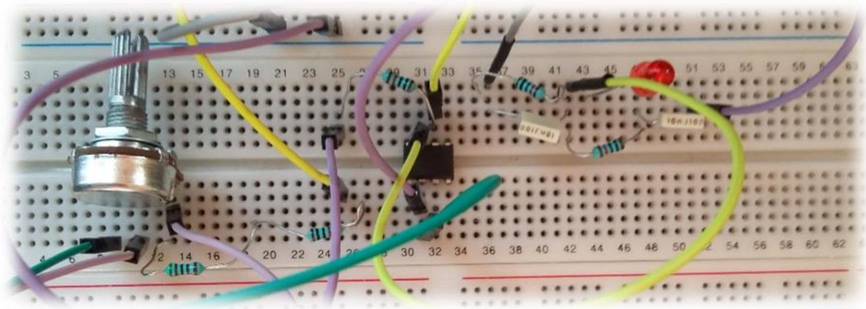


FUNDAMENTAL ELECTRONIC CIRCUITS

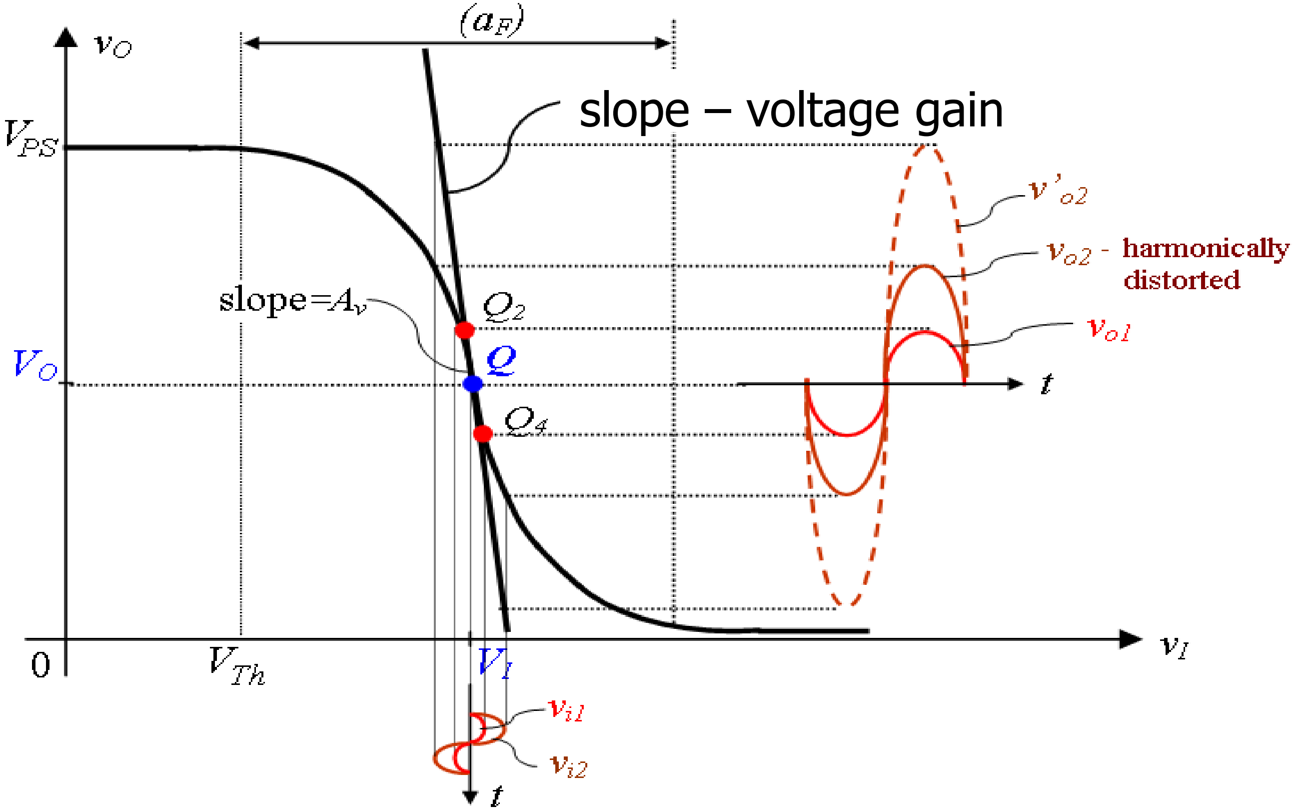
Assist. prof. Laura-Nicoleta IVANCIU, Ph.D.

C3 – MOSFET basic amplifiers

Contents

- MOSFET small-signal model
- MOSFET basic amplifiers

➢ Small-signal motivation - revisited

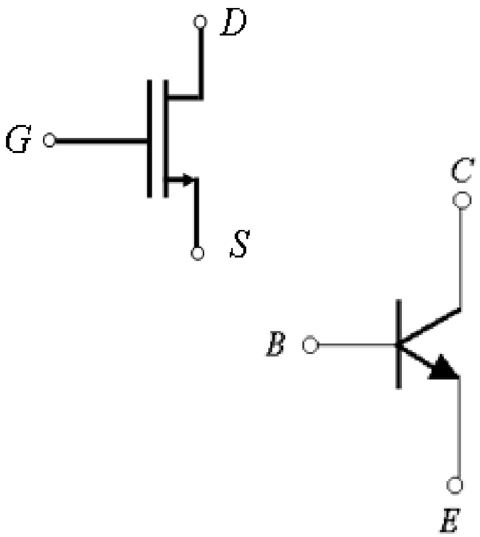


Small-signal model (linear model)
needed to compute

Voltage gain: $A_v = \frac{v_o}{v_i}$

Small-signal model is valid in the **narrow linear region around *Q***.

Small-signal operation - intro



small-signal →

Some components

Some connections

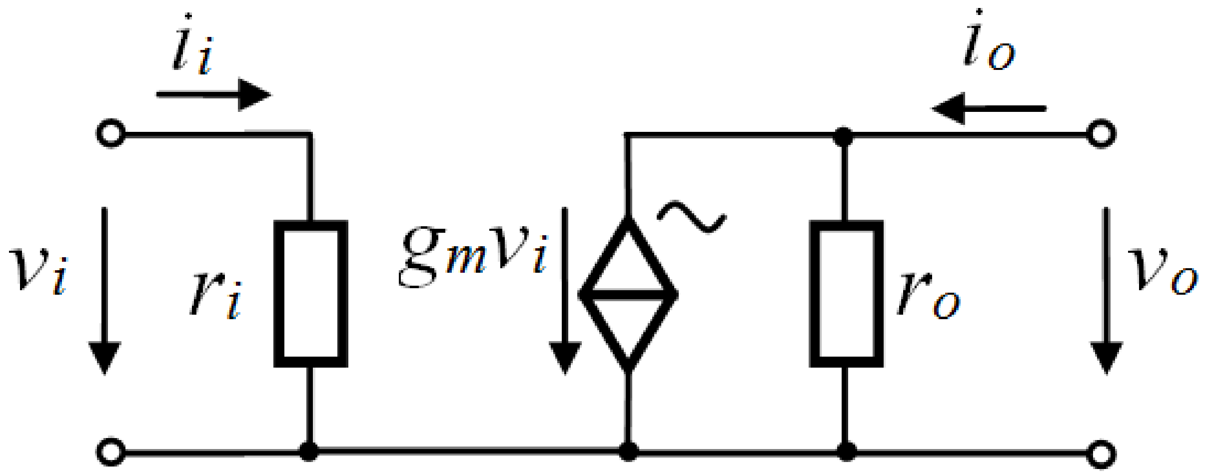
Some parameters

small-signal model of T

Hints:

