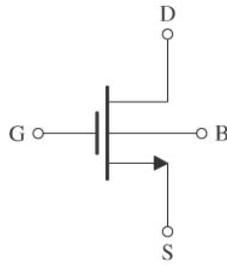


## Lecture 26: MOSFET Circuit Symbols, $i_D$ - $v_{DS}$ Characteristics.

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

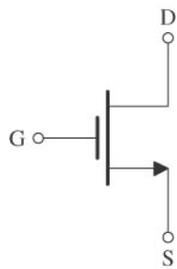


(Fig. 5.11b)

Referring to this circuit symbol:

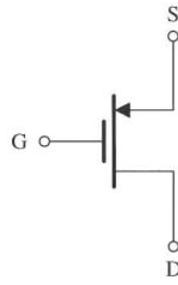
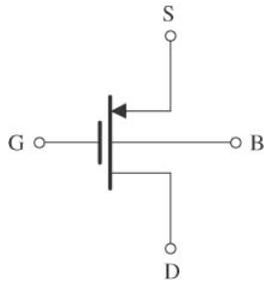
- ✓ The arrowed terminal indicates the source,
- ✓ This arrow direction indicates  $n$ -type (direction of current)
- ✓ The gap at the gate indicates the oxide layer.

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



(Fig. 5.11c)

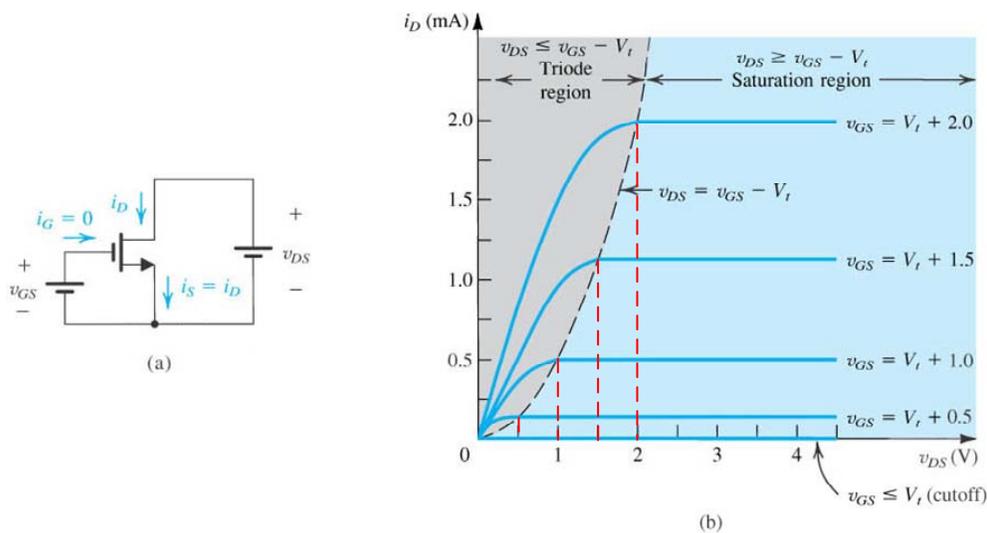
Similar circuit symbols are used for  **$p$ -channel** enhancement type MOSFETS:



(Figs. 5.19b,c)

## 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. 1 (or, similarly, Fig. 5.13) for an  $n$ -type MOSFET:



(Fig. 1)

(Sedra and Smith, 5<sup>th</sup> ed.)

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

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

If  $v_{GS} < V_t$  there is **no channel** and the device is cutoff, which we see in Fig. 1.

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

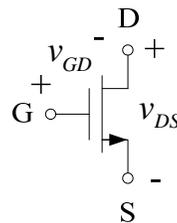
- (2) **Triode.** To operate in this mode, we **first must induce the channel** as in (1) above.

