Tikrit university

Collage of Engineering Shirqat

Department of Electrical Engineering

Second Class

Electronic II

Chapter 8

Lec 9

FET Amplifiers

Prepared by

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5 Voltage-Divider Configuration

The popular voltage-divider configuration for BJTs can also be applied to JFETs as demonstrated in Fig. 21.

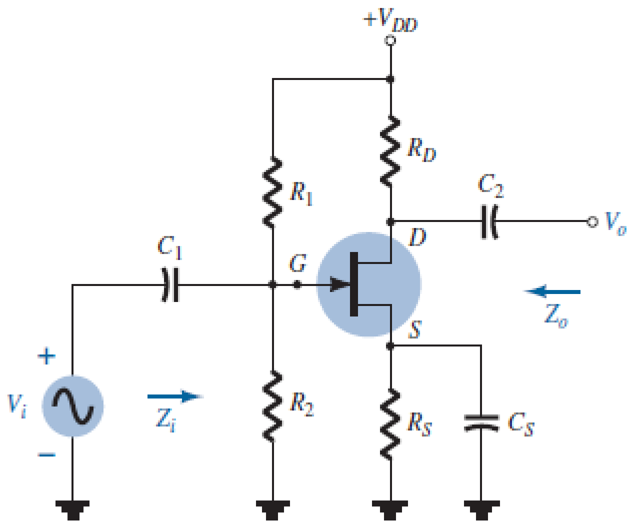


FIG. 21
JFET voltage-divider configuration.

Substituting the ac equivalent model for the JFET results in the configuration of Fig. 22. Replacing the dc supply VDD by a short-circuit equivalent has grounded one end of R1 and RD. Since each network has a common ground, R1 can be brought down in parallel with R2 as shown in Fig. 23. RD can also be brought down to ground, but in the output circuit across rd. The resulting ac equivalent network now has the basic format of some of the networks already analyzed.

Zi R1 and R2 are in parallel with the open-circuit equivalence of the JFET, resulting in

$$\boxed{Z_i = R_1 \| R_2} \qquad (28)$$

Zo Setting Vi = 0 V sets Vgs and gmVgs to zero, and

$$\boxed{Z_o = r_d \| R_D} \qquad (29)$$

For $r_d \geq 10R_D$,

$$\boxed{Z_o \cong R_D}_{r_d \geq 10R_D} \qquad (30)$$

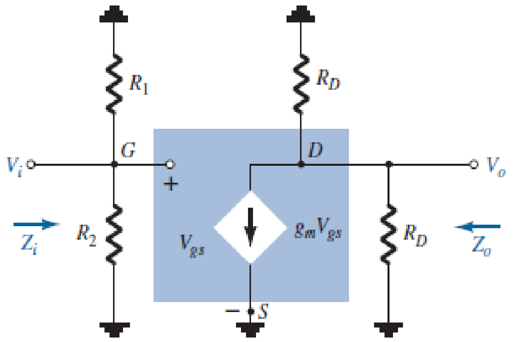


FIG. 22
Network of Fig. 21 under ac conditions.

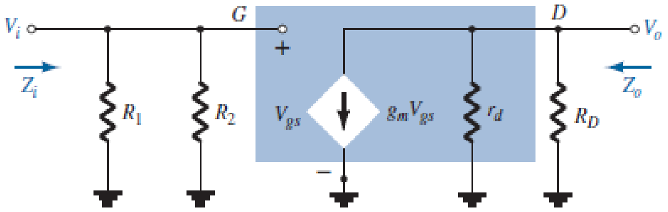


FIG. 23
Redrawn network of Fig. 22.

A_v

$$V_{gs} = V_i$$

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

so that
$$A_v = \frac{V_o}{V_i} = \frac{-g_m V_{gs}(r_d \| R_D)}{V_{gs}}$$

and
$$\boxed{A_v = \frac{V_o}{V_i} = -g_m(r_d \| R_D)} \qquad (31)$$

If $r_d \geq 10R_D$,
$$\boxed{A_v = \frac{V_o}{V_i} \cong -g_m R_D}_{r_d \geq 10R_D} \qquad (32)$$

Note that the equations for Zo and Av are the same as obtained for the fixed-bias and selfbias (with bypassed RS) configurations. The only difference is the equation for Zi, which is now sensitive to the parallel combination of R1 and R2.