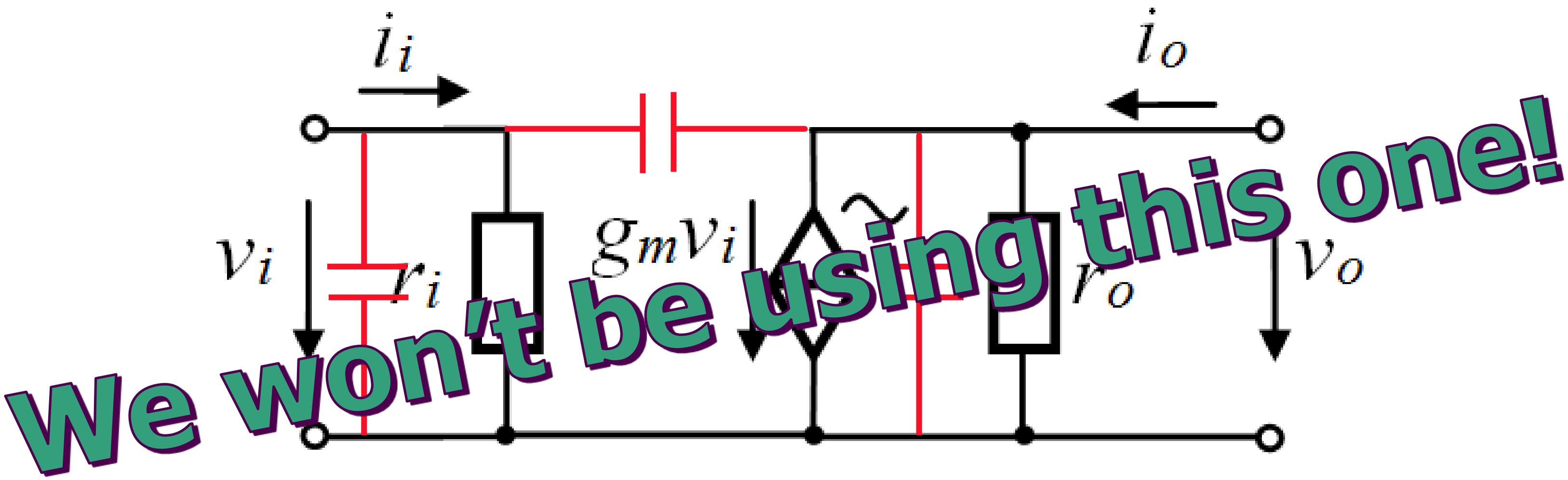
- keep names of terminals
- use voltage-controlled current source
- values of parameters are computed in $Q\,(V_{DS};\ I_D)$ or $Q\,(V_{CE};\ I_C)$

➢ Small-signal model – low & medium frequency



- **two-port network**
  - ✓ input resistance: r_i
  - ✓ transfer: voltage-controlled current source: $g_m v_i$
  - ✓ output resistance: r_o

➢ Small-signal model – high frequency

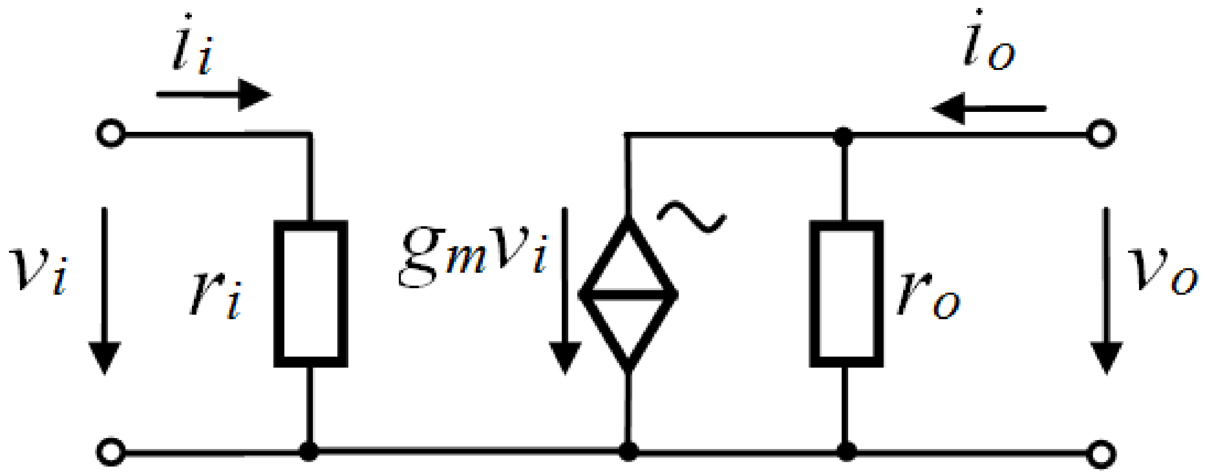


- **two-port network**
  - ✓ r_i
  - ✓ $g_m v_i$
  - ✓ r_o

+ parasitic capacitances between terminals

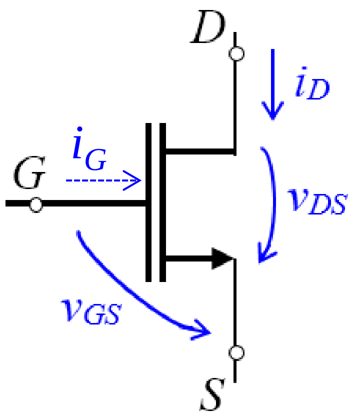
MOSFET small-signal model

- Small-signal model – low & medium frequency



Custom model for MOSFET?

- ✓ $r_i = ?$
- ✓ $g_m = ?, v_i = ?$
- ✓ $r_o = ?$



➢ Small-signal parameters

Input resistance r_i

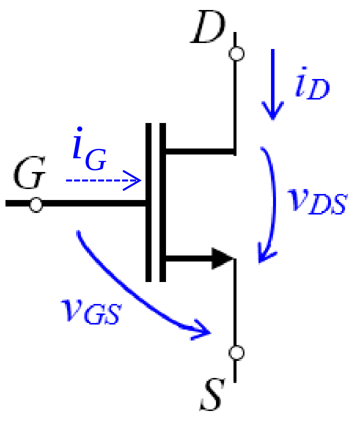
$$r_i = r_{gs} = \left.\frac{\partial v_{GS}}{\partial i_G}\right|_{v_{DS}=cst} = \left.\frac{v_{gs}}{i_g}\right|_{v_{DS}=cst}$$

$\frac{\partial v_{GS}}{\partial i_G}$ - derivative of v_{GS} with respect to i_G

