MOSFET Amplifiers and High-Frequency Performance

- In many applications, MOSFET is used as a linear (small-signal) amplifier

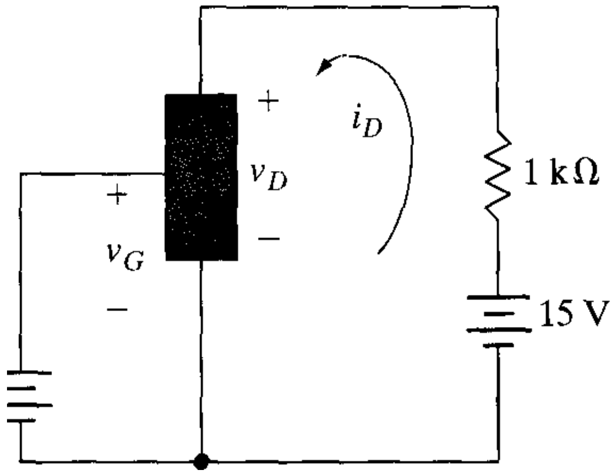
- A small signal equivalent circuit for MOSFET is needed to analyze the MOSFET frequency performance.

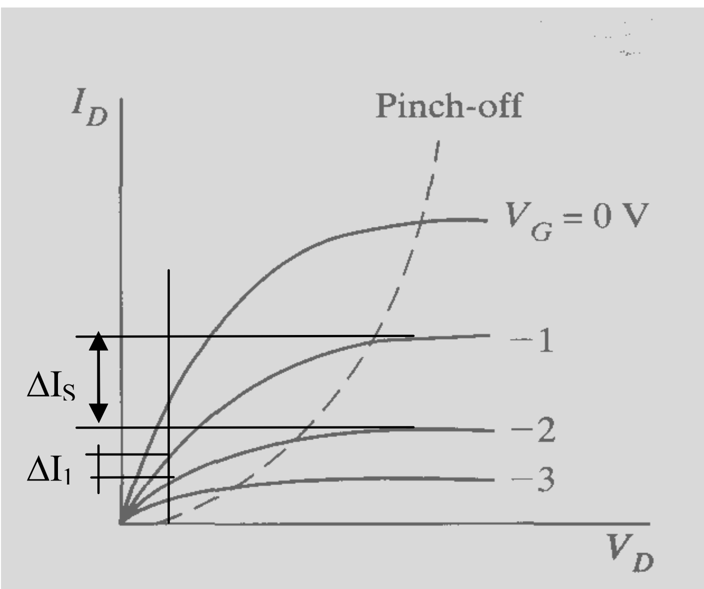
Small-Signal equivalent circuit:

- The equivalent circuit is constructed from the basic MOSFET geometry
- Resistance and capacitances are incorporated
- Input and output signals are assumed small as compared to the steady-state DC current and voltage (operating point)

Operating point is based on the MOSFET I-Vs and circuit conditions

MOSFET amplifier: low operating frequencies





Simple FET amplifier circuit:

$$\Delta V_L = \Delta I \times R_L$$

Voltage gain $K_V = \Delta V_L / \Delta V_G = (\Delta I \times R_L) / \Delta V_G$

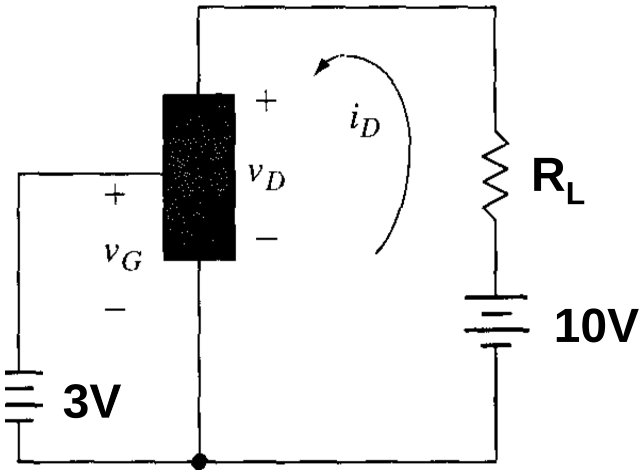
$$\mathbf{K_V = (\Delta I \;/\; \Delta V_G) \times R_L = g_m \times R_L}$$

