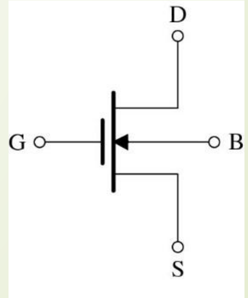
ENGR 305

MOSFET Current-Voltage Characteristics

September 25, 2025

Current-voltage characteristics

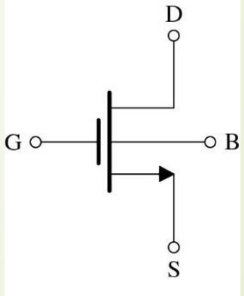
- These characteristics can be measured at dc or at low frequencies and thus are called static characteristics.
- The circuit symbol for the *n*-channel MOSFET is shown below.
  - The spacing between the two vertical lines representing the gate and the channel indicates that the gate electrode is insulated from the body of the device.
  - The polarity of the *p*-type substrate (body) and the *n* channel is indicated by the arrowhead on the line representing the body (B).



(a)

Current-voltage characteristics

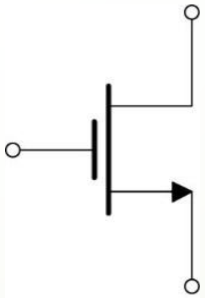
- Although the MOSFET is a symmetrical device, it is often useful in circuit design to designate one terminal as the source and the other as the drain.
- The modified circuit symbol accomplishes that by placing an arrowhead on the source terminal. The arrowhead points in the normal direction of current flow.
- The drain is always positive relative to the source in an n-channel MOSFET.



(b)

Current-voltage characteristics

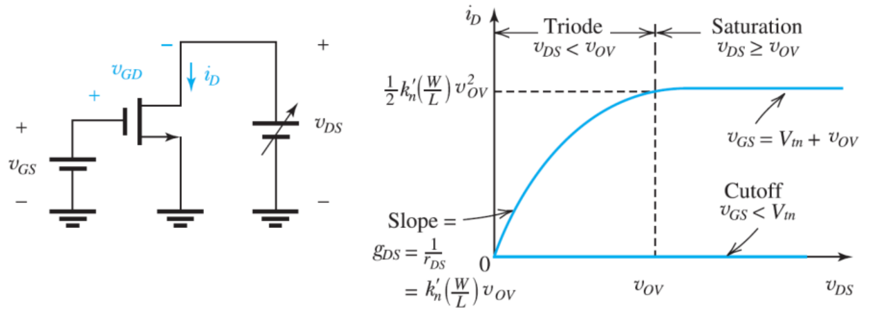
- In applications where the source is connected to the body of the device, a further simplification of the circuit symbol is possible
- This symbol is also used when the effect of the body on circuit operation is not important.



(c)

The $i_D - v_{DS}$ characteristics

Table 5.1 Regions of Operation of the Enhancement NMOS Transistor



- $v_{GS} < V_{tn}$: no channel; transistor in cutoff; $i_D = 0$
- $v_{GS} = V_{tn} + v_{OV}$: a channel is induced; transistor operates in the triode region or the saturation region depending on whether the channel is continuous or pinched off at the drain end;

Triode Region

Continuous channel, obtained by:

$$v_{GD} > V_{tn}$$

or equivalently:

$$v_{DS} < v_{OV}$$

Then,

$$i_D = k_n'\left(\frac{W}{L}\right)\left[(v_{GS} - V_{tn})v_{DS} - \frac{1}{2}v_{DS}^2\right]$$

or equivalently,

$$i_D = k_n'\left(\frac{W}{L}\right)\left(v_{OV} - \frac{1}{2}v_{DS}\right)v_{DS}$$

Saturation Region

Pinched-off channel, obtained by:

$$v_{GD} \leq V_{tn}$$

or equivalently:

$$v_{DS} \geq v_{OV}$$

Then

$$i_D = \frac{1}{2}k_n'\left(\frac{W}{L}\right)(v_{GS} - V_{tn})^2$$

or equivalently,

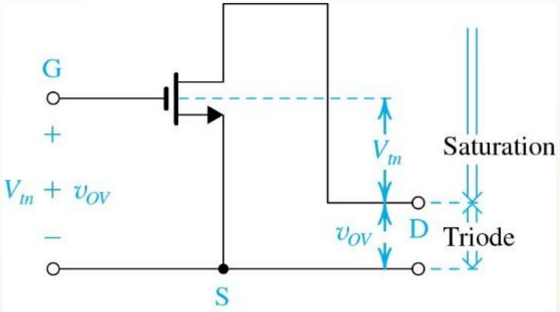
$$i_D = \frac{1}{2}k_n'\left(\frac{W}{L}\right)v_{OV}^2$$

The $i_D - v_{DS}$ characteristics

- There are three possible regions of operation for the MOSFET: the cutoff region, the triode region, and the saturation region.
- The cutoff and triode regions are useful when we want to operate the MOSFET as a switch.
- If we want to design an amplifier, the MOSFET must be operated in the saturation region.

