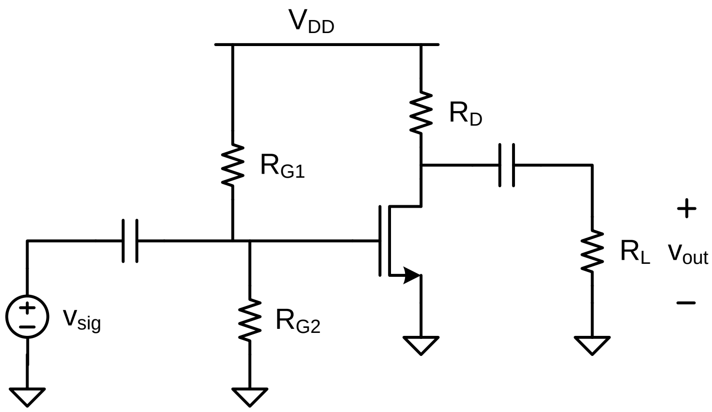
9 Common source amplifier

The common source amplifier uses a single MOSFET and is similar to the common emitter in several ways. The signal input is at the transistor gate and the output at the drain with the source common and often grounded. A typical configuration for this type of amplifier is shown below.



A single power source, V_{DD}, is used here and a voltage divider, R_{G1} and R_{G2}, sets the gate voltage. Because there is no gate current for the MOSFET, this is the simplest way to bias the gate without a second supply voltage. The gate voltage is found directly from the unloaded voltage divider. The drain voltage is set by the drain current and resistor, R_D. The input and output are again capacitively coupled.

The bias condition is determined by assuming saturation mode. (Remember MOSFET amplifiers require saturation mode; BJTs use active mode.) In saturation mode, the drain current depends only on gate voltage in addition to transistor properties.

$$I_D = \mu_n C_{ox} (W / L) \tfrac{1}{2} (V_{GS} - V_{th})^2$$

where μ_n, C_{ox}, W, L, V_{th} are all physical characteristics of the transistor.

We note that it is true that I_D also depends weakly on V_{DS} (recall the sloping characteristic curves in the saturation region) but we will typically ignore that for our approximate DC bias calculations.

For drain voltage, we have

$$V_D = V_{DD} - I_D R_D$$

where we must have

$V_{GS} > V_{th}$ => MOSFET "on"

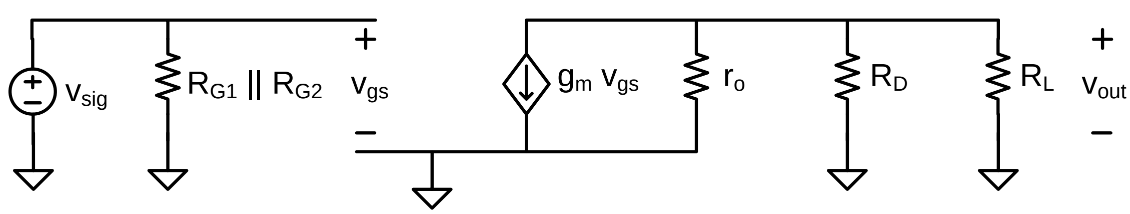
$V_{GD} < V_{th}$ => saturation mode

From the value of drain current follows the small signal model parameters.

$$g_m = 2 I_D / (V_{GS} – V_{th})$$

$$r_o = V_A / I_D$$

The small signal circuit is



The unilateral, linear amplifier model parameters are easily found.

$R_{in} = R_{G1} \,||\, R_{G2}$

$R_{out} = r_o \,||\, R_D$ (R_L removed)

R_{in} can be very large. The voltage divider, R_{G1} and R_{G2}, can use resistances of almost arbitrarily large values. The MOSFET gate takes no current. There is no possibility of loading the voltage divider.

The open circuit voltage gain is (R_L removed)

$$A_v = v_{out} / v_{sig} = -g_m v_{gs} (r_o \| R_D) / v_{sig}$$
$$= -g_m (r_o \| R_D)$$

The transconductance of the amplifier is (output shorted)

$$G_m = i_{sc} / v_{sig} = -g_m v_{gs} / v_{sig}$$
$$= -g_m$$

Then the voltage gain including the load resistance, R_L, for our common source amplifier circuit is

