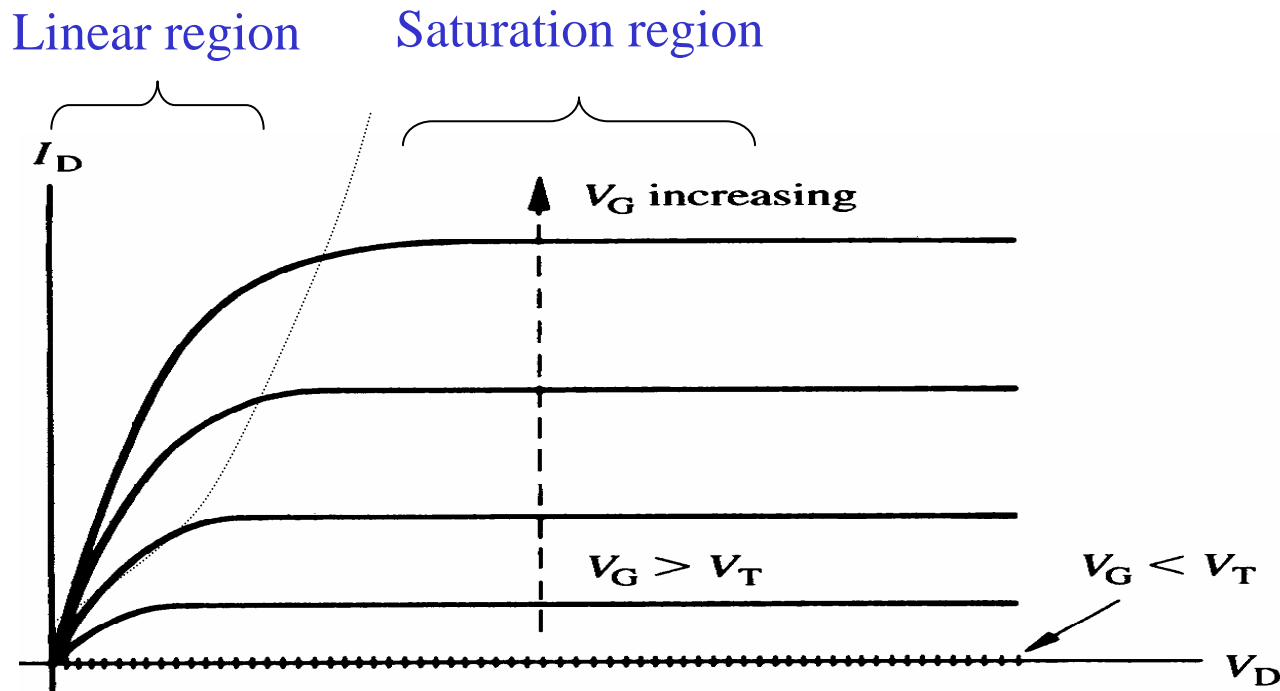


## Chapter 17-2. MOSFET small-signal equivalent circuit

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

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

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



## 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  $I_D$

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

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

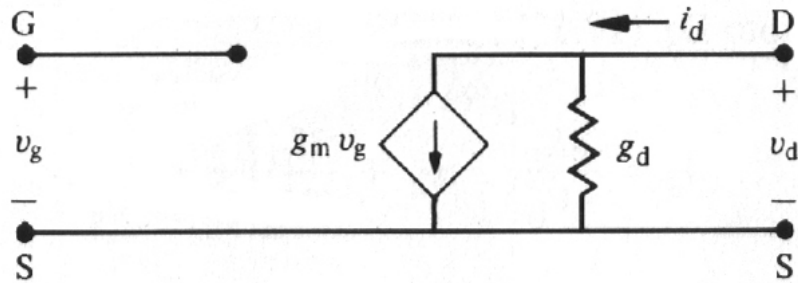
$g_m$  = trans-conductance

$g_d$  = drain or channel conductance

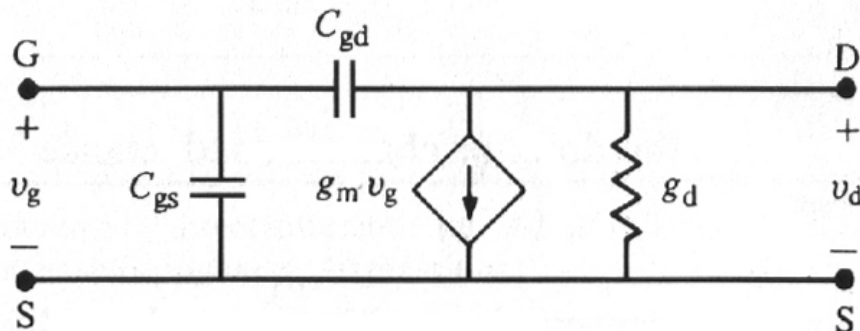
Note:  $i_d$ ,  $v_g$  and  $v_d$  are small-signal ac currents and voltages. They are different from  $I_D$ ,  $V_G$  and  $V_{DS}$  which are dc currents and voltages.

## 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. in linear region or below pinch-off)

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

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

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

$$g_d = 0$$

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

**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.

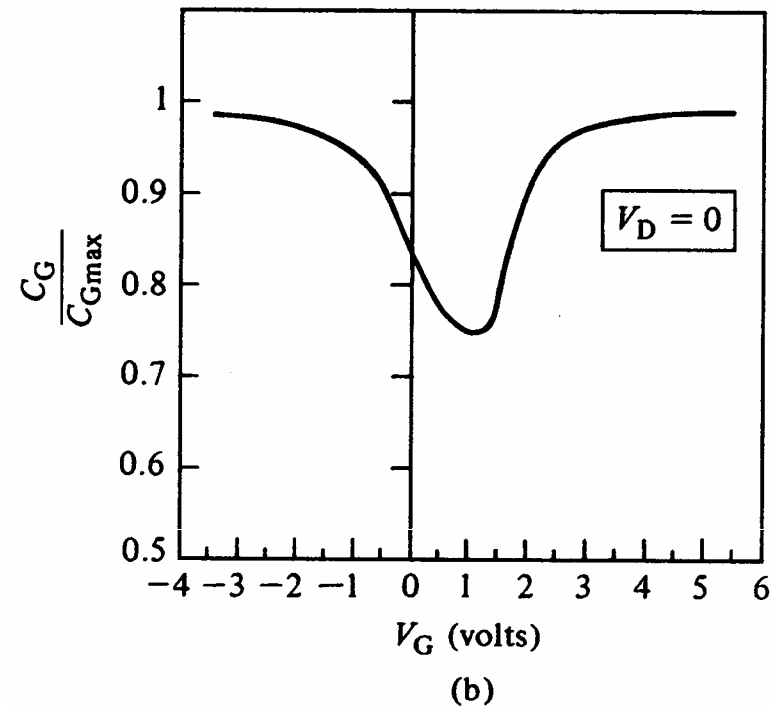
$$\left. \begin{array}{l} \text{Input current} = j = \omega C_{GS} v_G \\ \text{Output current} = g_m v_G \end{array} \right\} \begin{array}{l} v_G \text{ here is ac signal} \\ C_{GS} \text{ is approximately equal to} \\ \text{the gate capacitance, } \cong Z L C_{ox} \end{array}$$

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

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

# $C_G$ - $V_G$ characteristics: MOS-Capacitor versus MOSFET

$C_G$  vs.  $V_G$  characteristics of a MOSFET at high frequency looks similar to the low-frequency response (unlike the MOS-Cap.). 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.