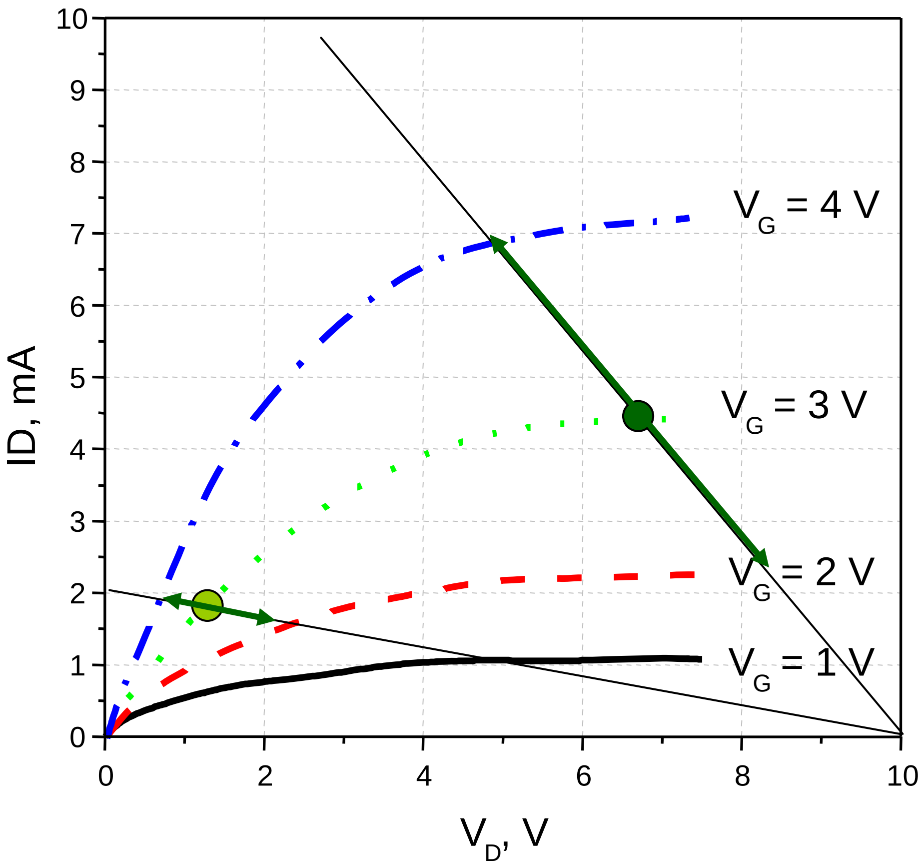
The larger the transconductance $g_m = \Delta I / \Delta V_G$, the higher is the voltage gain K_V

g_m is maximal in the saturation regime, i.e. for $V_D > V_{D\,sat}$

In the amplifier circuits, FETs usually work in the saturation regime,
In this regime, current DOES NOT depend on drain voltage.
Current is the function of the GATE VOLTAGE ONLY.

MOSFET operating point:
Effect of Load Resistance on the output Current amplitude





Consider the circuit with the drain bias V_{DD}= 10 V and the gate bias V_{GG} = 3 V ;

1. **Load resistance R_L = 5 kOhm**

   Op. point: $V_D \approx 1.2$ V; $I_D \approx 1.8$ mA; $g_{m1} \approx$ (2-1.5)mA/(4-2)V ≈ 0.25 mA/V;