6 Common-Gate Configuration

The last JFET configuration to be analyzed in detail is the common-gate configuration of Fig. 24, which parallels the common-base configuration employed with BJT transistors. Substituting the JFET equivalent circuit results in Fig. 25. Note the continuing requirement that the controlled source *gmVgs* be connected from drain to source with *rd* in parallel. The isolation between input and output circuits has obviously been lost since the gate terminal is now connected to the common ground of the network and the controlled current source is connected directly from drain to source. In addition, the resistor connected between input terminals is no longer *RG*, but the resistor *RS* connected from source to ground. Note also the location of the controlling voltage *Vgs* and the fact that it appears directly across the resistor *RS*.

$$\boxed{Z_i' = \frac{V'}{I'} = \frac{\left[1 + \frac{R_D}{r_d}\right]}{\left[g_m + \frac{1}{r_d}\right]}} \qquad (33)$$

$$Z_i = R_S \| Z_i'$$

$$\boxed{Z_i = R_S \| \left[\frac{r_d + R_D}{1 + g_m r_d}\right]} \qquad (34)$$

$$\boxed{Z_i \cong R_S \| 1/g_m}_{r_d \geq 10R_D} \qquad (35)$$

$$\boxed{Z_o = R_D \| r_d} \qquad (36)$$

$$\boxed{Z_o \cong R_D}_{r_d \geq 10R_D} \qquad (37)$$

$$\boxed{A_v = \frac{V_o}{V_i} = \frac{\left[g_m R_D + \frac{R_D}{r_d}\right]}{\left[1 + \frac{R_D}{r_d}\right]}} \qquad (38)$$

$$\boxed{A_v \cong g_m R_D}_{r_d \geq 10R_D} \qquad (39)$$

phase relationship The fact that Av is a positive number will result in an in-phase relationship between Vo and Vi for the common-gate configuration.

EXAMPLE 9 Although the network of Fig. 27 may not initially appear to be of the common-gate variety, a close examination will reveal that it has all the characteristics of Fig. 24. If $V_{GS_Q} = -2.2$ V and $I_{D_Q} = 2.03$ mA:

a. Determine g_m.
b. Find r_d.
c. Calculate Z_i with and without r_d. Compare results.
d. Find Z_o with and without r_d. Compare results.
e. Determine V_o with and without r_d. Compare results.

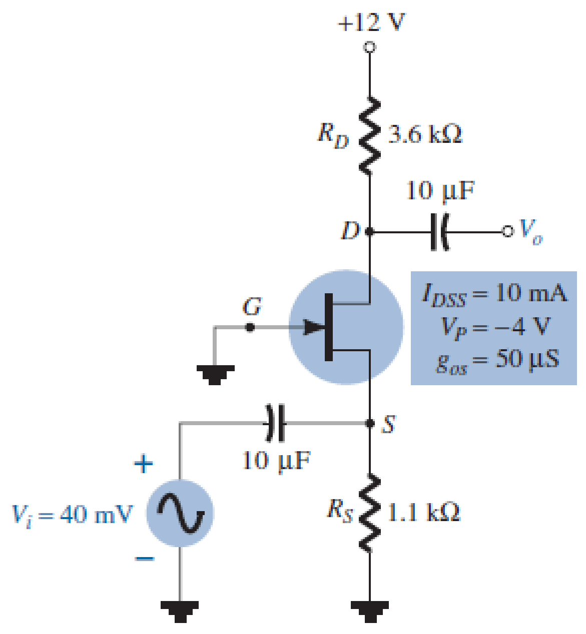


FIG. 27
Network for Example 9.

Solution:

a. $g_{m0} = \dfrac{2I_{DSS}}{|V_P|} = \dfrac{2(10\text{ mA})}{4\text{ V}} = 5\text{ mS}$

$$g_m = g_{m0}\left(1 - \frac{V_{GS_Q}}{V_P}\right) = 5\text{ mS}\left(1 - \frac{(-2.2\text{ V})}{(-4\text{ V})}\right) = \mathbf{2.25\text{ mS}}$$

b. $r_d = \dfrac{1}{g_{os}} = \dfrac{1}{50\,\mu\text{S}} = \mathbf{20\text{ k}\Omega}$

c. With r_d,

$$Z_i = R_S \| \left[\frac{r_d + R_D}{1 + g_m r_d}\right] = 1.1\text{ k}\Omega \| \left[\frac{20\text{ k}\Omega + 3.6\text{ k}\Omega}{1 + (2.25\text{ mS})(20\text{ k}\Omega)}\right]$$
$$= 1.1\text{ k}\Omega \| 0.51\text{ k}\Omega = \mathbf{0.35\text{ k}\Omega}$$

