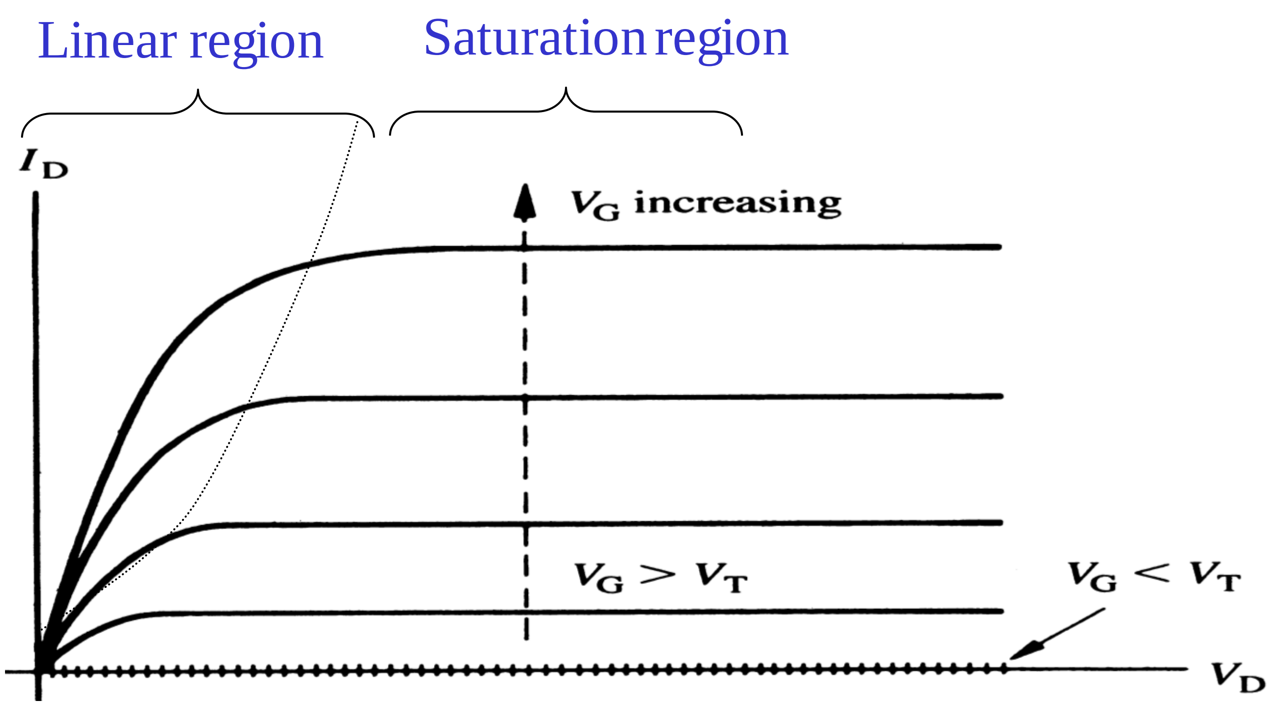
Chapter 17-2. MOSFET small-signal equivalent circuit

Last class, we discussed the dc characteristics of MOSFETs.
The dc characteristics for NMOS are reviewed below.

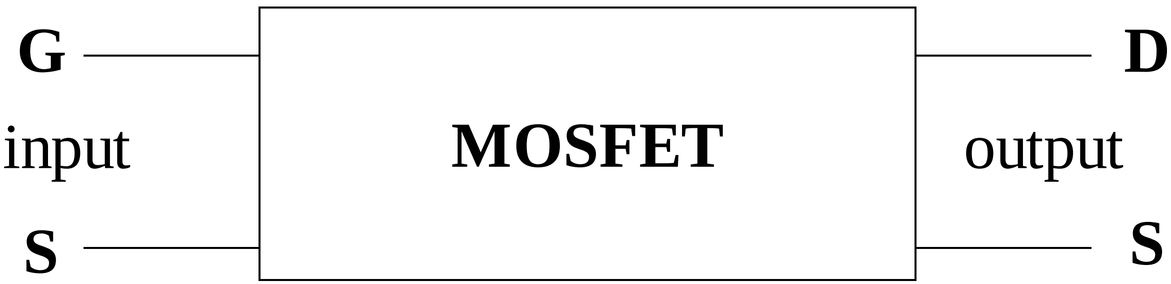
$$I_D = \frac{Z\mu_n}{L} C_{ox}\left[(V_G - V_T)V_{DS} - \frac{V_{DS}^2}{2}\right] \qquad 0 < V_{DS} < V_{DS,sat} \quad ; \quad V_G > V_T$$

$$I_{D,sat} = \frac{Z\mu C_{ox}}{2L}(V_G - V_T)^2 \qquad V_{DS} > V_{DS,sat} \quad ; \quad V_G > V_T$$



MOSFET ac response

MOSFET ac response is routinely expressed in terms of small-signal equivalent circuits. This circuit can be derived from the two-port network shown below:



The input looks like an open circuit, except for the presence of the gate capacitor.