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

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

[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

$$v_{DS} = v_{GS} + v_{DG} = v_{GS} - v_{GD}$$

or 
$$v_{GD} = v_{GS} - v_{DS} \quad (3)$$

For a continuous channel, using (3) we can express (2) as

$$v_{GD} = v_{GS} - v_{DS} > V_t$$

Therefore,

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

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

$$i_D = k_n' \frac{W}{L} \left[ (v_{GS} - V_t) v_{DS} - \frac{1}{2} v_{DS}^2 \right] \quad (5.16), (5)$$

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

$$i_D \approx \underbrace{k_n' \frac{W}{L} (v_{GS} - V_t)}_{g_{DS} \equiv r_{DS}^{-1}} v_{DS} \equiv g_{DS} v_{DS} \quad (5.10), (6)$$

where  $r_{DS} \equiv g_{DS}^{-1}$  is defined as the (linear) **resistance** between the drain and source terminals. The value of  $r_{DS}$  is controlled by  $v_{GS}$ . (See Fig. 5.4).

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

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

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

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

or equivalently

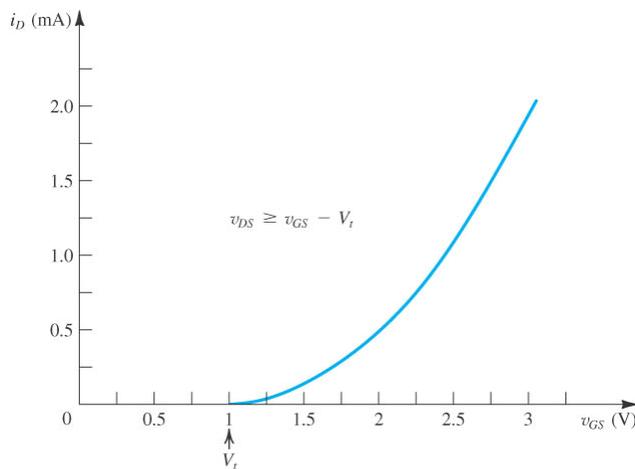
$$v_{DS} \geq v_{GS} - V_t \quad (\text{pinch off}) \quad (9)$$

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

$$i_D = \frac{1}{2} k_n' \frac{W}{L} (v_{GS} - V_t)^2 \quad (5.20), (10)$$

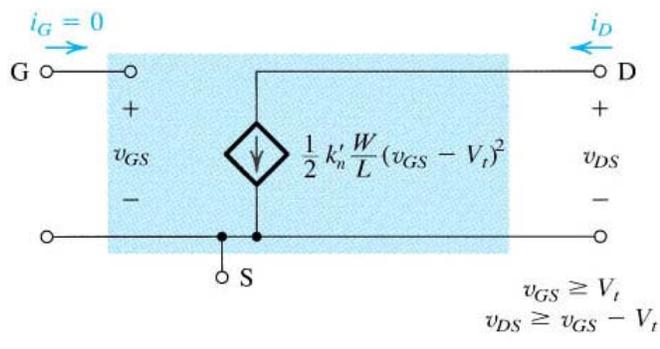
and is not dependent on  $v_{DS}$ , as shown in Fig. 1.

A plot of  $i_D$  versus  $v_{GS}$  in (5.20) for an enhancement type NMOS device in saturation is shown in Fig. 5.14:



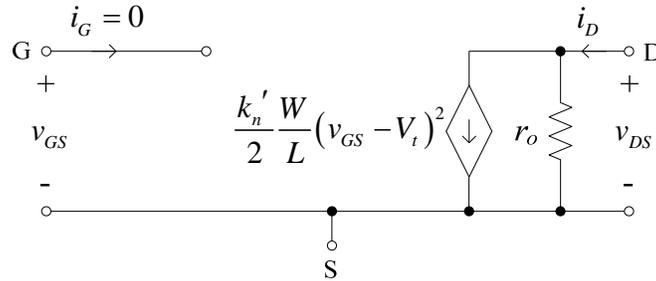
(Fig. 5.14)