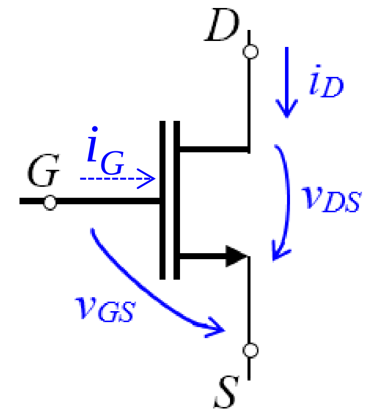
the gate is electrically insulated from the rest of structure: $i_G = 0$

the input resistance is infinite (open-circuit)

$$r_{gs} = \infty$$



MOSFET small-signal model



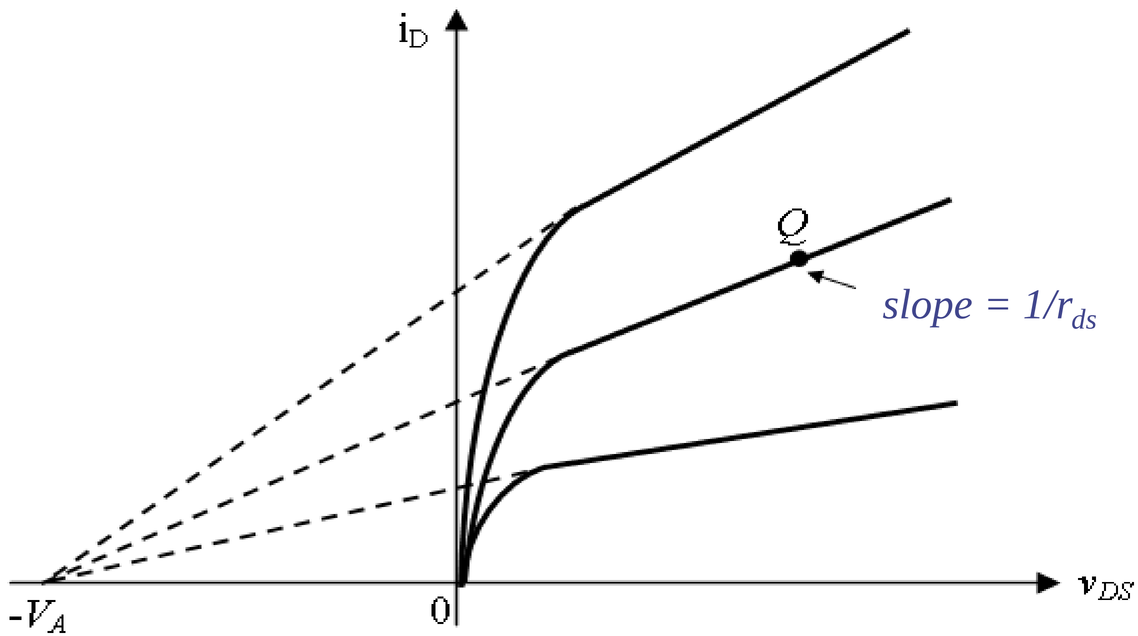
➢ Small-signal parameters

Output resistance r_o

$$r_o = r_{ds} = \frac{1}{g_o} = \left.\frac{\partial v_{DS}}{\partial i_D}\right|_{v_{GS}\,=\,cst} = \left.\frac{v_{ds}}{i_d}\right|_{v_{GS}\,=\,cst}$$

$\frac{\partial v_{DS}}{\partial i_D}$ - derivative of v_{DS} with respect to i_D

$$r_{ds} = \frac{V_A}{I_D}$$



$$i_D = \beta(v_{GS} - V_{Th})^2\left(1 + \frac{v_{DS}}{V_A}\right)$$

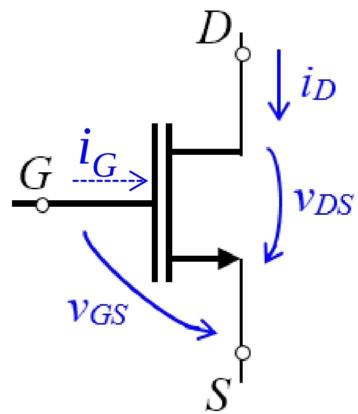
V_A – Early voltage

V_A = 100 V for n-channel MOSFET

V_A = 50 V for p-channel MOSFET

$V_A = \frac{1}{\lambda}$, λ – channel length modulation factor [V^{-1}]

MOSFET small-signal model



➢ Small-signal parameters

Transconductance g_m

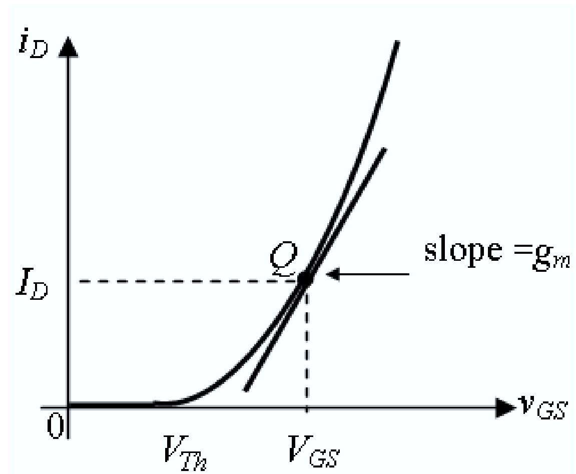
- shows the transfer from variable input voltage v_{GS} to variable output current i_D

$$g_m = \left.\frac{\partial i_D}{\partial v_{GS}}\right|_{v_{DS} = cst} = \left.\frac{i_d}{v_{gs}}\right|_{v_{DS} = cst}$$

$$i_D = \beta(v_{GS} - V_{Th})^2$$

$$i_D = \frac{K}{2}\frac{W}{L}(v_{GS} - V_{Th})^2$$ - integrated transistors

$$g_m = \frac{\partial(\beta(v_{GS} - V_{Th})^2}{\partial v_{GS}} = 2\beta(V_{GS} - V_{Th})$$



$$g_m = 2\beta(V_{GS} - V_{Th}) = \frac{2I_D}{V_{GS} - V_{Th}} = 2\sqrt{\beta I_D}$$