At output, we have a current I_D which is controlled by V_G and V_{DS}.

$$I_D = f\,(V_G, V_{DS})$$

MOSFET small-signal equivalent circuit

Any ac signal in V_G or V_{DS} will result in corresponding ac variation in I_D

$$\Delta I_D = \left.\frac{\partial I_D}{\partial V_G}\right|_{V_{DS}} \Delta V_G + \left.\frac{\partial I_D}{\partial V_{DS}}\right|_{V_G} \Delta V_{DS}$$

$$i_d = g_m v_g + g_d v_d \qquad \text{where} \quad g_m = \left.\frac{\partial I_D}{\partial V_G}\right|_{V_{DS}} \quad \text{and} \quad g_d = \left.\frac{\partial I_D}{\partial V_{DS}}\right|_{V_G}$$

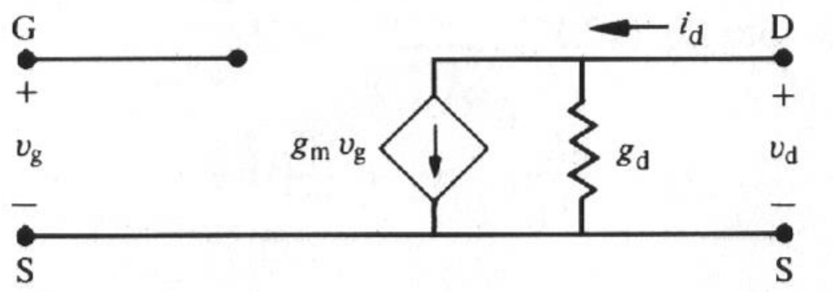
g_m = trans-conductance

g_d = drain or channel conductance

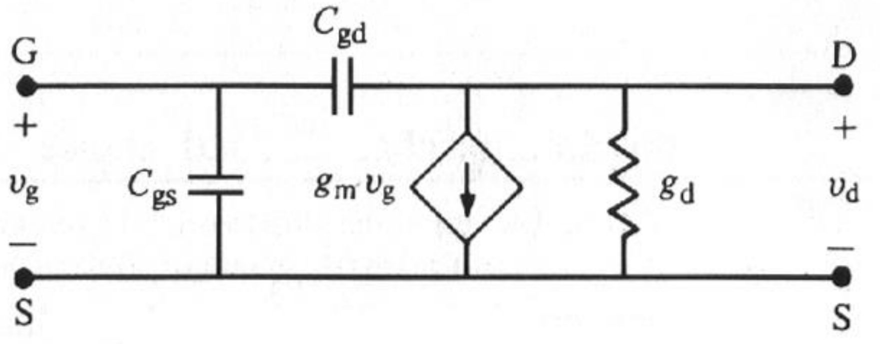
Note: i_d, v_g and v_d are small-signal ac currents and voltages. They are different from I_D, V_G and V_{DS} which are dc currents and voltages.

Small-signal equivalent circuit

So, the equivalent circuit at low-frequency looks like (neglecting the gate capacitance low frequency):



For high-frequency, we have to include the capacitive effects:



MOSFET small-signal parameters

When $V_{DS} < V_{DS,sat}$ (i.e., below pinch-off or linear region)

$$g_d = \frac{Z\mu_n C_{ox}}{L}(V_G - V_T - V_{DS})$$

$$g_m = \frac{Z\mu_n C_{ox}}{L} V_{DS}$$

When $V_{DS} > V_{DS,sat}$ (i.e., above pinch-off or saturation region)

$$g_d = 0$$

$$g_m = \frac{Z\mu_n C_{ox}}{L}(V_G - V_T)$$

Note: The parameters depend on the dc bias, V_G and V_{DS}

Frequency response of MOSFET

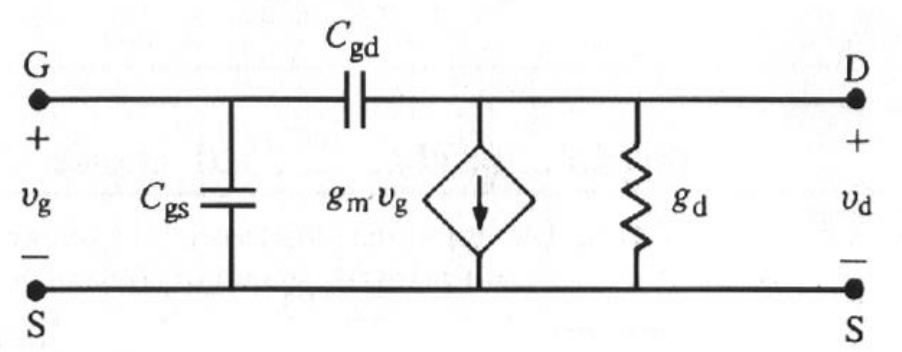
The cut-off frequency f_T is defined as the frequency when the current gain is 1.

