voltage is 180 degrees out of phase with respect to the input sinusoidal signal.

EXERCISE PROBLEM

Ex 4.2: For the circuit shown in Figure 4.1, $V_{DD} = 10$ V and $R_D = 10$ kΩ. The transistor parameters are $V_{TN} = 2$ V, $K_n = 0.5$ mA/V^2, and $\lambda = 0$. Assume the transistor is biased such that $I_{DQ} = 0.4$ mA. Determine the small-signal voltage gain. (Ans. $A_v = -8.94$)

Problem-Solving Technique: MOSFET AC Analysis

Since we are dealing with linear amplifiers, superposition applies, which means that we can perform the dc and ac analyses separately. The analysis of the MOSFET amplifier proceeds as follows:

1. Analyze the circuit with only the dc sources present. This solution is the dc or quiescent solution. The transistor must be biased in the saturation region in order to produce a linear amplifier.

2. Replace each element in the circuit with its small-signal model, which means replacing the transistor by its small-signal equivalent cicuit.
3. Analyze the small-signal equivalent circuit, setting the dc source components equal to zero, to produce the response of the circuit to the time-varying input signals only.

The previous discussion was for an n-channel MOSFET amplifier. The same basic analysis and equivalent circuit also applies to the p-channel transistor. Figure 4.8(a) shows a circuit containing a p-channel MOSFET. Note that the power supply voltage V_{DD} is connected to the source. (The subscript DD can be used to indicate that the supply is connected to the drain terminal. Here, however, V_{DD} is simply the usual notation for the power supply voltage in MOSFET circuits.) Also note the change in current directions and voltage polarities compared to the circuit containing the NMOS transistor. Figure 4.8(b) shows the ac equivalent circuit, with the dc voltage sources replaced by ac short circuits, and all currents and voltages shown are the time-varying components.

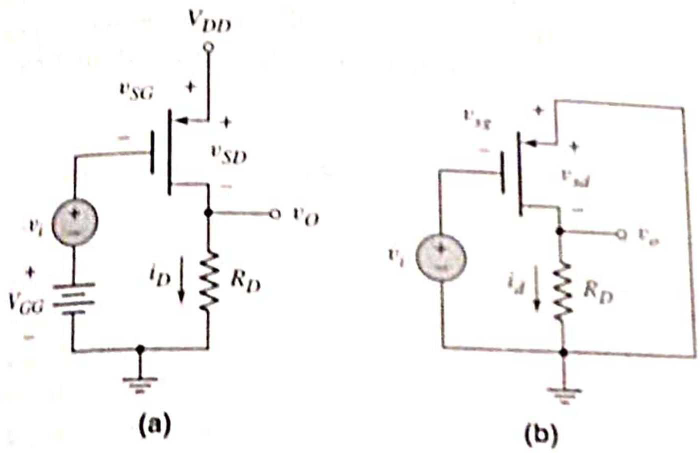


Figure 4.8 (a) Common-source circuit with PMOS transistor and (b) corresponding ac equivalent circuit

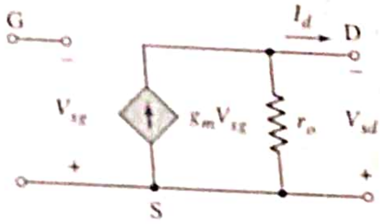


Figure 4.9 Small-signal equivalent circuit of PMOS transistor

In the circuit of Figure 4.8(b), the transistor can be replaced by the equivalent circuit in Figure 4.9. The equivalent circuit of the p-channel MOSFET is the same as that of the n-channel device, except that all current directions and voltage polarities are reversed.

The final small-signal equivalent circuit of the p-channel MOSFET amplifier is shown in Figure 4.10. The output voltage is

$$V_o = g_m V_{sg}(r_o \| R_D)$$

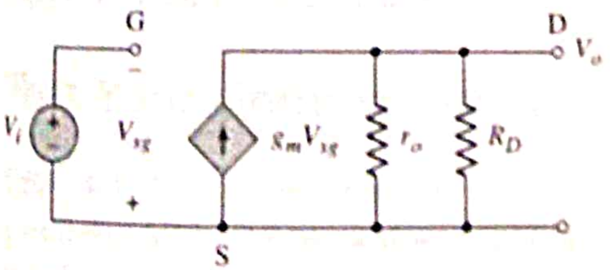


Figure 4.10 Small-signal equivalent circuit of common-source amplifier with PMOS transistor model

The control voltage V_{sg}, given in terms of the input signal voltage, is

$$V_{sg} = -V_i \tag{4.20}$$

and the small-signal voltage gain is

$$A_v = \frac{V_o}{V_i} = -g_m(r_o \| R_D) \tag{4.21}$$

This expression for the small-signal voltage gain of the p-channel MOSFET amplifier is exactly the same as that for the n-channel MOSFET amplifier. The negative sign indicates that a 180-degree phase reversal exists between the ouput and input signals, for both the PMOS and the NMOS circuit.

We may note that if the polarity of the small-signal gate-to-source voltage is reversed, then the small-signal drain current direction is reversed and the small-signal equivalent circuit of the PMOS device is exactly identical to that of the NMOS device. This change of polarity is shown in Figure 4.11. Figure 4.11(a) shows the conventional voltage polarity and current directions in a PMOS transistor. If the control voltage polarity is reversed as shown in Figure 4.11(b), then the dependent current direction is also reversed. The equivalent circuit shown in Figure 4.11(b) is the same as that of the NMOS transistor. However, the author prefers to use the small-signal equivalent circuit in Figure 4.9 to be consistent with the voltage polarities and current directions of the PMOS transistor.

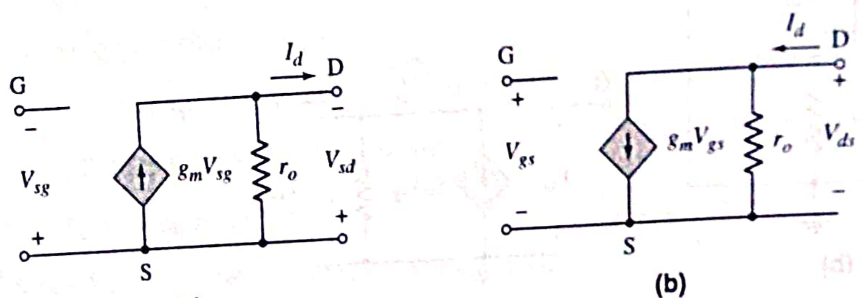


Figure 4.11 Small signal equivalent circuit of a p-channel MOSFET showing (a) the conventional voltage polarities and current directions and (b) the case when the voltage polarities and current directions are reversed.