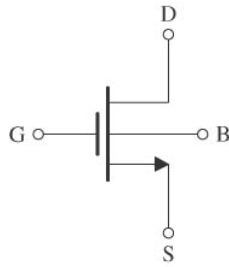


Lecture 26: MOSFET Circuit Symbols, i_D - v_{DS} Characteristics.

There are **two circuit symbols** you may encounter for the enhancement type MOSFET. For the n -channel, one symbol is

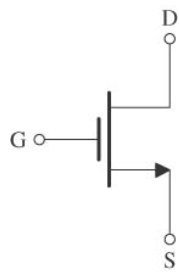


(Fig. 4.10b)

Referring to this circuit symbol:

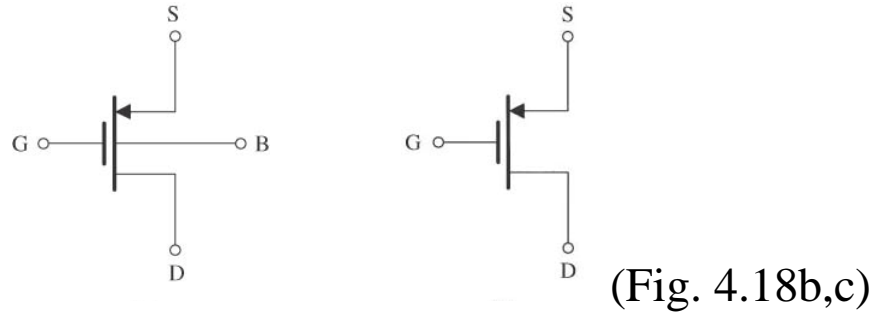
- ✓ The arrowed terminal indicates the source,
- ✓ This arrow direction indicates n -type (direction of current)
- ✓ The gap at the gate indicates the oxide layer.

However, the body is often connected to the source. This leads to a **more common** circuit symbol:



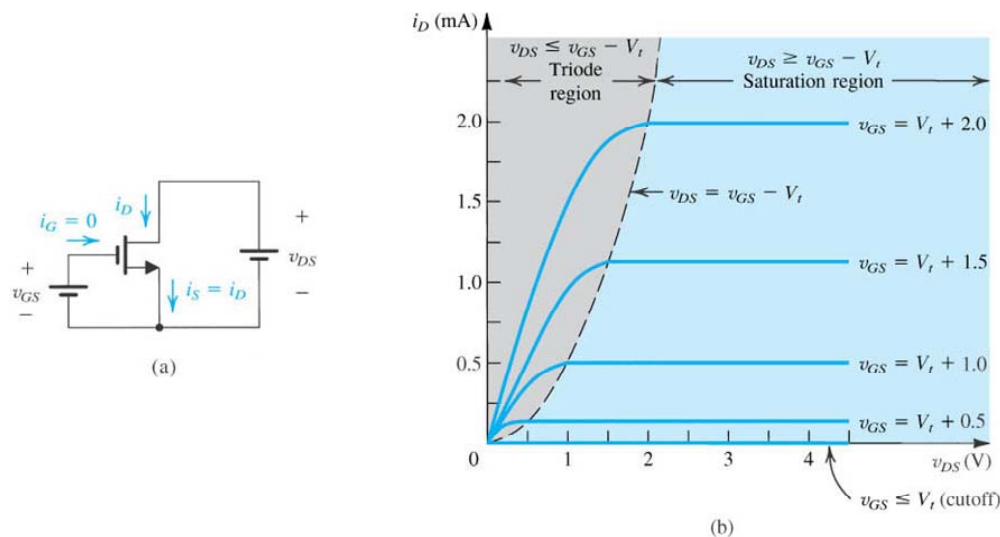
(Fig. 4.10c)

Similar circuit symbols are used for **p -channel** enhancement type MOSFETS:



MOSFET i_D - v_{DS} Characteristics

Similar to a BJT, we can generate a set of i_D - v_{DS} characteristic curves for a MOSFET by setting v_{GS} and varying v_{DS} . This is shown in Fig. 4.11 for an n -type MOSFET:



(Fig. 4.11)

There are **three regions** of operation:

- (1) **Cutoff.** To operate an enhancement type MOSFET, we first must induce the channel. For NMOS, this means that

$$v_{GS} \geq V_t \quad (\text{induce}) \quad (4.8),(1)$$

If $v_{GS} < V_t$ there is **no channel** and the device is cutoff, which we see in Fig. 4.11.

When the MOSFET is cutoff, $i_D = i_S = 0$.

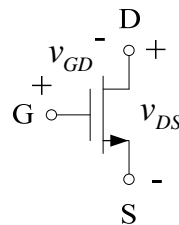
- (2) **Triode.** To operate in this mode, we **first must induce the channel** as in (1) above.

We must also keep v_{DS} small enough so the **channel is continuous** (not pinched off):

$$v_{GD} > V_t \quad (\text{continuous}) \quad (4.9), (2)$$

[Note how similar this last criterion is to $v_{GS} > V_t$ for the channel to be induced. Here in (2), we have $v_{GD} > V_t$ for a continuous channel at the drain end. This observation can help us to remember these criterion.]