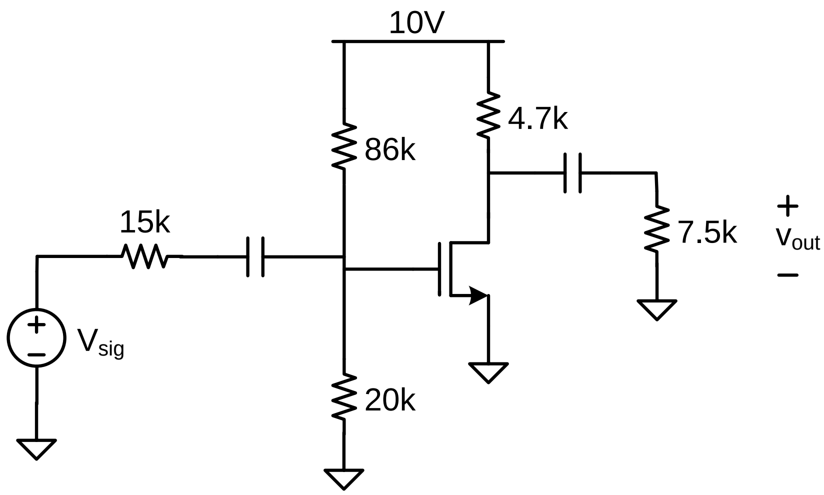
$$A = -g_m (r_o \| R_D) \frac{R_L}{R_{out} + R_L}$$
$$= -g_m (r_o \| R_D) \frac{R_L}{(r_o \| R_D) + R_L}$$
$$= -g_m (r_o \| R_D \| R_L)$$

If we have an input signal resistance, R_{sig}, this is further modified by the voltage divider between R_{sig} and R_{in}. In that case we have $A_{overall}$, given by

$$A_{overall} = -g_m (r_o \| R_D \| R_L) \frac{R_{in}}{R_{sig} + R_{in}}$$

Example 9-1

For this common source amplifier, find the DC bias solution and the AC small signal parameters. Draw the small signal circuit. Then determine the input and output resistance, the open circuit voltage gain and the overall voltage gain. The transistor parameters are $\mu_n C_{ox} = 160\ \mu A/V^2$, $W / L = 18$, $V_{th} = 0.8$ V, and $V_A = 110$ V.



Solution:

We assume saturation mode. For the DC bias solution

$$V_{GS} = V_{DD} [R_{G2} / (R_{G1} + R_{G2})]$$

$$= 10 \text{ V} (20 \text{ k}\Omega / 106 \text{ k}\Omega) = 1.9 \text{ V}$$

$$I_D = \mu_n C_{ox} (W / L) \tfrac{1}{2} (V_{GS} - V_{th})^2$$

$$= 160 \times 10^{-3} \text{ mA/V}^2 \; 18 \bullet \tfrac{1}{2} (1.9 \text{ V} - 0.8 \text{ V})^2 = 1.7 \text{ mA}$$

$$V_D = V_{DD} - I_D R_D = 10 \text{ V} - 1.7 \text{ mA } 4.7 \text{ k}\Omega = 2.0 \text{ V}$$

note $V_D > V_G - V_{th}$ => saturation mode

For the small signal parameters

$$g_m = 2 I_D / (V_{GS} - V_{th})$$

$$= 2 \bullet 1.7 \text{ mA} / (1.9 \text{ V} - 0.8 \text{ V}) = 3.1 \text{ mA/V}$$

$$r_o = V_A / I_D = 110 \text{ V} / 1.7 \text{ mA} = 65 \text{ k}\Omega$$

The linear amplifier model parameters are

$$R_{in} = R_{G1} \,||\, R_{G2} = 86 \text{ k}\Omega \,||\, 20 \text{ k}\Omega = 16 \text{ k}\Omega$$

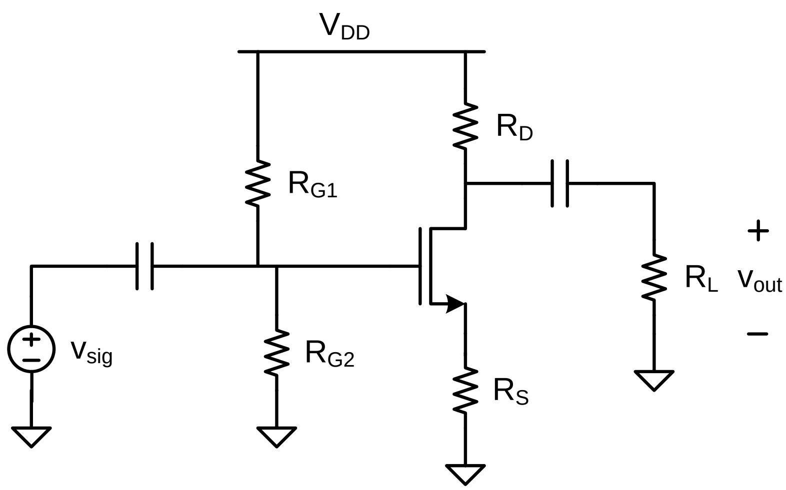
$$R_{out} = R_D \,||\, r_o = 4.7 \text{ k}\Omega \,||\, 65 \text{ k}\Omega = 4.4 \text{ k}\Omega$$

$$A_v = - g_m R_D \,||\, r_o = 3.1 \text{ mA/V } 4.7 \text{ k}\Omega \,||\, 65 \text{ k}\Omega = - 13.6$$