integrated transistors: $$g_m = 2\sqrt{\frac{K}{2}\frac{W}{L}I_D}$$

MOSFET: voltage-controlled current source for small signal $$i_d = g_m v_{gs}$$

Small-signal model & parameters - summary

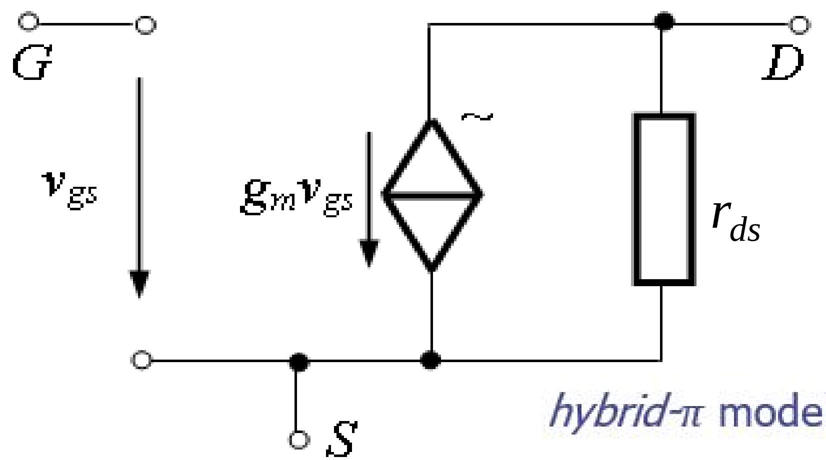
$$r_i = r_{gs} = \infty$$

$$g_m = 2\beta(V_{GS} - V_{Th}) = 2\sqrt{\beta I_D}$$

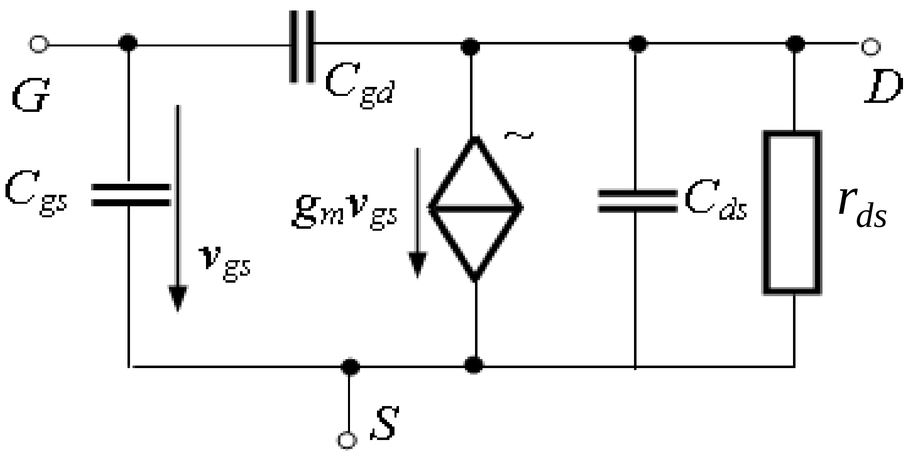
$$g_m = 2\sqrt{\frac{K}{2}\frac{W}{L}I_D}$$

$$r_o = r_{ds} = \frac{V_A}{I_D}$$

$$i_d = g_m v_{gs} = 2\beta(V_{GS} - V_{Th})v_{gs}$$



Small-signal model, low & medium frequency



Small-signal model, high frequency

Parasitic capacitances (pF or less) between terminals

➢ Small-signal model & parameters - examples

Ex. 1 $\beta = 2\ \mathrm{mA/V^2},\ V_A = 100\ \mathrm{V};\ I_D = 2\ \mathrm{mA}$

$$g_m = 2\sqrt{\beta I_D} = 2\sqrt{2 \cdot 2} = 4\ \mathrm{mS} \qquad r_{ds} = \frac{V_A}{I_D} = \frac{100}{2} = 50\ \mathrm{K\Omega}$$

Ex. 2 $\beta = 2\ \mathrm{mA/V^2},\ V_{Th} = 1.5\ \mathrm{V},\ V_A = 100\ \mathrm{V};\ V_{GS} = 2.5\ \mathrm{V}$

$$g_m = 2\beta(V_{GS} - V_{Th}) = 2 \cdot 2(2.5 - 1.5) = 4\ \mathrm{mS}$$

$$I_D = \beta(V_{GS} - V_{Th})^2 = 2(2.5 - 1.5)^2 = 2\ \mathrm{mA} \qquad r_{ds} = \frac{V_A}{I_D} = \frac{100}{2} = 50\ \mathrm{K\Omega}$$

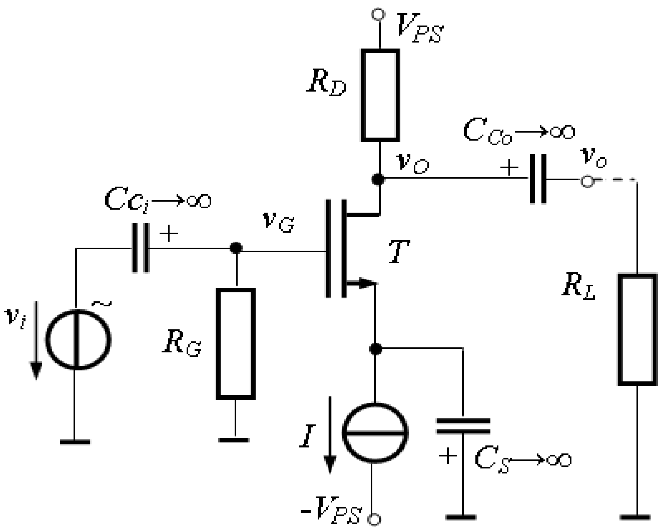
Ex. 3 $K = 100\ \mathrm{\mu A/V^2},\ W/L = 1,\ V_A = 100\ \mathrm{V};\ I_D = 100\ \mathrm{\mu A}$

$$g_m = \sqrt{2K}\sqrt{\frac{W}{L}}\sqrt{I_D} = \sqrt{2 \cdot 100} \cdot \sqrt{1} \cdot \sqrt{100} = 0.14\ \mathrm{mS}$$

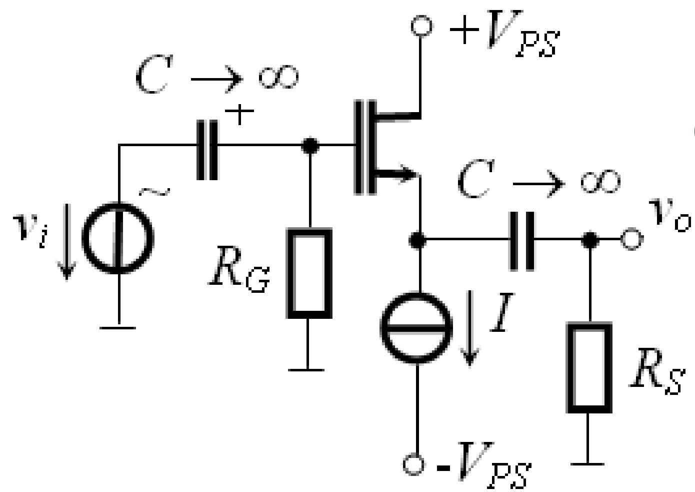
$$r_{ds} = \frac{V_A}{I_D} = \frac{100}{0.1} = 1\ \mathrm{M\Omega}$$

MOSFET basic amplifiers

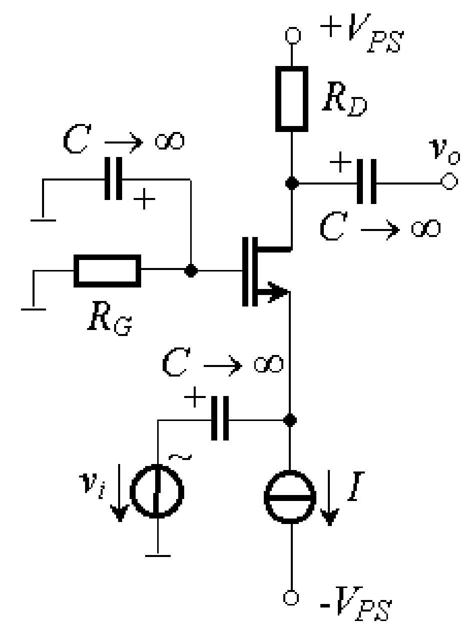
➢ Configurations



Common source (CS)



Common drain (CD)



Common gate (CG)

Where do the names of the configurations come from?

Why are the capacitors necessary?

How are the circuits analyzed?

➢ Configurations

- Where do the names of the configurations come from?

The terminal that is connected to ground in the small-signal equivalent schematic gives the name of the configuration.

- Why are the capacitors necessary?

Capacitors separate the variable signals from the dc ones (at the input, output, or in other points of the circuit).