Another way of writing this criterion in (2) is in terms of v_{DS} . Referring to this circuit element



we see that

$$v_{DS} = v_{GS} + v_{DG} \quad (3)$$

For a continuous channel, as required by (2), (3) becomes

$$v_{DS} - v_{GS} = v_{DG} < -V_t$$

Therefore,

$$v_{DS} < v_{GS} - V_t \quad (\text{continuous}) \quad (4.10),(4)$$

We can use **either (2) or (4)** to check for triode operation of the MOSFET.

As given in the last lecture, in the triode region

$$i_D = k_n' \frac{W}{L} \left[(v_{GS} - V_t) v_{DS} - \frac{1}{2} v_{DS}^2 \right] \quad (4.11),(5)$$

If $v_{DS}^2/2 \ll (v_{GS} - V_t) v_{DS}$ then

$$i_D \approx k_n' \frac{W}{L} (v_{GS} - V_t) v_{DS} \equiv \underbrace{r_{DS}^{-1}}_{\equiv r_{DS}^{-1}} v_{DS} \quad (4.12),(6)$$

where r_{DS} is defined as the (linear) **resistance** between the drain and source terminals. The value of r_{DS} is controlled by v_{GS} . (See Fig. 4.4).

- (3) **Saturation.** To operate in this mode we need to **first induce the channel**

$$v_{GS} \geq V_t \quad (\text{induce}) \quad (4.16),(7)$$

then ensure that the channel is **pinched off at the drain end**

$$v_{GD} \leq V_t \quad (\text{pinch off}) \quad (4.17),(8)$$

or equivalently

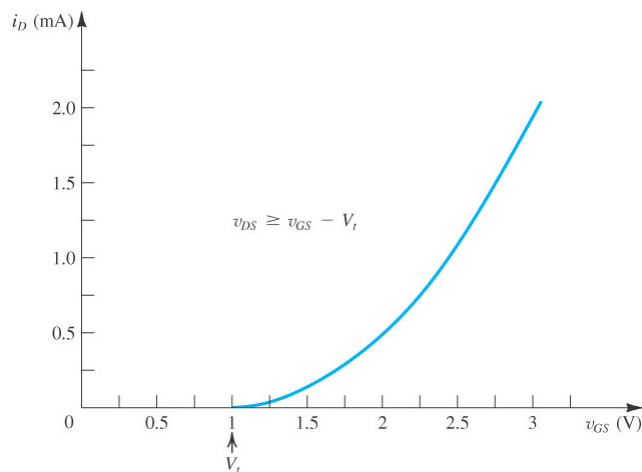
$$v_{DS} \geq v_{GS} - V_t \quad (\text{pinch off}) \quad (4.18),(9)$$

As we saw in the previous lecture, the drain current in this region is

$$i_D = \frac{1}{2} k_n' \frac{W}{L} (v_{GS} - V_t)^2 \quad (4.20), (10)$$

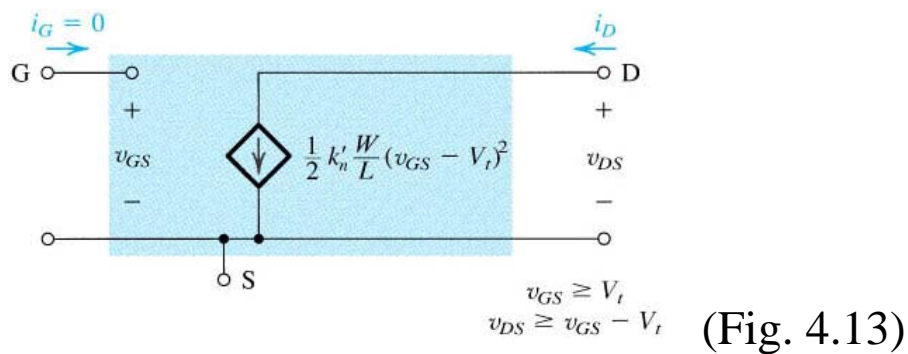
and is not dependent on v_{DS} .

A plot of i_D versus v_{GS} for an enhancement type NMOS device in saturation is shown in Fig. 4.12:



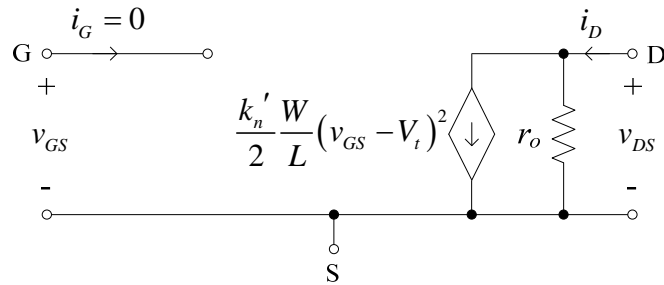
(Fig. 4.12)

In the saturation mode, this device behaves as an **ideal current source** controlled by v_{GS} :



(Fig. 4.13)