The overall gain is

$$A_{overall} = A_v [R_{in} / (R_{sig} + R_{in})] [R_L / (R_{out} + R_L)]$$
$$= -13.6 (16 \text{ k}\Omega / 31 \text{ k}\Omega) (7.5 \text{ k}\Omega / 11.9 \text{ k}\Omega) = -4.4$$

As with the BJT case, we can include an additional resistor in the common connection to the transistor, the source connection in the MOSFET case. We identify this as a common source amplifier with source degeneration. The saturation mode equation, $I_D = \mu_n C_{ox} (W / L) \frac{1}{2} (V_{GS} - V_{th})^2$ still applies, but now $V_S \neq 0$ and $V_{GS} \neq V_G$.



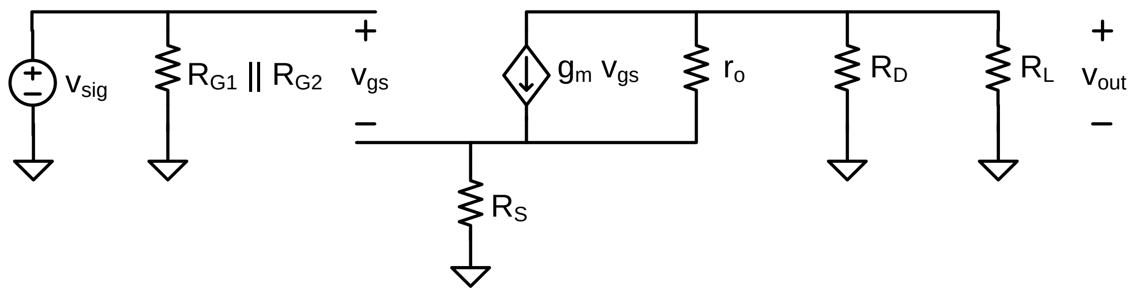
In the BJT case, we found that emitter degeneration increased input resistance and lowered open circuit voltage gain and transconductance. The MOSFET case has some similarities.

We first find the DC bias condition. The drain current and drain voltage are found from these equations.

$$I_D = \mu_n C_{ox} (W / L) \tfrac{1}{2} (V_{GS} - V_{th})^2$$
$$V_S = I_D R_S$$
$$V_G = V_{DD} R_{G2} / (R_{G1} + R_{G2})$$
$$V_D = V_{DD} - I_D R_D$$

With the source resistor, R_S, we now have $V_S > 0$ and $V_{GS} < V_G$. Saturation mode still requires $V_G \geq V_S + V_{th}$ and $V_D > V_G - V_{th}$. We also must now solve a quadratic equation for I_D and V_S. To obtain the solution, V_{GS} is written $V_G - V_S$, and the first two equations above can be combined to form a single equation that is quadratic in I_D or V_S. V_G is obtained directly from the third equation. Generally there are two solutions, only one of which will be consistent with saturation mode and make physical sense. We ignore the other solution. The last of the four equations above must give us $V_D > V_G - V_{th}$ for saturation mode.

The small signal circuit is



If we ignore r_o as we did for the common emitter with emitter degeneration, we can easily find the amplifier parameters.

$$R_{in} = R_{G1} \| R_{G2}$$

$$R_{out} = R_D$$

$$A_v = v_{out} / v_{sig}$$

$$v_{out} = -g_m v_{gs} R_D \quad (R_L \text{ removed})$$

$$v_{sig} = v_{gs} + g_m v_{gs} R_S$$

$$A_v = -g_m v_{gs} R_D / (v_{gs} + g_m v_{gs} R_S)$$

$$= -g_m R_D / (1 + g_m R_S)$$

$$G_m = i_{sc} / v_{sig}$$

$$= -g_m v_{gs} / (v_{gs} + g_m v_{gs} R_S)$$

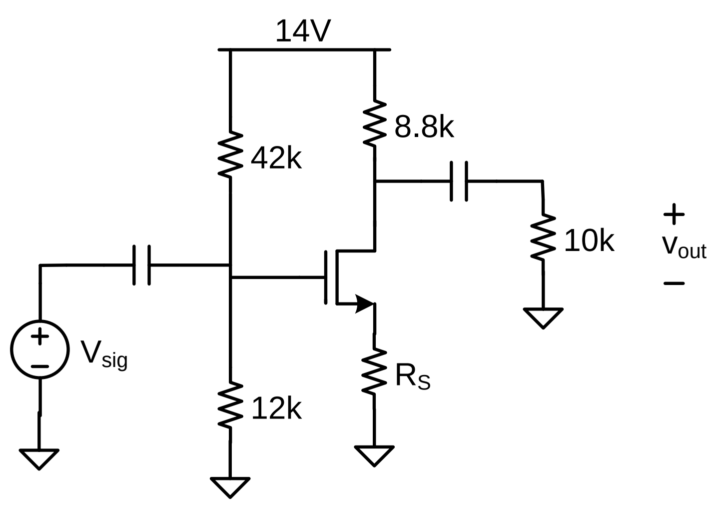
$$= -g_m / (1 + g_m R_S)$$

So the open circuit voltage gain and the transconductance are reduced by the factor $(1 + g_m R_S)$ like the common emitter with emitter degeneration, but the input resistance and output resistance are essentially unchanged.

