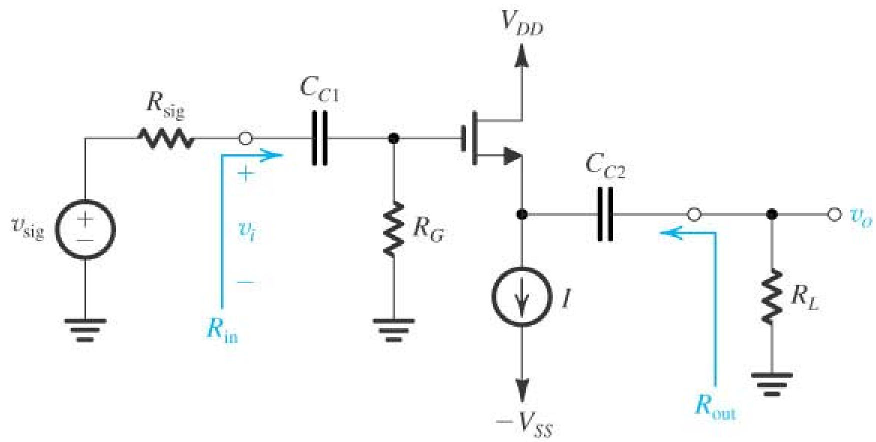
Lecture 36: MOSFET Common Drain (Source Follower) Amplifier.

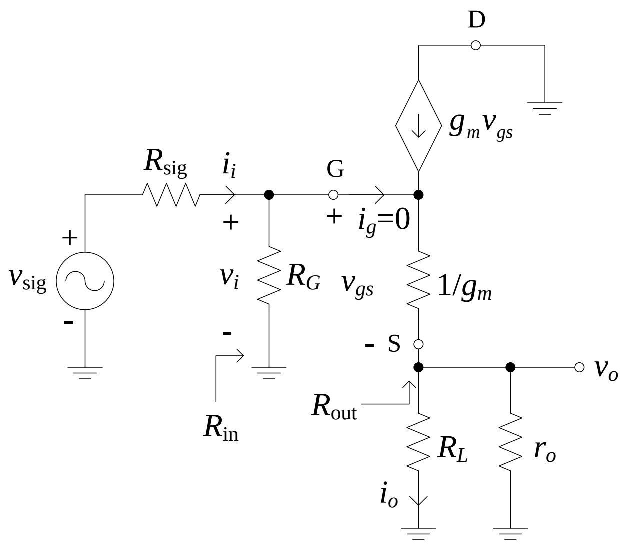
The third, and last, discrete-form MOSFET amplifier we'll consider in this course is the common drain amplifier. This type of amplifier has the input signal fed at the gate – similar to the CS amplifier – but the signal output is taken at the source terminal, as shown in Fig. 1:



(Fig. 1)
(Sedra and Smith, 5th ed.)

Small-Signal Amplifier Characteristics

We'll calculate the following small-signal quantities for this MOSFET common gate amplifier: R_{in}, A_v, A_{vo}, G_v, G_i, A_{is}, and R_{out}. To begin, we construct the small-signal equivalent circuit:



(Fig. 2)

Because the drain terminal is an AC ground, one end of the output resistance r_o was shifted so it appears in parallel with R_L. This makes the T model particularly well suited for the CD amplifier since $R_L \| r_o$ appears in series with $1/g_m$. (Recall that we did the same thing in Lecture 21 for the r_o of the BJT common collector amplifier.)

- Input resistance, R_{in}. With $i_g = 0$, we can see directly from this small-signal equivalent circuit that

$$R_{in} = R_G \tag{1}$$

- Partial small-signal voltage gains, A_v and A_{vo}. At the output side of the small-signal circuit with $i_g = 0$

$$v_o = g_m v_{gs} \left(R_L \| r_o \right) \tag{2}$$

At the input, using voltage division

$$v_{gs} = \frac{1/g_m}{1/g_m + R_L \| r_o} v_i \tag{3}$$

Substituting (3) into (2), gives the partial small-signal AC voltage gain to be

$$A_v \equiv \frac{v_o}{v_i} = \frac{R_L \parallel r_o}{R_L \parallel r_o + 1/g_m} \qquad (7.125),(4)$$