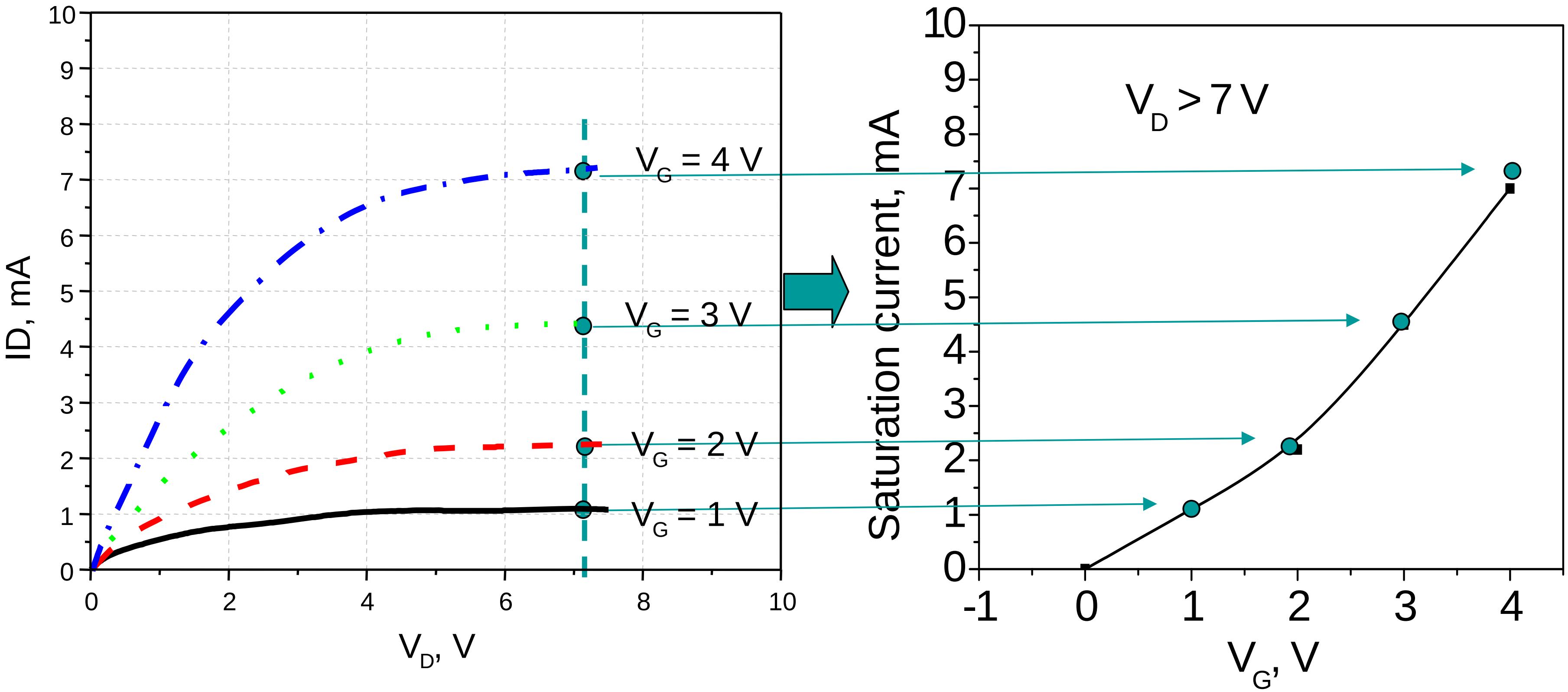
2. **Load resistance R_L = 0.6 kOhm**

   Op. point: $V_D \approx 6.8$ V; $I_D \approx 4.5$ mA; $g_{m2} \approx$ (7-2.4)mA/(4-2)V ≈ 2.3 mA/V;