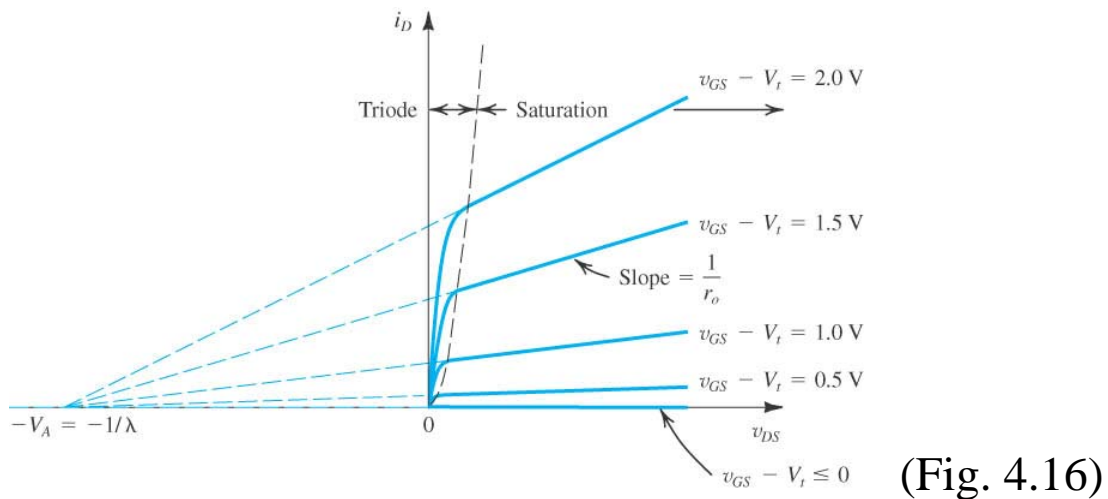
In reality, though, there is a **finite output resistance** (r_o) that should be added to this model:



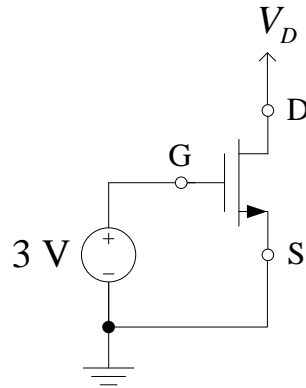
where

$$r_o = \frac{V_A}{I_D} \quad (4.26), (11)$$

This finite output resistance gives a **slope** to the i_D - v_{DS} characteristic curves:



Example N26.1 (similar to text exercise 4.4). Given an enhancement type NMOS with $V_t = 2$ V.



Determine the **region of operation** of this device for the following V_D . Use these criteria for the region of operation:

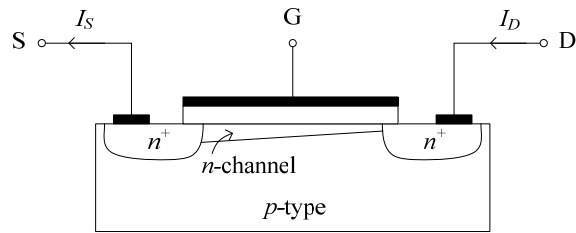
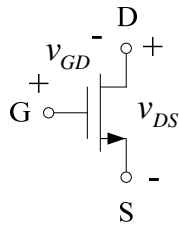
- Cutoff: $v_{GS} < V_t$
- Triode: $v_{GS} \geq V_t$ and $v_{DS} < v_{GS} - V_t$
- Saturation: $v_{GS} \geq V_t$ and $v_{DS} \geq v_{GS} - V_t$

(a) $V_D = 0.5 \text{ V}$. $V_{GS} = 3 \text{ V} > V_t = 2 \text{ V} \Rightarrow$ not cutoff. Then $V_{DS} = 0.5 \text{ V} < V_{GS} - V_t (= 3 - 2 = 1 \text{ V})$. \therefore **triode** mode.

(b) $V_D = 1 \text{ V}$. $V_{GS} = 3 \text{ V} > V_t = 2 \text{ V} \Rightarrow$ not cutoff. Then $V_{DS} = 1 \text{ V} = V_{GS} - V_t (= 1 \text{ V})$. \therefore **saturation (or triode)** mode.

(c) $V_D = 5 \text{ V}$. $V_{GS} = 3 \text{ V} > V_t = 2 \text{ V} \Rightarrow$ not cutoff. Then $V_{DS} = 5 \text{ V} > V_{GS} - V_t (= 1 \text{ V})$. \therefore **saturation** mode.

Example N26.2 (similar to text problem 4.16). An NMOS enhancement type MOSFET has $V_t = 2 \text{ V}$. If V_{GS} ranges from 2.5 to 5 V what is the **largest V_{DS}** for which the channel remains continuous?



- ✓ $V_{GS} > V_t, \forall V_{GS}$ so the channel is always present.
- ✓ Then for the channel to remain open at the drain end,

$$V_{DS} < V_{GS} - V_t \quad (\text{triode})$$

Which V_{GS} to use here? The smallest. Therefore,

$$V_{DS}|_{\max} < 2.5 - 2 = 0.5 \text{ V}$$