Without r_d,

$$Z_i = R_S \| 1/g_m = 1.1\text{ k}\Omega \| 1/2.25\text{ ms} = 1.1\text{ k}\Omega \| 0.44\text{ k}\Omega$$
$$= \mathbf{0.31\text{ k}\Omega}$$

Even though the condition $r_d \geq 10R_D$ is not satisfied with $r_d = 20\text{ k}\Omega$ and $10R_D = 36\text{ k}\Omega$, both equations result in essentially the same level of impedance. In this case, $1/g_m$ was the predominant factor.

d. With r_d,

$$Z_o = R_D \| r_d = 3.6\text{ k}\Omega \| 20\text{ k}\Omega = \mathbf{3.05\text{ k}\Omega}$$

Without r_d,

$$Z_o = R_D = \mathbf{3.6\text{ k}\Omega}$$

Again the condition $r_d \geq 10R_D$ is *not* satisfied, but both results are reasonably close. R_D is certainly the predominant factor in this example.

e. With r_d,

$$A_v = \frac{\left[g_m R_D + \dfrac{R_D}{r_d}\right]}{\left[1 + \dfrac{R_D}{r_d}\right]} = \frac{\left[(2.25\text{ mS})(3.6\text{ k}\Omega) + \dfrac{3.6\text{ k}\Omega}{20\text{ k}\Omega}\right]}{\left[1 + \dfrac{3.6\text{ k}\Omega}{20\text{ k}\Omega}\right]}$$
$$= \frac{8.1 + 0.18}{1 + 0.18} = \mathbf{7.02}$$

and $\quad A_v = \dfrac{V_o}{V_i} \Rightarrow V_o = A_v V_i = (7.02)(40\text{ mV}) = \mathbf{280.8\text{ mV}}$

Without r_d,

$$A_v = g_m R_D = (2.25\text{ mS})(3.6\text{ k}\Omega) = \mathbf{8.1}$$

with $\quad V_o = A_v V_i = (8.1)(40\text{ mV}) = \mathbf{324\text{ mV}}$

In this case, the difference is a little more noticeable, but not dramatically so.

Example 9 demonstrates that even though the condition rd Ú 10RD was not satisfied, the results for the parameters given were not significantly different using the exact and approximate equations. In fact, in most cases, the approximate equations can be used to find a reasonable idea of particular levels with a reduced amount of effort.

7 Source-Follower (Common-Drain) Configuration

The JFET equivalent of the BJT emitter-follower configuration is the source-follower configuration of Fig. 28. Note that the output is taken off the source terminal and, when the dc supply is replaced by its short-circuit equivalent, the drain is grounded (hence, the terminology *common-drain*).

Substituting the JFET equivalent circuit results in the configuration of Fig. 29. The controlled source and the internal output impedance of the JFET are tied to ground at one end and *RS* on the other, with *Vo* across *RS*. Since *gmVgs*, *rd*, and *RS* are connected to

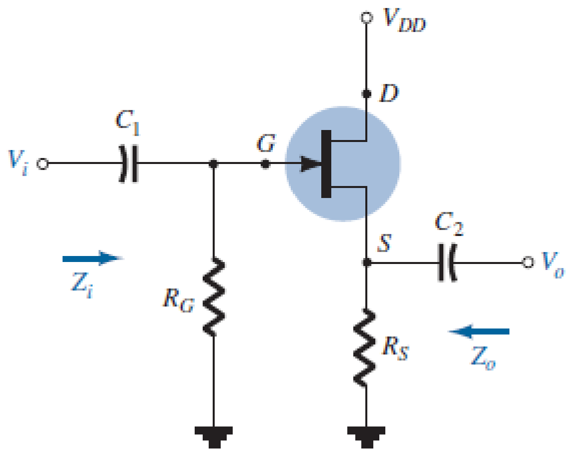


FIG. 28
JFET source-follower configuration.