In MOSFET amplifiers, the operating point is normally in the saturation region

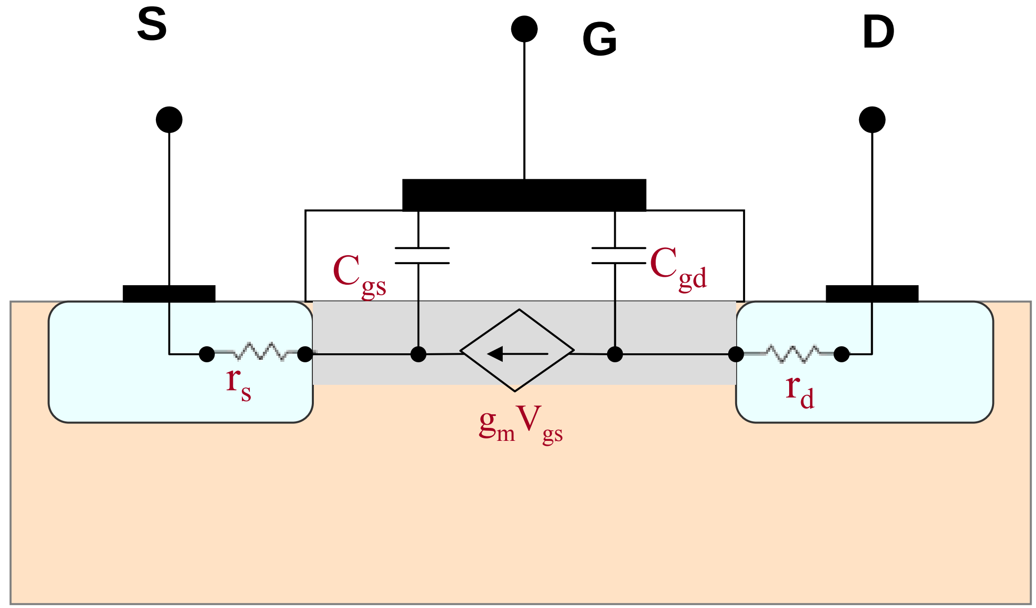
MOSFET Transfer Characteristics

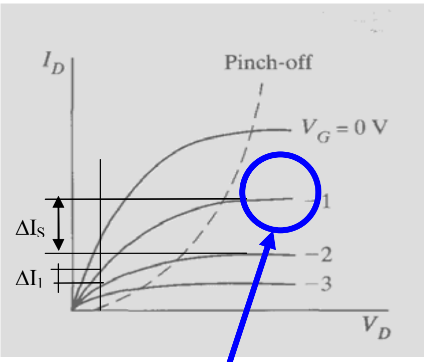
In saturation regime, the drain current does not depend on the drain voltage