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



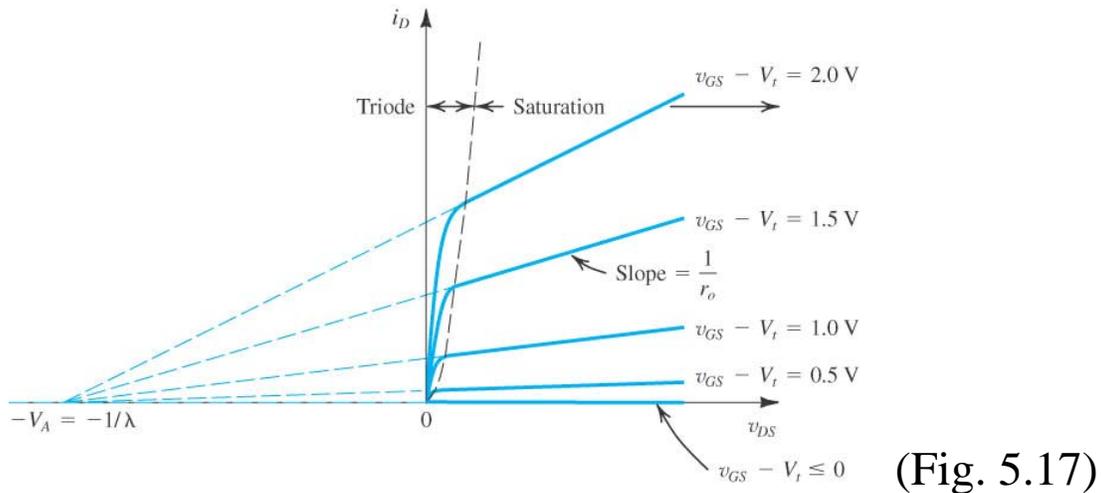
(Fig. 5.15)

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

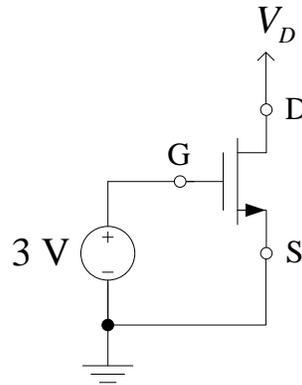


where 
$$r_o = \frac{V_A}{I'_D} \quad (5.27), (11)$$

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



**Example N26.1** 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.

Alternatively,  $V_{GD} = 3 - 0.5 = 2.5 \text{ V} > V_t$ , therefore the channel is open : Triode region.

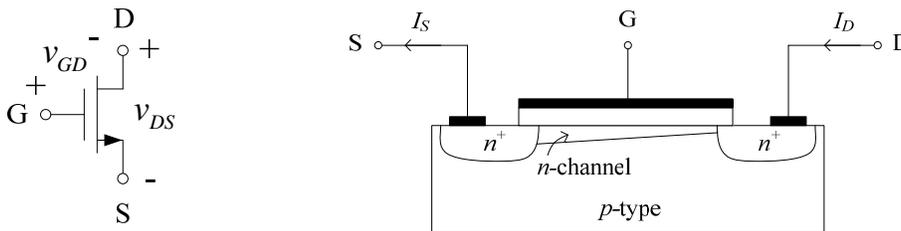
- (b)  $V_D = 1 \text{ V}$ .  $V_{GS} = 3 \text{ V} > V_t = 2 \text{ V} \Rightarrow$  not cutoff. Then  $V_{DS} = 1 \text{ V} = V_{GS} - V_t (= 1 \text{ V})$ .  $\therefore$  **saturation (or triode)** mode.

Alternatively,  $V_{GD} = 3 - 1 = 2 \text{ V} > V_t$ , therefore the channel is open : Triode region.

- (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.

Alternatively,  $V_{GD} = 3 - 5 = -2 \text{ V} < V_t$ , therefore the channel is closed, or pinched off, at the drain end: Saturation region.

**Example N26.2** (similar to text Problem 5.22). 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 open (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,

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