Notice that if $r_o \gg R_L$ and $R_L \gg 1/g_m$ then

$$A_v \lessapprox 1 \qquad (7.126)$$

In the case of an open circuit load ($R_L \to \infty$), the small-signal partial voltage gain becomes

$$A_{vo} \equiv A_v\Big|_{R_L \to \infty} = \frac{r_o}{r_o + 1/g_m} \qquad (5)$$

- <u>Overall small-signal voltage gain, G_v</u>. Using voltage division at the input to the small-signal equivalent circuit

$$v_i = \frac{R_{\text{in}}}{R_{\text{in}} + R_{\text{sig}}} v_{\text{sig}} \qquad (6)$$

Substituting this into

$$G_v \equiv \frac{v_o}{v_{\text{sig}}} = \frac{v_i}{v_{\text{sig}}} \underbrace{\frac{v_o}{v_i}}_{=A_v} = \frac{v_i}{v_{\text{sig}}} A_v \qquad (7)$$

and using (1) and (4) gives the overall small-signal voltage gain of this common drain amplifier to be

$$G_v \equiv \frac{v_o}{v_{\text{sig}}} = \frac{R_G}{R_G + R_{\text{sig}}} \frac{R_L \parallel r_o}{R_L \parallel r_o + 1/g_m} \qquad (8)$$

Again, notice that if $r_o \gg R_L$ and $R_L \gg 1/g_m$, as well as $R_G \gg R_{\text{sig}}$, then

$$G_v \lessapprox 1 \tag{9}$$

Consequently, this common drain amplifier is often called the **source follower amplifier**.

- Overall small-signal current gain, G_i. Applying current division at the output and noting that $i_g = 0$ then

$$i_o = \frac{r_o}{r_o + R_L} g_m v_{gs} \tag{10}$$

while at the input

$$i_i = \frac{v_i}{R_G} \underbrace{=}_{(3)} \frac{1 + g_m \left(R_L \parallel r_o \right)}{R_G} v_{gs} \tag{11}$$

Dividing (10) by (11) gives the overall small-signal AC current gain to be

$$G_i \equiv \frac{i_o}{i_i} = \frac{r_o}{r_o + R_L} \frac{g_m R_G}{1 + g_m \left(R_L \parallel r_o \right)} \tag{12}$$

With a little manipulation, this can be expressed as

$$G_i = \frac{g_m \left(R_L \parallel r_o \right)}{1 + g_m \left(R_L \parallel r_o \right)} \frac{R_G}{R_L} \tag{13}$$

If $r_o \gg R_L$ and $g_m R_L \gg 1$, then

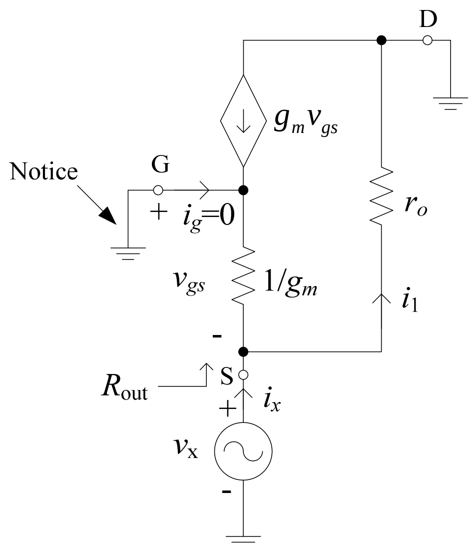
$$G_i \approx \frac{R_G}{R_L} \tag{14}$$

which likely is quite large.

- Short-circuit small-signal current gain, A_{is}. The short circuit small-signal AC current gain can be easily determined from (12) with $R_L = 0$ as

$$A_{is} \equiv G_i\big|_{R_L=0} = g_m R_G \tag{15}$$

- Output resistance, R_{out}. To determine R_{out} from the small-signal circuit above we set $v_{\text{sig}} = 0$ and apply a fictitious AC voltage source v_x at the output as shown:



(Fig. 3)

Notice that the gate terminal has zero voltage because $v_{\text{sig}} = 0$ **and** $i_{\text{sig}} = 0$.

By definition

$$R_{\text{out}} \equiv \frac{v_x}{i_x} \tag{16}$$

We can see that with v_x attached, the voltage v_{gs} will not usually be zero. This means the current in the dependent current source is also not zero.

In such instances, we would normally need to analyze this circuit to find the voltage v_x in terms of i_x, and then apply (16) to determine the output resistance of this amplifier.