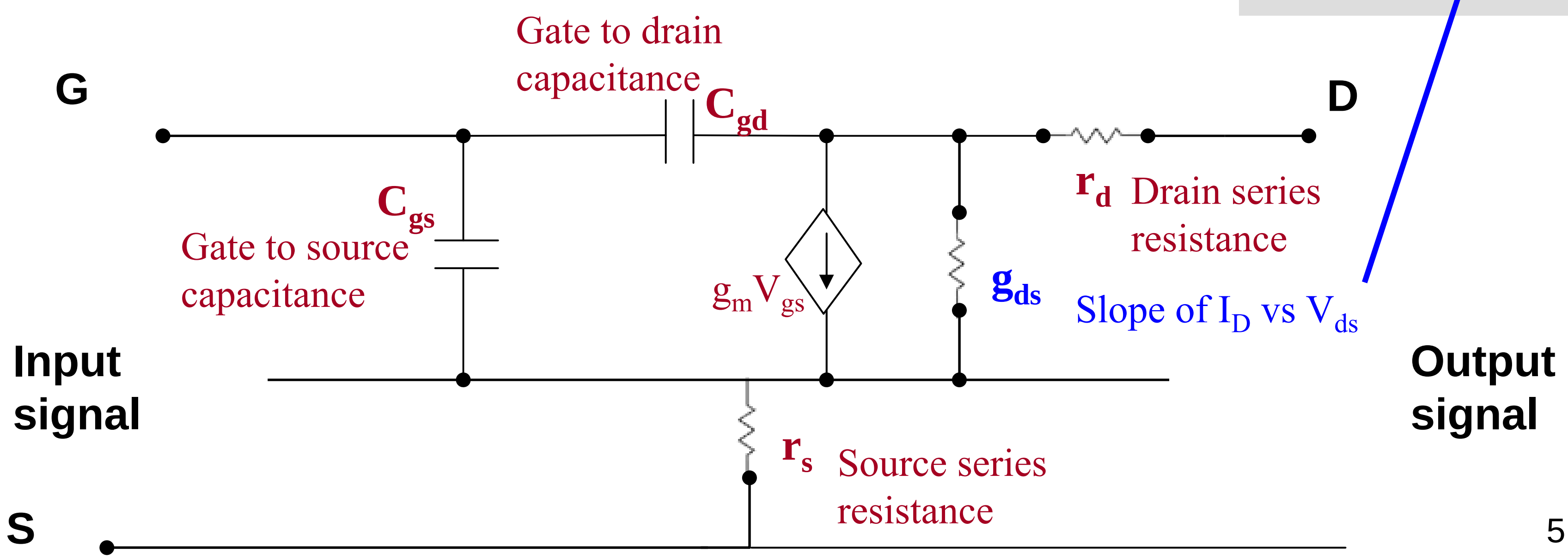


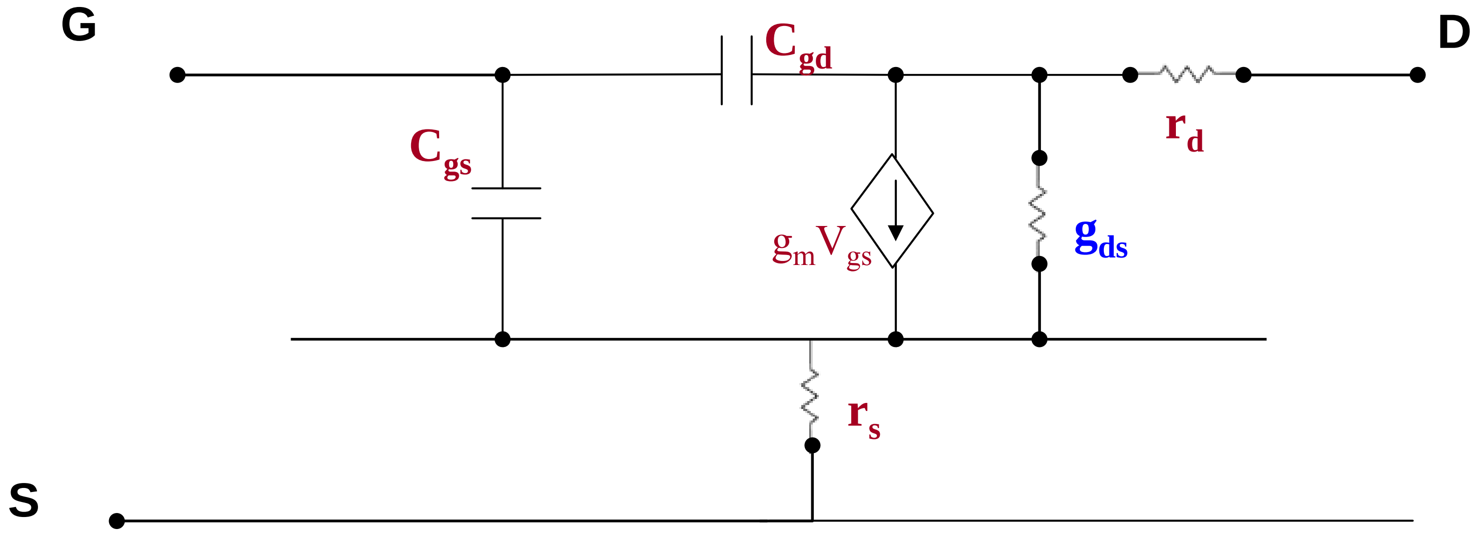
The dependence I_{Dsat} (V_G) is called
the TRANSFER CHARACTERISTIC of MOSFET