The advantage of emitter degeneration for BJTs is largely absent for the MOSFET case. Input resistance can be large without degeneration. Emitter degeneration does make gate biasing more robust when threshold voltage is not well controlled, but the loss of transconductance can be serious. MOSFET amplifiers often start with a considerably lower transconductance than their BJT counterpart.

Example 9-2

This common source amplifier with source degeneration uses a transistor with $\mu_n C_{ox}$ = 140 μA/V^2, W / L = 6, V_{th} = 1.2 V, and V_A = 90 V. For R_S = 0 (no source degeneration), show that the transistor is not in saturation mode. Then for R_S = 500 Ω, find I_D, confirm saturation mode, and determine the overall voltage gain.



Solution:

For R_S = 0, we have

$$V_G = V_{DD} [R_{G2} / (R_{G1} + R_{G2})] = V_{GS} \qquad (V_S = 0)$$

$$= 14 \text{ V} (12 \text{ k}\Omega / 54 \text{ k}\Omega) = 3.1 \text{ V}$$

$$I_D = \mu_n C_{ox} (W / L) ½ (V_{GS} – V_{th})^2 \quad \text{(assuming saturation mode)}$$
$$= 140 \times 10^{–3} \text{ mA/V}^2\ 6 \bullet ½ (3.1 \text{ V} – 1.2 \text{ V})^2 = 1.5 \text{ mA}$$
$$V_D = V_{DD} – I_D R_D = 14 \text{ V} – 1.5 \text{ mA } 8.8 \text{ k}\Omega = 0.8 \text{ V}$$

This result, I_D = 1.5 mA and V_D = 0.8 V, is not saturation mode since

$$V_D = 0.8 \text{ V} < V_G – V_{th} = 3.1 \text{ V} – 1.2 \text{ V} = 1.9 \text{ V}$$

To find the drain current and drain voltage we would need to calculate using the expression for I_D in linear mode.

Now with R_S = 500 Ω

$$V_G = 3.1 \text{ V}$$
$$I_D = \mu_n C_{ox} (W / L) ½ (V_{GS} – V_{th})^2 \quad \text{(assuming saturation mode)}$$
$$= \mu_n C_{ox} (W / L) ½ (V_G – V_S – V_{th})^2$$
$$V_S = I_D R_S$$

Combining these last two equations,

$$I_D = \mu_n C_{ox} (W / L) ½ (V_G – I_D R_S – V_{th})^2$$

Expanding and rearranging,

$$0 = R_S^2 I_D^2 – \{ 2 (V_G – V_{th}) R_S + 1 / [\mu_n C_{ox} (W / L) ½] \} I_D + (V_G – V_{th})^2$$
$$= 0.25 \text{ V}^2/\text{mA}^2\ I_D^2 – 4.28 \text{ V}^2/\text{mA}\ I_D + 3.6 \text{ V}^2$$

Solving,

$$I_D = 16.2 \text{ mA or } 0.89 \text{ mA}$$

For the first solution,

$$V_S = I_D R_S = 8.1 \text{ V}$$
$$V_{GS} = 3.1 \text{ V} – 8.1 \text{ V} < 0, \quad \text{(cutoff, no transistor current)}$$

For the second solution, we get

$$V_S = I_D R_S = 0.45 \text{ V}$$

$$V_{GS} = 3.1 \text{ V} - 0.45 \text{ V} = 2.65 \text{ V} > V_{th}$$

$$V_D = V_{DD} - I_D R_D = 6.2 \text{ V} > V_G - V_{th} = 1.9 \text{ V}$$

So we have saturation mode.

tThe small signal parameters are

$$g_m = 2 I_D / (V_{GS} - V_{th})$$
$$= 2 \bullet 0.89 \text{ mA} / (2.7 \text{ V} - 1.2 \text{ V}) = 1.2 \text{ mA/V}$$

$$r_o = V_A / I_D = 90 \text{ V} / 0.89 \text{ mA} = 100 \text{ k}\Omega$$

The overall gain is

$$A_{overall} = - g_m \; R_D \,||\, r_o \,||\, R_L$$
$$= - 1.2 \; (8.8 \text{ k}\Omega \,||\, 100 \text{ k}\Omega \,||\, 10 \text{ k}\Omega) = - 5.4$$