The capacitances need to be high enough so that they can be considered short circuits at the operating frequency (their equivalent impedance << the series/parallel resistances connected with them).

On the dc equivalent schematic (the one used to determine the operating point *Q*), the capacitors are considered open circuits.

- How are the circuits analyzed?

See next slide(s)

➢ Transistor amplifier analysis - steps

Start with full amplifier circuit (transistor, resistors, capacitors, dc sources, ac sources)

1. Draw dc equivalent circuit
    - compute the operating point $Q(V_{DS}; I_D)$
    - determine dc potentials in the three terminals of the transistor
    - compute small-signal parameters of the transistor: g_m, r_{ds}

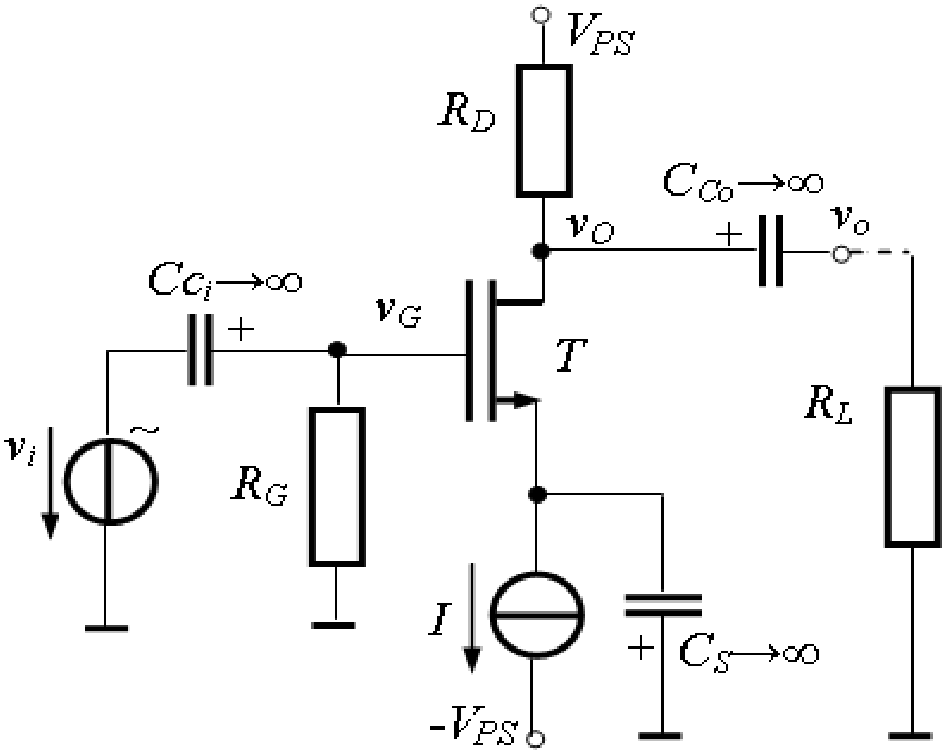
C – open-circuit

2. Draw small-signal equivalent circuit
    - compute amplifier performance: gain A_v, input resistance R_i, output resistance R_o

C – short-circuit
dc sources - passive

3. Plot waveforms in various points of the amplifier
    - small-signal waveforms
    - full waveforms (dc + small-signal)

➢ Common source (CS) basic amplifier



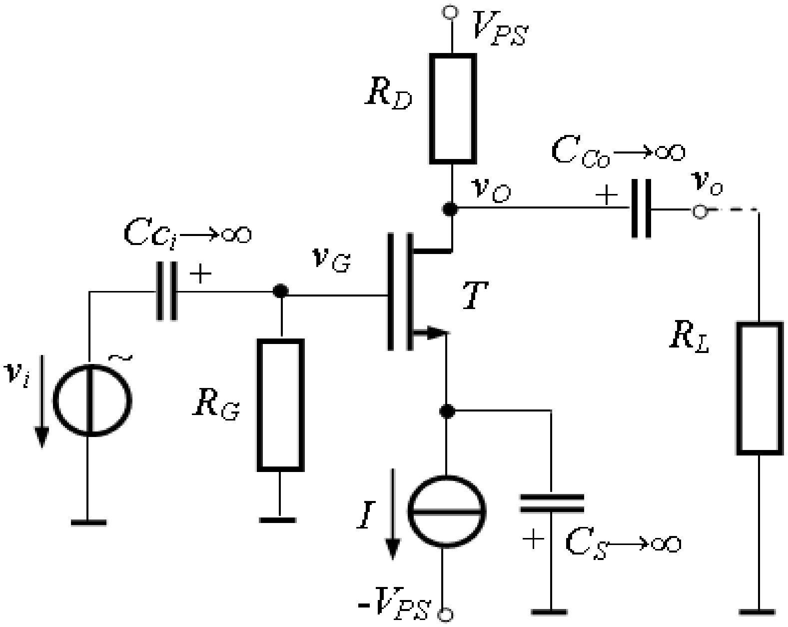
1. Draw dc equivalent circuit
   - compute the operating point $Q\,(V_{DS};\ I_D)$
   - determine dc potentials in the three terminals of the transistor
   - compute small-signal parameters of the transistor: g_m, r_{ds}

