Review of MOSFET

Example of MOSFET Circuit

1. Review of MOSFET

\[ K = 0.2 \text{mA/V}^2, \quad V_T = 1V, \quad V_{out} = ? \]

Step 1: Use KCL, KVL, device law to express input, output with equations.

\[ I_D = \frac{K}{2} (V_{GS} - V_T)^2 \quad (\text{assume } V_{GS} > V_T, \quad V_{DS} > V_{GS} - V_T, \text{ need to conform}) \]

\[ I_D = \frac{V_K}{R} = \frac{V_S - V_{out}}{R} \quad (\text{a}) \]

Known parameters: \( K, R, V_{GS}, V_{IN}, V_T \), unknown: \( I_D, V_{out} \)

Step 2: Large Signal Analysis.

The reason to do large + small signal Analysis.

Non-linear equations: \( y = x^2 \), \( x_1 \Rightarrow y_1 = x_1^2 \), \( x_1 + x_2 \Rightarrow y_2 = (x_1 + x_2)^2 \), \( x_1 \times x_2 \Rightarrow y = x_1 \times x_2 \)
In general, cannot do superposition. However, if we can separate input to large and small signals.

\[ x = x_0 + \delta x, \Rightarrow y = y_0 + \delta y, \quad \delta y = \frac{dy}{dx} x_0 \delta x, \] ("superposition")

\[
\begin{align*}
I_D &= \frac{K}{2} (V_{GS} - V_T)^2 
\Rightarrow I_D &= \frac{0.25mA}{V^2} \times (2.5V - 1V)^2 = 0.035\,mA \\
I_D &= \frac{V_S - V_{out}}{R} 
\Rightarrow V_{out} &= V_S - I_D \times R = 5V - \frac{0.035}{10k\Omega} \times 10k\Omega \\
&= 2.75V. \text{ (> 1V, saturation)}
\end{align*}
\]

or graphically:

- Step 3: Small signal analysis.
  - Analytically, \( V_{out} = V_{out} + V_{out} \).
    \[ V_{out} = \frac{dV_{out}}{dV_{in}} \cdot V_{in} \] (recall, \( \delta y = \frac{dy}{dx} x_0 \delta x \)).

From Eq. 0, \( \frac{dI_D}{dV_{in}} = K (V_{in} - V_T) \).

From Eq. 2, \( \frac{dV_{out}}{dI_D} = -R \).

\[ V_{out} = \frac{0.25mA}{V^2} \times 2.75V \times 1V \times \frac{1}{10k\Omega} \times 10k\Omega \times V_{in} \]

\[ V_{in} = -K (V_{in} - V_T) \cdot R \cdot V_{in}^2. \]
1. With small signal circuit.

\[ V_{in} = V_{in} + V_{in}, \]
\[ V_{out} = V_{out} + V_{out}, \]
\[ I_{d} = I_{d} + I_{d}, \]

The large signal part, \( V_{in}, V_{out}, V_{s}, I_{d} \) are already satisfied in Step 2.

Only keep small signal:

\[ V_{out} = -I_{d} \cdot R = -g_{m} R V_{in}. \]

\[ zmA = -K(V_{in} - V_{f}) R V_{in} \]
\[ = -0.2 mA / V^2 \times (2.75V - 1V) / 10k \Omega x 10mV \]
\[ = 35mV. \]
AC gain: 3.5

2. Example 2:

AC gain (assume MOSFET in saturation)

\[ \frac{V_{out}}{V_{in}} = ? \]
@ KCL, KVL, \[ \frac{V_o}{R} = \frac{K}{2} \left( V_{GS} - V_T \right)^2 = \frac{K}{2} (V_{IN} - V_{OUT} - V_T)^2 \quad \text{①} \]

\[ \left( V_{GS} \neq V_{IN} \right) \]

\[ \frac{V_o}{R} = \frac{V_{OUT}}{R} \quad \text{②} \]

③ Large Signal Analysis: combine ① and ②

\[ \frac{V_{OUT}}{R} = \frac{K}{2} (V_{IN} - V_{OUT} - V_T) \quad \text{③} \quad V_{OUT} = \]

⑤ Small Signal Analysis:

\[ V_{OUT} = \frac{dV_{OUT}}{dV_{IN}} \cdot V_{IN} \quad \text{⑤} \quad \frac{dV_{OUT}}{dV_{IN}} \quad \text{can be calculated by doing derivative on both sides of ③.} \]

Or, small signal circuit:

[Diagram of small signal circuit]

id: VCCS, controlled by Vgs.

Remove large signal part:

[Diagram showing removal of large signal component]
\[ g_m = \frac{dc}{dV_{GS}} = K(V_{GS} - V_t) = K(V_{IN} - V_{OUT} - V_t) \quad (V_{OUT} \text{ from Step 2}) \]

\[ V_{OUT} = g_m V_{GS} \cdot R \Rightarrow \]

\[ V_{GS} \ll \Rightarrow \quad V_{IN} = V_{GS} + V_{OUT}, \quad \Rightarrow \quad \frac{V_{OUT}}{V_{IN}} = \frac{g_m R}{1 + g_m R} \rightarrow 1 \]

Gain always smaller than 1, voltage follower (source follower)

Use to isolate different stages in a circuit (output stage of op-amp)

Output port: \[ R_{OUT} \approx \frac{1}{g_m} \] can be very small \( \Rightarrow \) close to ideal VS