However, in this case both terminals of the dependent current source are grounded so it makes no contribution to the output resistance. It's as if the dependent current source can be replaced by a short circuit. So then, by inspection the output resistance is simply

$$R_{\text{out}} = r_o \,\|\, \frac{1}{g_m} \tag{17}$$

Summary and Comparison with the BJT CE Amplifier

In summary, we find for the Common Drain MOSFET small-signal amplifier that it's:

- A non-inverting amplifier.
- Potentially very large input resistance [see (1)].
- Small-signal voltage gain less than one, and potentially close to one [see (8) and (9)].

- Potentially very large small-signal current gain [see (13) and (14)].
- Relatively moderate output resistance [see (17)].

Similar to the BJT common collector (emitter follower) amplifier we discussed in Lecture 21, the common drain (source follower) amplifier finds use in applications that require a unity-gain voltage buffering function. That is, in applications where a voltage signal source has sufficient amplitude, for example, but it has a large internal resistance while the signal needs to be supplied to a "load" with a much smaller resistance.

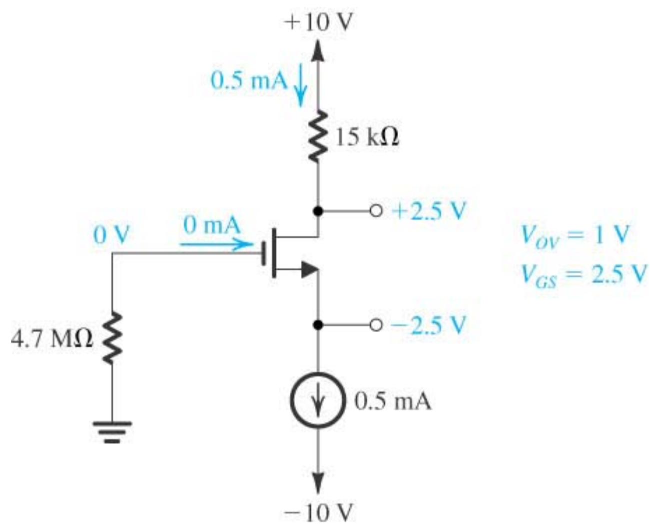
Other applications of voltage buffering amplifiers are:

- The output stage of a multi-stage amplifier chain to provide a low resistance output.
- To separate a filter circuit from a subsequent amplifier circuit that "loads" the filter with a varying impedance load, which will likely adversely affect the filter behavior.

Example N36.1 Use the circuit of Fig. 4 to design a common drain amplifier. Assume $R_{\text{sig}} = 1$ MΩ, $R_L = 15$ kΩ, and $r_o = 150$ kΩ. Compute R_{in}, A_{vo}, A_v, G_v, G_i, and R_{out} both with and without considering r_o.

This is the same DC biasing circuit we used in Example N34.1 for the design of a common gate amplifier. Here we're going to use it as the basis for a common drain amplifier.

The DC analysis results are shown in Fig. 4:

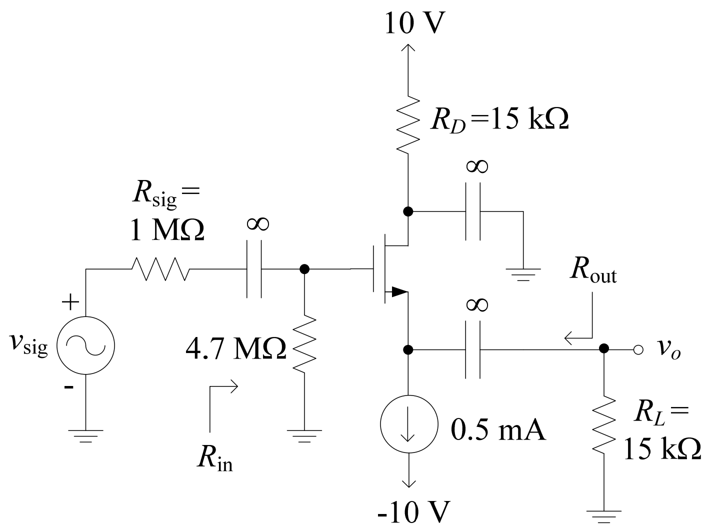


(Fig. 4)
(Sedra and Smith, 5th ed.)