See Seminar 1 and C2

$$g_m = 2\sqrt{\beta I_D}$$

$$r_{ds} = \frac{V_A}{I_D}$$

➢ Common source (CS) basic amplifier

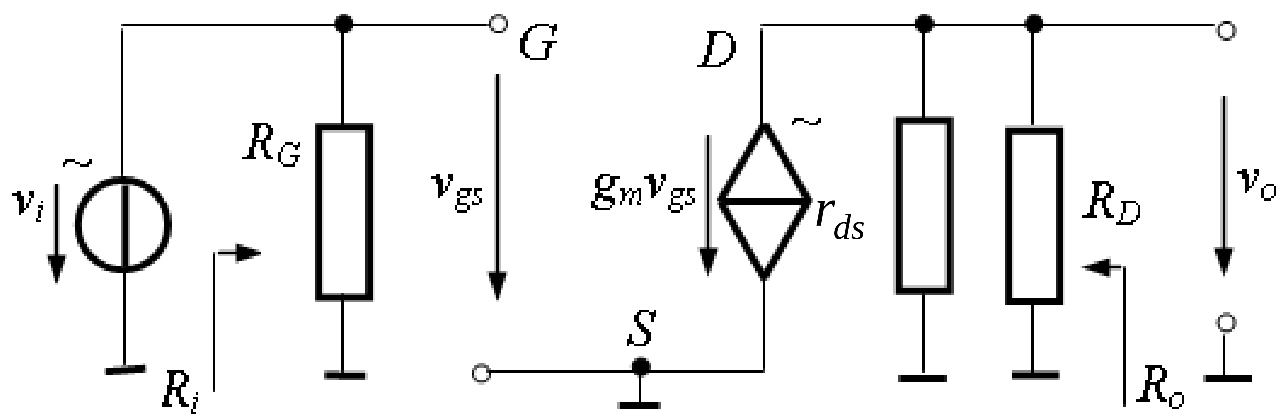


2. Draw small-signal equivalent circuit
   - compute amplifier performance:

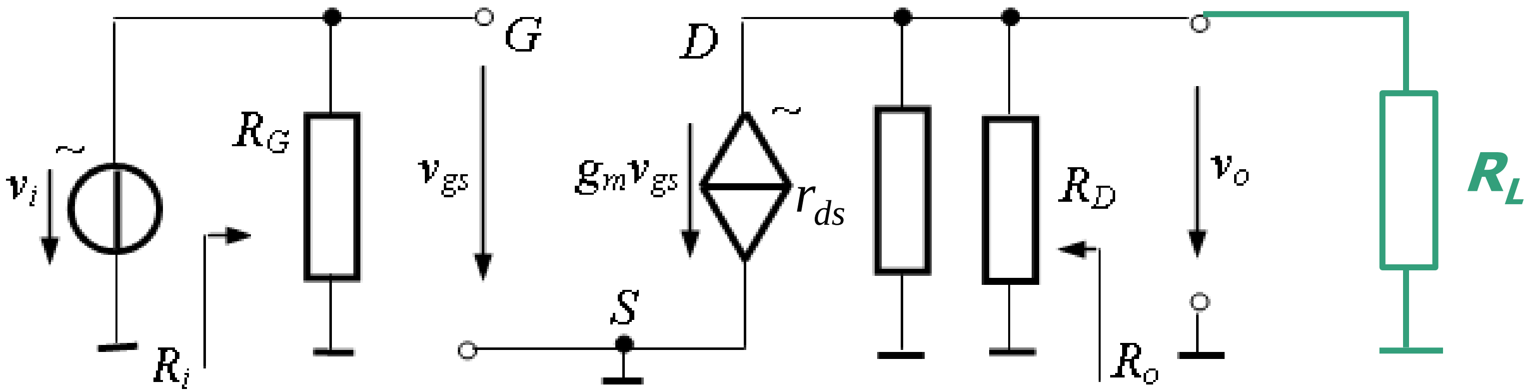
     gain A_v

     input resistance R_i

     output resistance R_o



➢ Common source (CS) basic amplifier



$$R_i = R_G$$

Usually, $R_D \ll r_{ds}$, so $A_v \approx -g_m R_D$

$$R_o = R_D || r_{ds} \approx R_D$$

$$A_v = \frac{v_o}{v_i}$$

$$v_i = v_{gs}$$

$A_v < 0$ – inverting amplifier

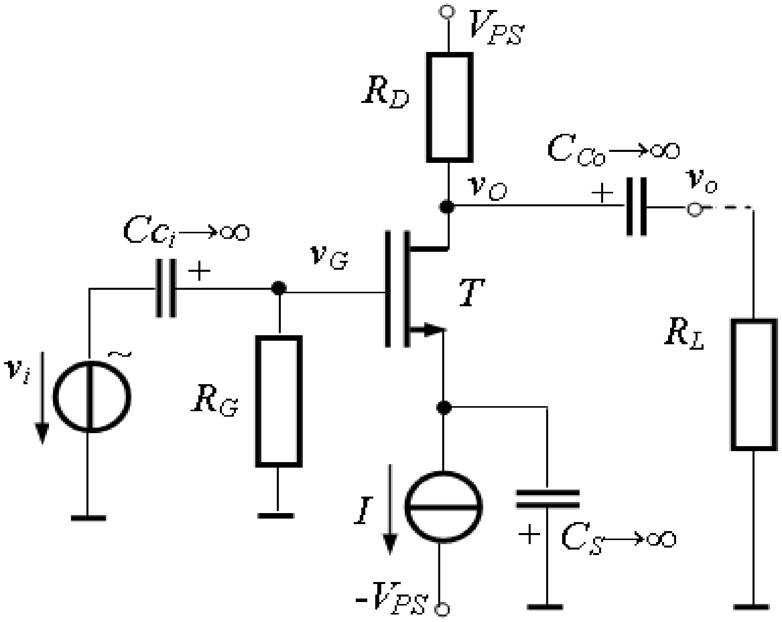
$$v_o = -g_m v_{gs}(R_D || r_{ds})$$

If R_L is present:

$$A_v = -g_m(R_D || r_{ds} || \boldsymbol{R_L})$$
$$A_v \approx -g_m(R_D || \boldsymbol{R_L})$$

$$A_v = -g_m(R_D || r_{ds})$$

➢ Common source (CS) basic amplifier - example



R_G = 1 MΩ; R_D = 50 KΩ;

I = 0.1 mA; V_{PS} = 12 V

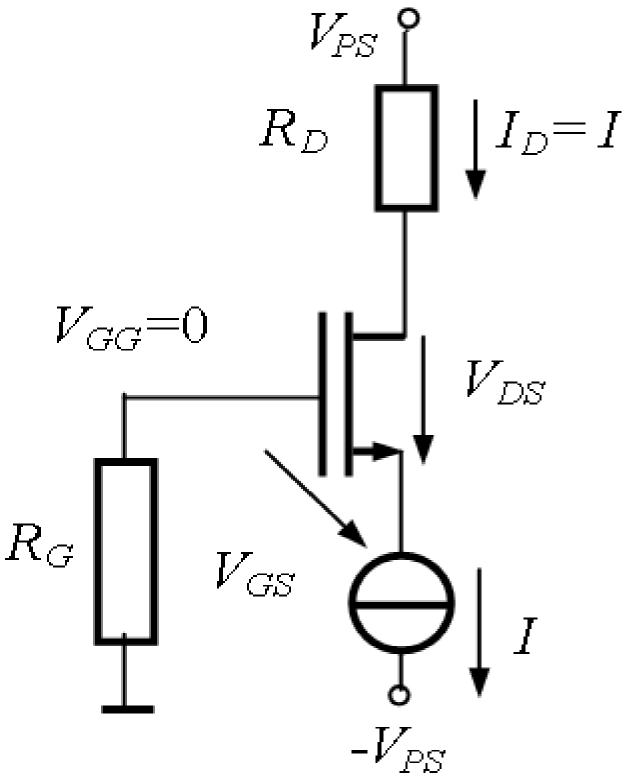
K = 0.1 mA/V^2, W/L = 2, V_{Th} = 0.6 V

V_A = 100 V

a) Draw the dc equivalent circuit.
b) Determine $Q(V_{DS}, I_D)$.
c) Compute the small-signal parameters of the transistor, g_m and r_{ds}.
d) Draw the small-signal equivalent circuit. What is the configuration of the stage? Justify.
e) Compute the gain, input and output resistances.
f) For $v_i(t)$ - triangular wave, 50 mV amplitude, plot $v_G(t)$, $v_o(t)$, $v_O(t)$, $v_S(t)$.