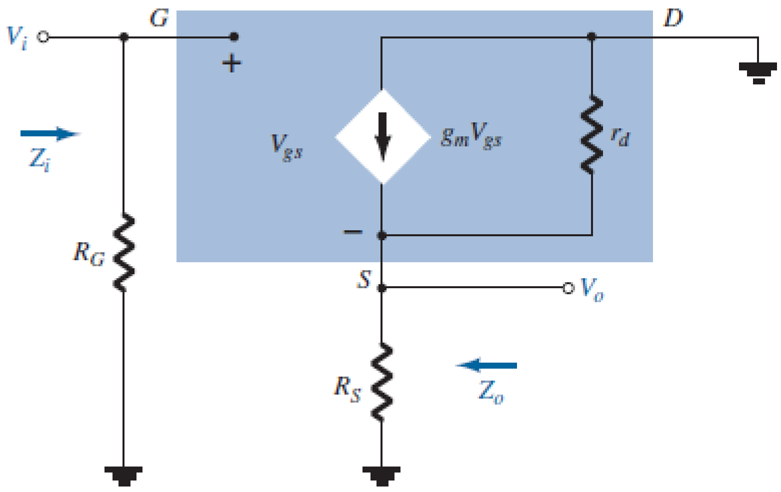


FIG. 29
Network of Fig. 28 following the substitution of the JFET ac equivalent model.

the same terminal and ground, they can all be placed in parallel as shown in Fig. 30. The current source reversed direction, but *Vgs* is still defined between the gate and source terminals.

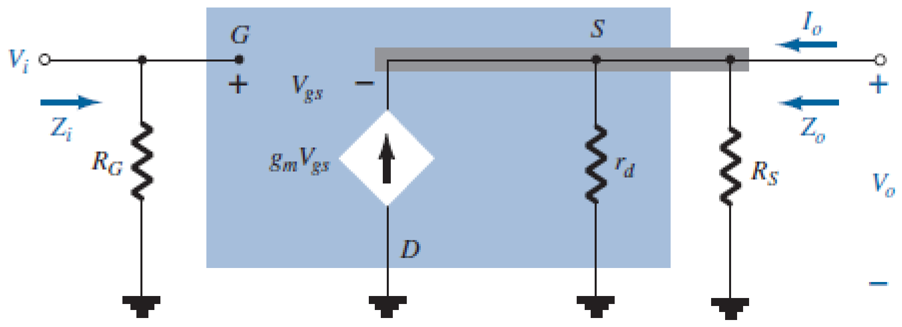


FIG. 30
Network of Fig. 29 redrawn.

$$\boxed{Z_i = R_G} \qquad (40)$$

$$\boxed{Z_o = r_d \| R_S \| 1/g_m} \qquad (41)$$

$$\boxed{Z_o \cong R_S \| 1/g_m}_{r_d \geq 10R_S} \qquad (42)$$

$$\boxed{A_v = \frac{V_o}{V_i} = \frac{g_m(r_d \| R_S)}{1 + g_m(r_d \| R_S)}} \qquad (43)$$

$$\boxed{A_v = \frac{V_o}{V_i} \cong \frac{g_m R_S}{1 + g_m R_S}}_{r_d \geq 10R_S} \qquad (44)$$

EXAMPLE 10 A dc analysis of the source-follower network of Fig. 32 results in $V_{GS_Q} = -2.86$ V and $I_{D_Q} = 4.56$ mA.

a. Determine g_m.
b. Find r_d.
c. Determine Z_i.
d. Calculate Z_o with and without r_d. Compare results.
e. Determine A_v with and without r_d. Compare results.

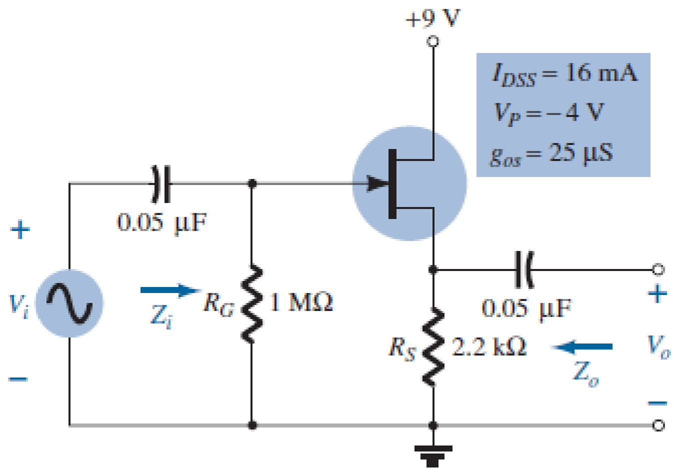


FIG. 32
Network to be analyzed in Example 10.