$$\left.\begin{aligned}\text{Input current} &= j\omega C_G v_G \\ \text{Output current} &= g_m v_G\end{aligned}\right\}$$

v_G here is ac signal
C_{GS} is approximately equal to the gate capacitance, $\approx Z\,L\,C_{ox}$

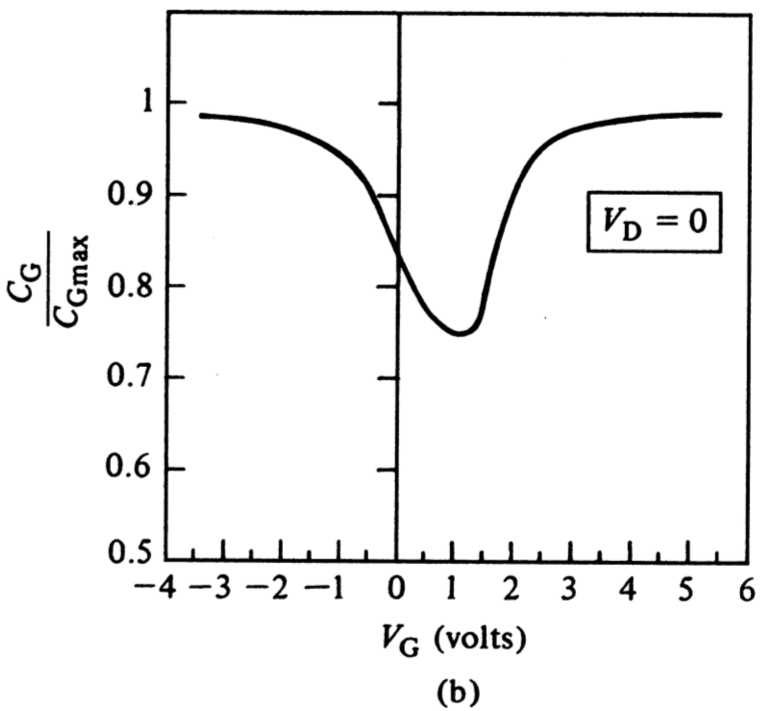
So, at f_T, $$\frac{g_m v_G}{2\pi\, f_T \times C_{GS} v_G} = 1$$

So, $$\boxed{f_T = \frac{g_m}{2\pi\, C_{GS}}}$$

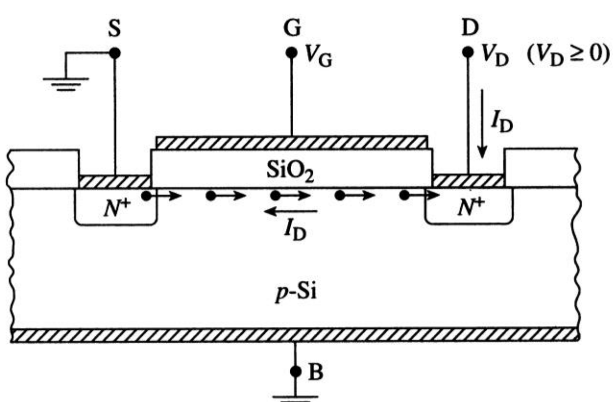


C_G-V_G characteristics: MOS-C versus MOSFET

C_G vs. V_G characteristics of a MOSFET at high frequency looks similar to the low-frequency response (unlike the MOS-C). This is because, even at high frequency, the source and drain can supply the minority carriers required for the structure to follow the ac fluctuations in the gate potential when the device is inversion biased.



C_G vs. V_G characteristics of a MOSFET with $V_{DS} = 0$



Enhancement mode MOSFETs

The devices we discussed so far are called “enhancement-mode MOSFETs.

For NMOS, V_T is positive and one has to apply a positive gate voltage to turn on the device. At zero gate voltage, the device will be off.

For PMOS, V_T is negative and one has to apply a negative gate voltage to turn on the device. At zero gate voltage, the device will be off.

Exercise: Draw the I_D-V_{DS} characteristics for NMOS and PMOS enhancement-mode devices.

Next class, we will discuss depletion-mode devices.