➢ Common source (CS) basic amplifier - example

a) Draw the dc equivalent circuit.
b) Determine $Q(V_{DS}, I_D)$.
c) Compute g_m and r_{ds}.



$$I_D = I = 0.1\ \text{mA} \qquad V_{GG} = 0\text{V}$$

$$V_{PS} = R_D I_D + V_{DS} - V_{GS} + V_{GG}$$
$$V_{DS} = V_{PS} - R_D I_D + V_{GS} - V_{GG}$$

$$I_D = \frac{k}{2}\frac{W}{L}(V_{GS} - V_{Th})^2$$

$$V_{GS} = V_{Th} + \sqrt{\frac{I_D}{\frac{k}{2}\frac{W}{L}}} = 0.6 + \sqrt{\frac{0.1}{\frac{0.1}{2}\cdot 2}} = 1.6\ \text{V}$$

$$V_{DS} = 12 - 50 \cdot 0.1 + 1.6 - 0 = 8.6\ \text{V}$$

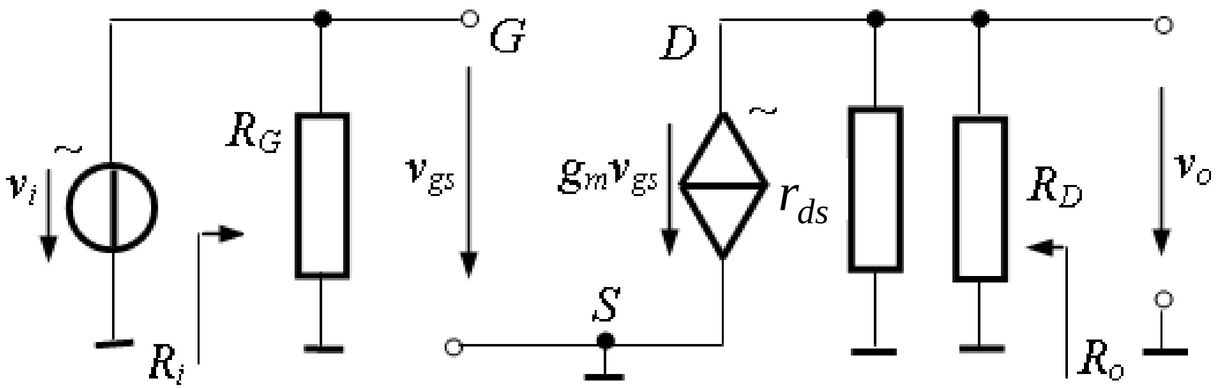
$$\boxed{Q(8.6\ \text{V}; 0.1\ \text{mA})}$$

$$g_m = \sqrt{2K}\sqrt{\frac{W}{L}}\sqrt{I_D} = \sqrt{2\cdot 0.1}\cdot\sqrt{2}\cdot\sqrt{0.1} = 0.2\ \text{mS}$$

$$r_{ds} = \frac{V_A}{I_D} = \frac{100}{0.1} = 1\text{M}\Omega$$

➢ Common source (CS) basic amplifier - example

d) Draw the small-signal equivalent circuit. What is the configuration of the stage? Justify.
e) Compute the gain, input and output resistances.



common source, terminal S is connected to ground

$$A_v = -g_m(R_D||r_{ds}) = -0.2 \cdot (50||1000) = -9.5$$

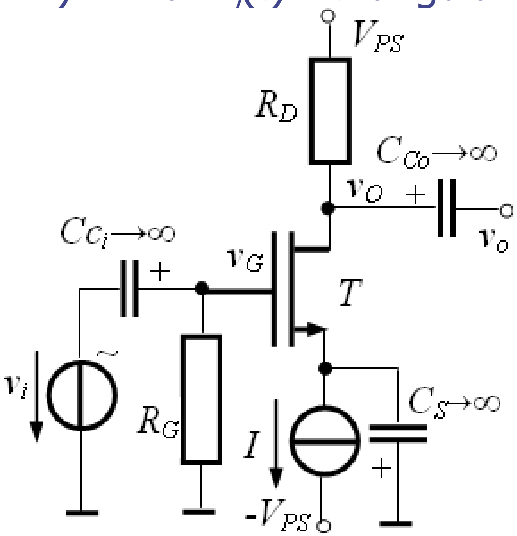
or $A_v \approx -g_m R_D = -0.2 \cdot 50 = -10$

$R_i = R_G = 1\ \text{M}\Omega$

$R_o = R_D||r_{ds} = 47.6\ \text{K}\Omega$ or $R_o \approx R_D = 50\ \text{K}\Omega$

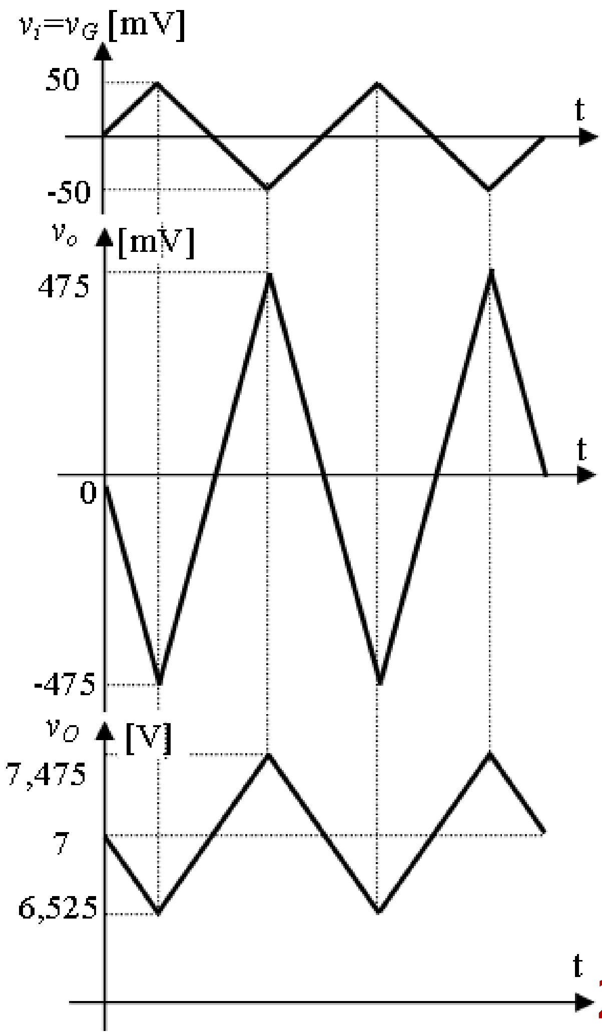
➢ Common source (CS) basic amplifier - example

f) For $v_i(t)$ - triangular wave, 50 mV amplitude, plot $v_G(t)$, $v_o(t)$, $v_O(t)$, $v_S(t)$.