Using (7.42)

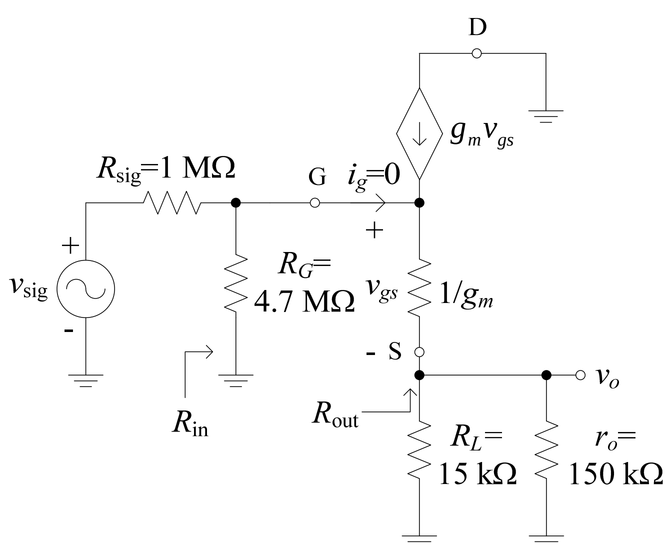
$$g_m = \frac{2I_D}{V_{OV}} = \frac{2 \cdot 0.5 \text{ m}}{2.5 - 1.5} = 1 \text{ mS}$$

Based on this DC biasing, the corresponding common drain amplifier circuit is:



Notice the addition of the bypass capacitor on the drain terminal of the MOSFET. This was added so that R_D will affect only the DC functionality of the circuit. In the AC operation, the drain terminal will be an AC ground, which fits the analysis presented in this lecture.

The small-signal equivalent circuit for this amplifier is then:



- From (1), $R_{in} = R_G = 4.7 \text{ M}\Omega$ (with and without r_o).

- From (17), $R_{\text{out}} = r_o \,\|\, \dfrac{1}{g_m} = 150\text{k} \,\|\, 10^3 = 0.993\ \text{k}\Omega$ (w/ r_o), or
  $R_{\text{out}} = \dfrac{1}{g_m} = 1\ \text{k}\Omega$ (w/o r_o).

- From (5), $A_{vo} = \dfrac{r_o}{r_o + 1/g_m} = \dfrac{150\text{k}}{150\text{k} + 1/10^{-3}} = 0.9993\ \dfrac{\text{V}}{\text{V}}$ (w/ r_o),
  or $A_{vo} = 1\ \dfrac{\text{V}}{\text{V}}$ (w/o r_o).

- From (4), $A_v = \dfrac{R_L \,\|\, r_o}{R_L \,\|\, r_o + 1/g_m} = \dfrac{15\text{k} \,\|\, 150\text{k}}{15\text{k} \,\|\, 150\text{k} + 10^3} = 0.932\ \dfrac{\text{V}}{\text{V}}$
  (w/ r_o), or $A_v = \dfrac{R_L \,\|\, r_o}{R_L \,\|\, r_o + 1/g_m} = \dfrac{15\text{k}}{15\text{k} + 10^3} = 0.938\ \dfrac{\text{V}}{\text{V}}$ (w/o r_o).

- From (8),
  $$G_v = \frac{R_G}{R_G + R_{\text{sig}}} \frac{R_L \,\|\, r_o}{R_L \,\|\, r_o + 1/g_m} = \frac{4.7\text{M}}{4.7\text{M} + 1\text{M}} \frac{15\text{k} \,\|\, 150\text{k}}{15\text{k} \,\|\, 150\text{k} + 10^3}$$
  $= 0.768\ \dfrac{\text{V}}{\text{V}}$ (w/ r_o), or $G_v = \dfrac{R_G}{R_G + R_{\text{sig}}} \dfrac{R_L}{R_L + 1/g_m}$
  $$= \frac{4.7\text{M}}{4.7\text{M} + 1\text{M}} \frac{15\text{k}}{15\text{k} + 10^3} = 0.773\ \frac{\text{V}}{\text{V}}$$ (w/o r_o).

- From (13),

$$G_i = \frac{g_m (R_L \parallel r_o)}{1 + g_m (R_L \parallel r_o)} \frac{R_G}{R_L} = \frac{10^{-3}(15\text{k} \parallel 150\text{k})}{1 + 10^{-3}(15\text{k} \parallel 150\text{k})} \frac{4.7\text{M}}{15\text{k}} = 313.3 \ \frac{\text{A}}{\text{A}}$$

(w/ r_o), or $G_i = \frac{g_m R_L}{1 + g_m R_L} \frac{R_G}{R_L} = \frac{10^{-3} \cdot 15\text{k}}{1 + 10^{-3} \cdot 15\text{k}} \frac{4.7\text{M}}{15\text{k}} = 293.8 \ \frac{\text{A}}{\text{A}}$

(w/o r_o).