Solution:

a. $g_{m0} = \dfrac{2I_{DSS}}{|V_P|} = \dfrac{2(16\text{ mA})}{4\text{ V}} = 8\text{ mS}$

$$g_m = g_{m0}\left(1 - \frac{V_{GS_Q}}{V_P}\right) = 8\text{ mS}\left(1 - \frac{(-2.86\text{ V})}{(-4\text{ V})}\right) = \mathbf{2.28\text{ mS}}$$

b. $r_d = \dfrac{1}{g_{os}} = \dfrac{1}{25\ \mu\text{S}} = \mathbf{40\ k\Omega}$

c. $Z_i = R_G = \mathbf{1\ M\Omega}$

d. With r_d,

$$Z_o = r_d \| R_S \| 1/g_m = 40\text{ k}\Omega \| 2.2\text{ k}\Omega \| 1/2.28\text{ mS}$$
$$= 40\text{ k}\Omega \| 2.2\text{ k}\Omega \| 438.6\ \Omega$$
$$= \mathbf{362.52\ \Omega}$$

which shows that Z_o is often relatively small and determined primarily by $1/g_m$.
Without r_d,

$$Z_o = R_S \| 1/g_m = 2.2\text{ k}\Omega \| 438.6\ \Omega = \mathbf{365.69\ \Omega}$$

which shows that r_d typically has little effect on Z_o.

e. With r_d,

$$A_v = \frac{g_m(r_d \| R_S)}{1 + g_m(r_d \| R_S)} = \frac{(2.28\text{ mS})(40\text{ k}\Omega \| 2.2\text{ k}\Omega)}{1 + (2.28\text{ mS})(40\text{ k}\Omega \| 2.2\text{ k}\Omega)}$$
$$= \frac{(2.28\text{ mS})(2.09\text{ k}\Omega)}{1 + (2.28\text{ mS})(2.09\text{ k}\Omega)} = \frac{4.77}{1 + 4.77} = \mathbf{0.83}$$

which is less than 1, as predicted above.

Without r_d,

$$A_v = \frac{g_m R_S}{1 + g_m R_S} = \frac{(2.28\text{ mS})(2.2\text{ k}\Omega)}{1 + (2.28\text{ mS})(2.2\text{ k}\Omega)}$$
$$= \frac{5.02}{1 + 5.02} = \mathbf{0.83}$$

which shows that r_d usually has little effect on the gain of the configuration.

8 Depletion-Type MOSFETs

The fact that Shockley's equation is also applicable to depletion-type MOSFETs (D-MOSFETs) results in the same equation for gm. In fact, the ac equivalent model for D MOSFETs shown in Fig. 33 is exactly the same as that employed for JFETs, as shown in Fig. 8. The only difference offered by D-MOSFETs is that VGSQ can be positive for n-channel devices and negative for p-channel units. The result is that gm can be greater than gm0, as demonstrated by the example to follow. The range of rd is very similar to that encountered for JFETs.

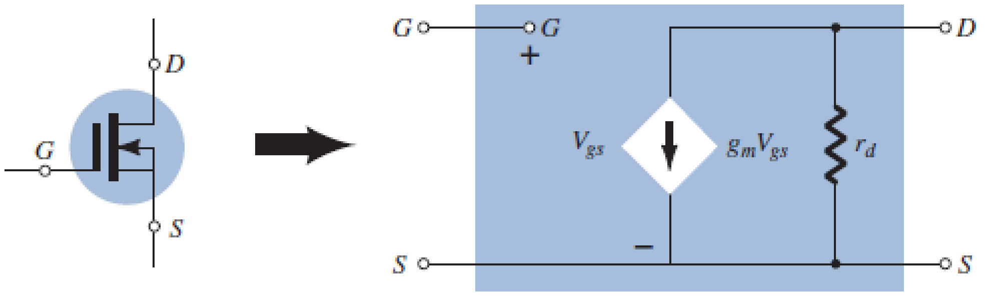


FIG. 33
D-MOSFET ac equivalent model.

EXAMPLE 11 The network of Fig. 34 was analyzed as Example 7, resulting in $V_{GS_Q} = 0.35$ V and $I_{D_Q} = 7.6$ mA.

a. Determine g_m and compare to g_{m0}.
b. Find r_d.
c. Sketch the ac equivalent network for Fig. 34.
d. Find Z_i.
e. Calculate Z_o.
f. Find A_v.