MOSFET amplifier: high operating frequencies

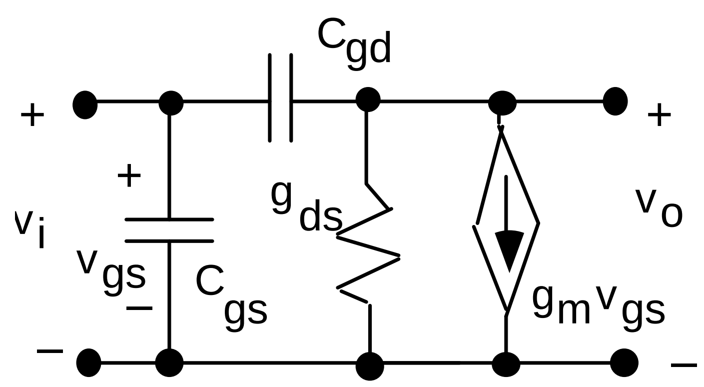








Simplified equivalent circuit diagram

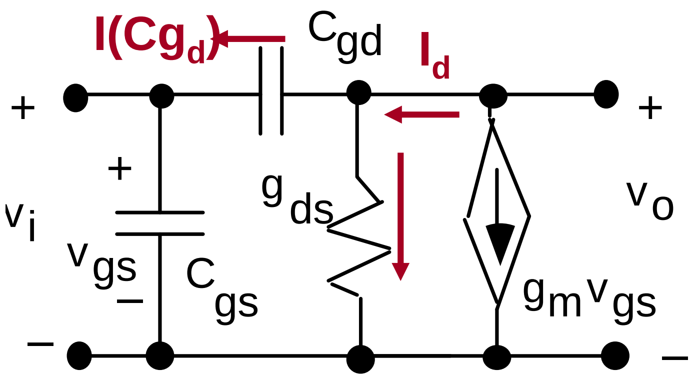


Assuming

r_d, r_s=0

MOSFET Gain

- voltage gain



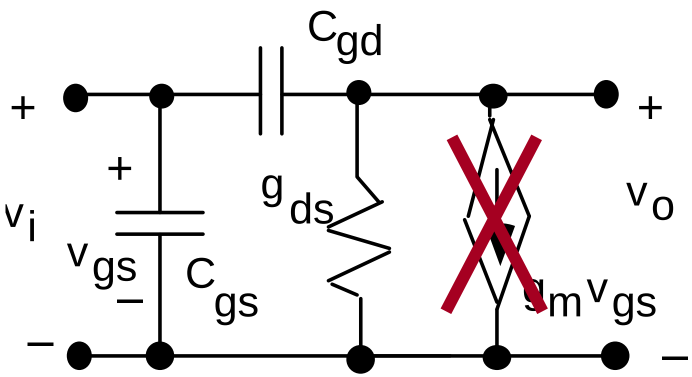
Input voltage $v_i = v_{gs}$
Output voltage v_o = voltage across g_{ds}

v_o can be found using superposition.
1) Assume $v_i = 0$.
The output voltage component is v_{01}
The output current $i_d = i(g_{ds})+i(C_{gd})$
$i(g_{ds}) = v_{01} \times g_{ds}$; $i(C_{gd}) = v_{01} \times j\omega C_{gd}$
From this, $i_d = v_{01} \times (g_{ds} + j\omega C_{gd})$;
On the other hand, $i_d = - g_m v_{gs}$
Substituting i_d, we obtain:
$- g_m v_{gs} = v_{01} \times (g_{ds} + j\omega C_{gd})$;

$$v_{01} = \frac{-g_m}{g_{ds} + j\omega C_{gd}} v_{gs}$$

MOSFET Gain

- voltage gain



2) Now, turn off the current $g_m v_{gs}$

The output voltage component is v_{02}

The voltage across $g_{ds} = 1/r_{ds}$:

$v_{02} = v_i \times r_{ds}/(r_{ds} + 1/j\omega C_{gd}) =$

$v_i \times r_{ds} j\omega C_{gd}/(j\omega C_{gd} r_{ds} + 1) =$

$v_i \times j\omega C_{gd}/(j\omega C_{gd} + 1/r_{ds}) =$

$v_i \times j\omega C_{gd}/(j\omega C_{gd} + g_{ds})$;

$$v_{02} = \frac{j\omega C_{gd}}{g_{ds} + j\omega C_{gd}} v_{gs}$$

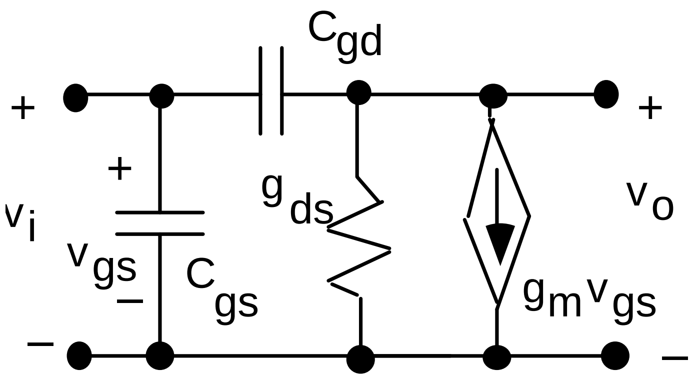
The total output voltage, $v_0 = v_{01} + v_{02}$:

$$v_{01} = \frac{-g_m}{g_{ds} + j\omega C_{gd}} v_{gs}$$

$$v_0 = \frac{-g_m + j\omega C_{gd}}{g_{ds} + j\omega C_{gd}} v_{gs}$$

MOSFET Gain

- voltage gain



The voltage gain:

$$A_v = \frac{v_0}{v_{gs}} = \frac{-g_m + j\omega C_{gd}}{g_{ds} + j\omega C_{gd}}$$

The gate - drain capacitance is very low in the saturation region. Hence,

$$A_v = \frac{v_0}{v_{gs}} \approx \frac{-g_m}{g_{ds} + j\omega C_{gd}}$$

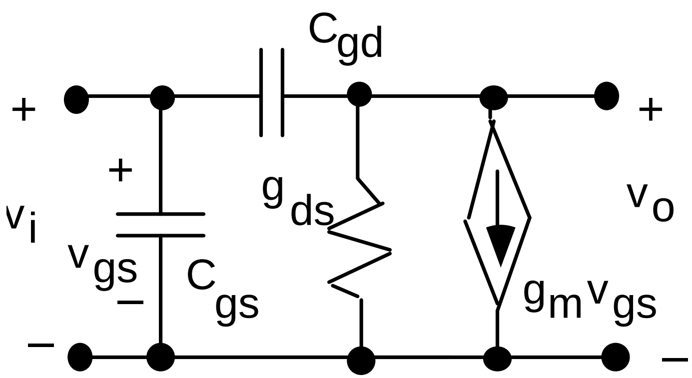
The voltage gain decreases with frequency when $\omega C_{gd} \approx g_{ds};$

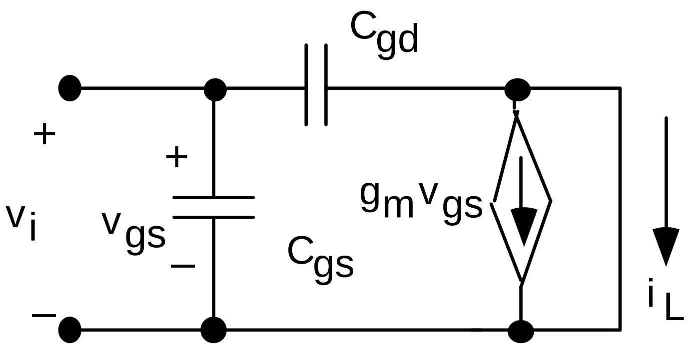
Corresponding characteristic frequency: $f_v \approx \dfrac{g_{ds}}{2\pi C_{gd}}$

At frequencies f > f$_v$ $A_v \approx \dfrac{-g_m}{j\omega C_{gd}}$

MOSFET Gain

- short circuit current gain





Output current, $i_L = i_0 = - g_m v_{gs}$

Input current, $i_i = i\,(C_{gs}) + i(C_{gs}) =$

$= v_i \times j\omega\, C_{gs} + v_i \times j\omega\, C_{gd} =$

$= v_i \times j\omega\, (C_{gs} + C_{gd})$;

Also note that $v_i = v_{gs}$;

Therefore: $i_i = v_i \times j\omega\, (C_{gs} + C_{gd})$;

The current gain: $A_i = i_0/i_i = i_L/i_i$

$$A_i = \frac{i_L}{i_i} = \frac{-g_m}{j\omega\left(C_{gs} + C_{gd}\right)}$$

MOSFET current cutoff frequency f_T

f_T is the frequency at which the modulus of the short circuit current gain is unity

From:

$$A_i = \frac{i_L}{i_i} = \frac{-g_m}{j\omega\left(C_{gs} + C_{gd}\right)} \qquad f_T = \frac{g_m}{2\pi\left(C_{gs} + C_{gd}\right)}$$

f_T estimation

Assume that $C_{gs} + C_{gd} \sim C_i$ where $C_i = \varepsilon_i WL/d_i$ is the gate oxide capacitance.