$$v_G(t) = V_G + v_i(t) \qquad V_G = 0\text{ V}$$

$$V_O = V_{PS} - R_D I = 7\text{ V}$$



$$\widehat{V}_o = |A_v|\ \widehat{V}_i = 9.5 * 50 = 475\text{ mV}$$

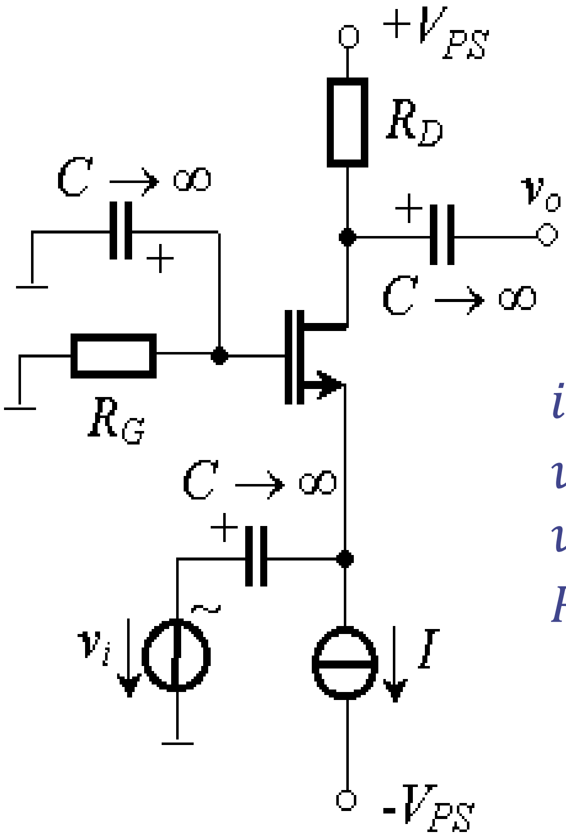
$$v_o(t) = A_v v_i(t) = -9.5\, v_i(t)$$

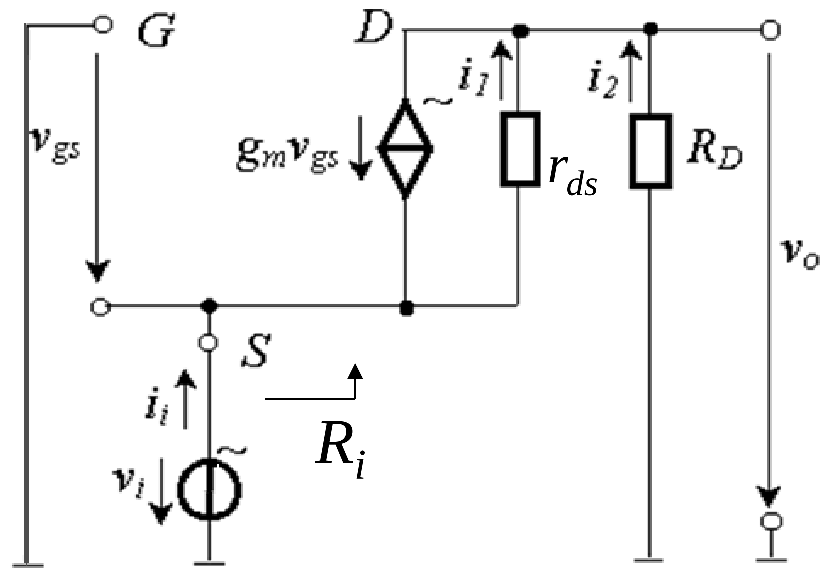
$$v_O(t) = V_O + v_o(t) = 7 - 9.5\, v_i(t)$$

$$V_S = -V_{GS} + V_G = -1.6\text{ V} \qquad v_s(t) = 0\text{ V}$$

$$v_S(t) = V_S + v_s(t) = -1.6\text{ V}$$

➢ Common gate (CG) basic amplifier





$$i_1 = g_m v_{gs} - i_2$$
$$v_o = -R_D i_2$$
$$v_i = -v_{gs}$$
$$R_D i_2 - i_1 r_{ds} + v_i = 0$$

$$i_i \approx -g_m v_{gs}$$
$$v_i = -v_{gs}$$

$$R_i = \frac{v_i}{i_i} \approx \frac{1}{g_m}$$

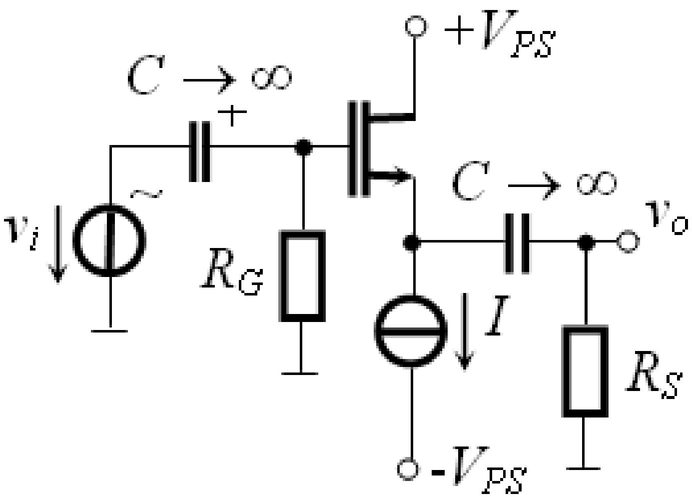
$$A_v = \frac{R_D(g_m r_{ds} + 1)}{R_D + r_{ds}}$$

If $g_m r_{ds} >> 1$

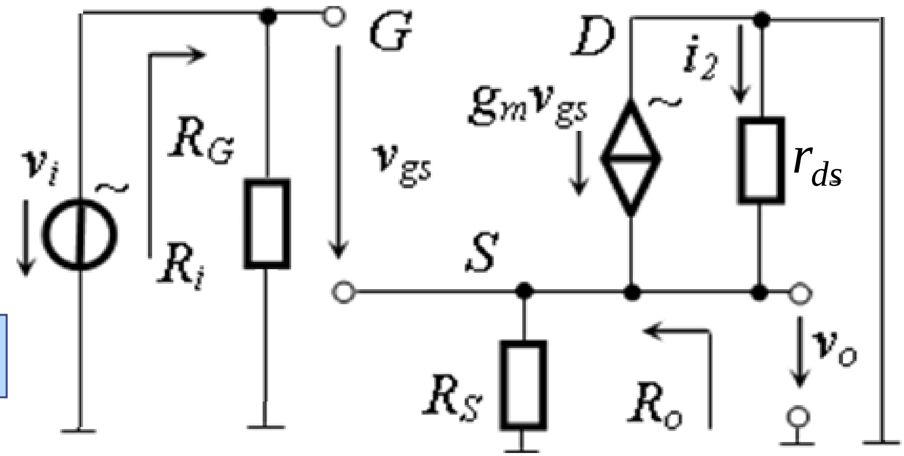
$$A_v \approx g_m(R_D||r_{ds}) \approx g_m R_D$$

$$R_o = r_{ds} \,||\, R_D \approx R_D$$

➢ Common drain (CD) basic amplifier



$R_i = R_G$



$$v_o = (R_S || r_{ds}) g_m v_{gs}$$

$$v_i = v_{gs} + v_o$$

$$A_v = \frac{v_o}{v_i} = \frac{(R_S || r_{ds}) g_m}{1 + (R_S || r_{ds}) g_m} \approx \frac{g_m R_S}{1 + g_m R_S}$$

If $g_m R_S >> 1$ $\quad A_v \approx 1$

Voltage follower (source follower)

r_s - resistance seen into S when $v_i = 0$

$$r_s = \frac{-v_{gs}}{-g_m v_{gs} - v_{gs}/r_{ds}} = \frac{1}{g_m + 1/r_{ds}} = r_{ds} || \frac{1}{g_m}$$

$$R_o = R_S || r_s = R_S || r_{ds} || \frac{1}{g_m} \approx R_S || \frac{1}{g_m}$$

MOSFET basic amplifiers - summary

Common source CS

$$A_v = -g_m(R_D||r_{ds})$$

$$R_i = R_G$$

$$R_o = R_D||r_{ds} \approx R_D$$

Common gate CG

$$A_v \approx g_m(R_D||r_{ds}) \approx g_m R_D$$

$$R_i = \frac{v_i}{i_i} \approx \frac{1}{g_m}$$

$$R_o = r_{ds} \,||\, R_D \approx R_D$$

Common drain CD

$$A_v \approx 1$$

$$R_i = R_G$$

$$R_o \approx R_S|| \frac{1}{g_m}$$

Which one is best? What does best mean for gain, input/output resistance?

Summary

- MOSFET small-signal model
- MOSFET basic amplifiers

Next week: BJT basic amplifiers.