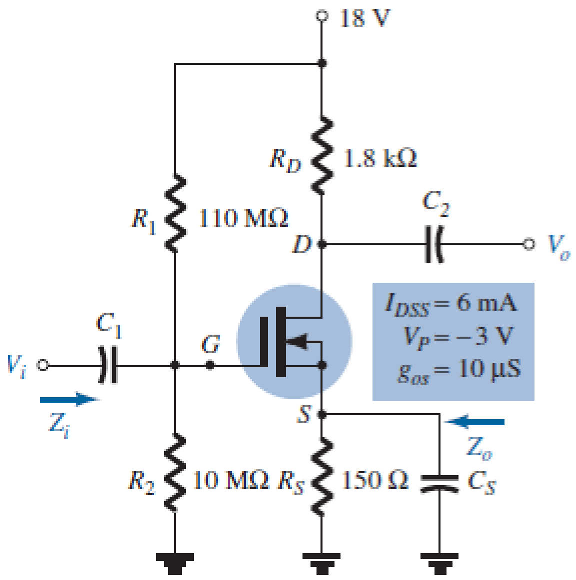


FIG. 34
Network for Example 11.

Solution:

a. $$g_{m0} = \frac{2I_{DSS}}{|V_P|} = \frac{2(6\text{ mA})}{3\text{ V}} = 4\text{ mS}$$

$$g_m = g_{m0}\left(1 - \frac{V_{GS_Q}}{V_P}\right) = 4\text{ mS}\left(1 - \frac{(+0.35\text{ V})}{(-3\text{ V})}\right) = 4\text{ mS}(1 + 0.117) = \mathbf{4.47\text{ mS}}$$

b. $$r_d = \frac{1}{y_{os}} = \frac{1}{10\ \mu\text{S}} = \mathbf{100\text{ k}\Omega}$$

c. See Fig. 35. Note the similarities with the network of Fig. 23. Equations (28) through (32) are therefore applicable.

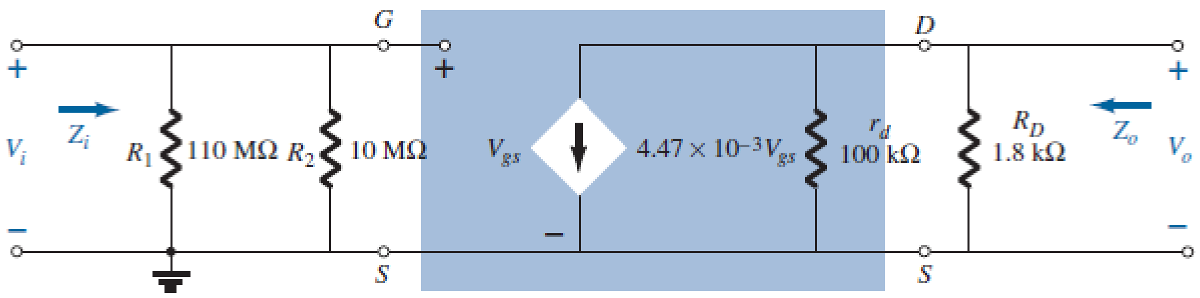


FIG. 35
AC equivalent circuit for Fig. 34.

d. Eq. (28): $Z_i = R_1 \| R_2 = 10\text{ M}\Omega \| 110\text{ M}\Omega = \mathbf{9.17\text{ M}\Omega}$

e. Eq. (29): $Z_o = r_d \| R_D = 100\text{ k}\Omega \| 1.8\text{ k}\Omega = \mathbf{1.77\text{ k}\Omega} \cong R_D = \mathbf{1.8\text{ k}\Omega}$