Transconductance, g_m

Consider short-gate MOSFETs at high drain voltage.

In short-gate devices, the electron velocity is saturated: $I_d = q\, n_s v_s W$

The transconductance: $g_m = dI_d/dV_g$

$$g_m = \frac{\partial I_d}{\partial V_g} = q \frac{\partial n_s}{\partial V_g} v_s W$$

MOSFET current cutoff frequency f_T

Induced sheet carrier density in MOSFETs (see lecture #18):

$$n_s = \frac{c_i}{q}\left(V_{GS} - V_T\right) = \frac{C_i}{qWL}\left(V_{GS} - V_T\right)$$

where W is the MOSFET width and L is the gate length

From this,
$$g_m = \frac{\partial I_d}{\partial V_g} = q\frac{\partial n_s}{\partial V_g} v_s W = q\left\{\frac{C_i}{qWL}\right\} v_s W$$

$$g_m = \frac{C_i v_s}{L}$$

The cutoff frequency becomes:
$$f_T = \frac{g_m}{2\pi\left(C_{gs} + C_{gd}\right)} = \frac{C_i v_s}{2\pi L C_i} = \frac{v_s}{2\pi L}$$

$$f_T = \frac{g_m}{2\pi\left(C_{gs} + C_{gd}\right)} = \frac{C_i v_s}{2\pi\, L C_i} = \frac{v_s}{2\pi\, L}$$

Note that, $\boldsymbol{L/v_s = t_{tr}}$, the electron transit time under the gate

Using this, $$f_T = 1/\,2\pi t_{tr}$$

Practical cut-off frequency must also include the parasitic and fringing capacitances, *Cp*, which add to the gate capacitance:

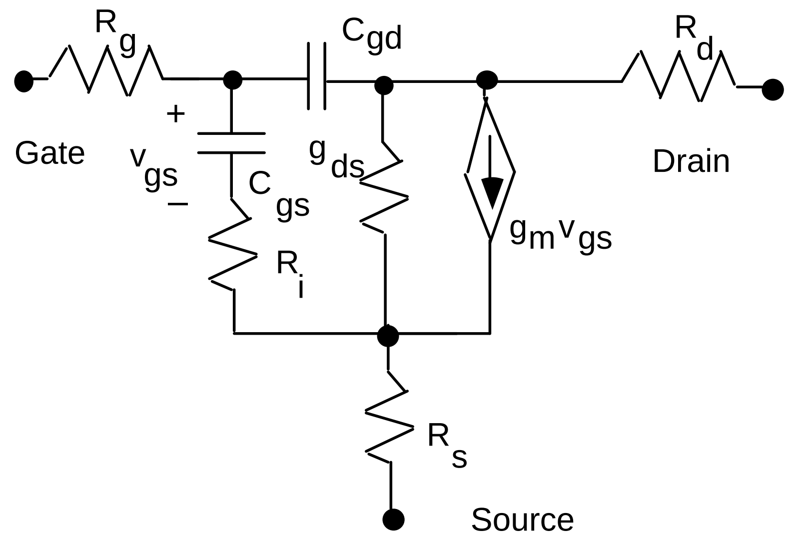
$$f_T = \frac{g_m}{2\pi\left(C_{gs} + C_{gd} + C_p\right)}$$

Maximum oscillation frequency, f_{max}

The cutoff frequency f_T is a characteristic of the intrinsic transistor (without parasitic series resistances).

f_{max} is the characteristic of the extrinsic device (which includes series source, drain, input, and gate resistances, R_s, R_d, R_i, and Rg

f_{max} is defined as the frequency at which the power gain of the transistor is equal to unity under optimum matching conditions for the input and output impedances.



Simplified expression for f_{max} is given by:

$$f_{max} \approx \frac{f_T}{\sqrt{r + f_T \tau}} \quad \text{where} \quad r = g_{ds}\left(R_s + R_i + R_d\right) \qquad \tau = 2\pi R_g C_{gd}.$$

In MOSFETs with small parasitic resistances, R_S, R_i and $R_d \approx 0$

$$f_{max} \approx \frac{f_T}{\sqrt{f_T \tau}} = \sqrt{\frac{f_T}{2\pi R_g C_{gd}}}$$