f. $r_d \geq 10R_D \rightarrow 100\text{ k}\Omega \geq 18\text{ k}\Omega$

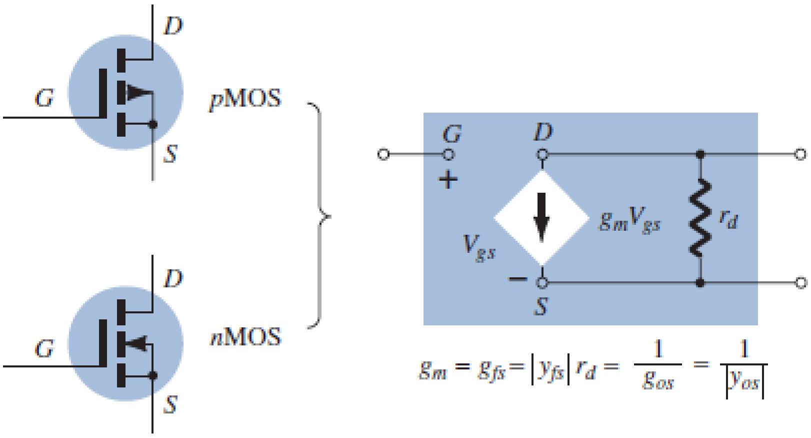
Eq. (32): $A_v = -g_m R_D = -(4.47\text{ mS})(1.8\text{ k}\Omega) = \mathbf{8.05}$

9 Enhancement-Type MOSFETs

The enhancement-type MOSFET (E-MOSFET) can be either an n-channel (nMOS) or p-channel (pMOS) device, as shown in Fig. 36. The ac small-signal equivalent circuit of either device is shown in Fig. 36, revealing an open-circuit between gate and drain source channel and a current source from drain to source having a magnitude dependent on the gateto- source voltage.

There is an output impedance from drain to source rd, which is usually provided on specification sheets as a conductance gos or admittance yos. The device transconductance gm is provided on specification sheets as the forward transfer admittance yfs. In our analysis of JFETs, an equation for gm was derived from Shockley's equation. For E-MOSFETs, the relationship between output current and controlling voltage is defined by

$$I_D = k(V_{GS} - V_{GS(\text{Th})})^2$$



$$g_m = g_{fs} = |y_{fs}| \quad r_d = \frac{1}{g_{os}} = \frac{1}{|y_{os}|}$$

FIG. 36
Enhancement MOSFET ac small-signal model.

$$\boxed{g_m = 2k(V_{GS_Q} - V_{GS(\text{Th})})} \qquad (45)$$

10 E-MOSFET Voltage-Divider Configuration

The last E-MOSFET configuration to be examined in detail is the voltage-divider network of Fig. 41. The format is exactly the same as appearing in a number of earlier discussions. Substituting the ac equivalent network for the E-MOSFET results in the configuration of Fig. 42, which is exactly the same as Fig. 23. The result is that Eqs. (28) through (32) are applicable, as listed below for the E-MOSFET.

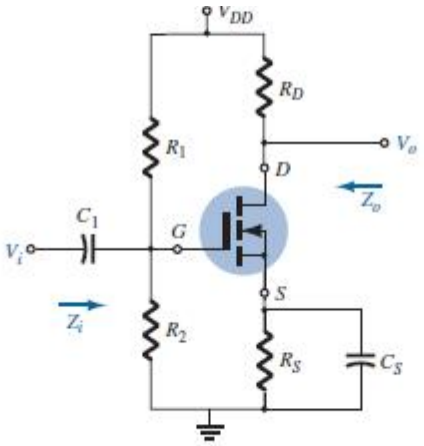


FIG. 41
E-MOSFET voltage-divider configuration.

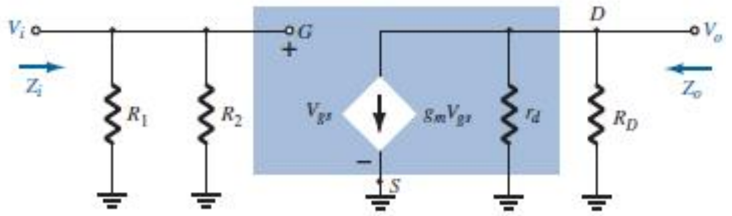


FIG. 42
AC equivalent network for the configuration of Fig. 41.

Z_i

$$\boxed{Z_i = R_1 \| R_2} \tag{52}$$

Z_o

$$\boxed{Z_o = r_d \| R_D} \tag{53}$$

For $r_d \geq 10R_D$,

$$\boxed{Z_o \cong R_d}_{r_d \geq 10R_D} \tag{54}$$

A_v

$$\boxed{A_v = \frac{V_o}{V_i} = -g_m(r_d \| R_D)} \tag{55}$$

and if $r_d \geq 10R_D$,

$$\boxed{A_v = \frac{V_o}{V_i} \cong -g_m R_D} \tag{56}$$