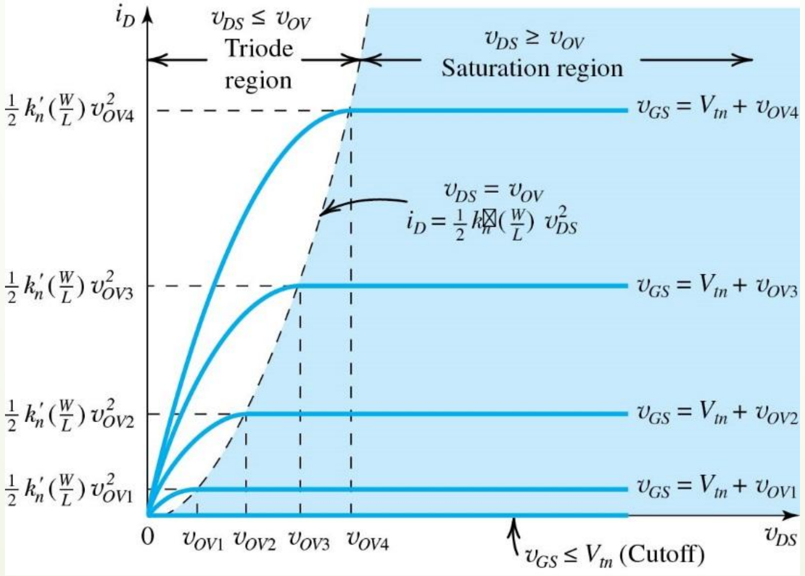
The $i_D - v_{DS}$ characteristics

- The boundary between the triode region and the saturation region is determined by whether v_{DS} is less or greater than the overdrive voltage v_{OV}.
- To operate in the triode region, the gate voltage must exceed the drain voltage by at least V_{tn} volts, ensuring that the channel remains continuous.
- To operate in saturation, the channel must be pinched off at the drain end; this is achieved by keeping v_D higher than $v_G - V_{tn}$.



The $i_D - v_{DS}$ characteristics

- In the figure, each graph is obtained by setting v_{GS} above V_{tn} by a specific value of overdrive voltage.



The $i_D - v_{DS}$ characteristics

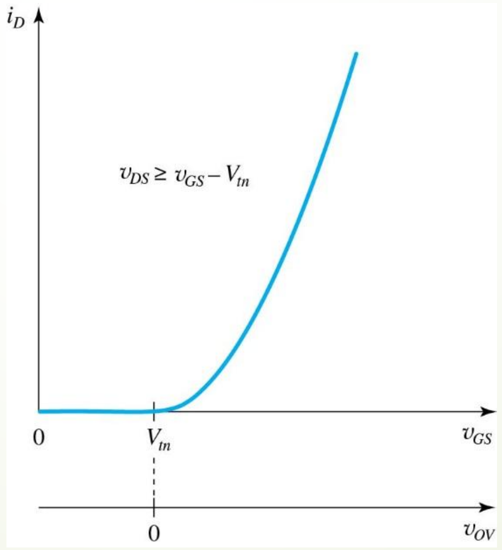
- For each curve in the figure, the value of v_{OV} is the value of v_{DS} at which the corresponding graph *saturates*.
- The value of the resulting saturation current for each curve is directly determined by the value of v_{OV} for that curve.
- Note that the boundary between the triode and saturation regions is described by
  - $i_D = \frac{1}{2} k_n' \left(\frac{W}{L}\right) v_{DS}^2$

The $i_D - v_{GS}$ characteristic

- When designing an amplifier, the MOSFET is operated in the saturation region.
- In saturation the drain current is a constant determined by v_{GS} or v_{OV}.
- The MOSFET operates as a voltage-controlled current source with the control relationship being
  - $i_D = \frac{1}{2} k_n' \left(\frac{W}{L}\right) (v_{GS} - V_{tn})^2$
- Writing this relationship in terms of v_{OV},
  - $i_D = \frac{1}{2} k_n' \left(\frac{W}{L}\right) v_{OV}^2$

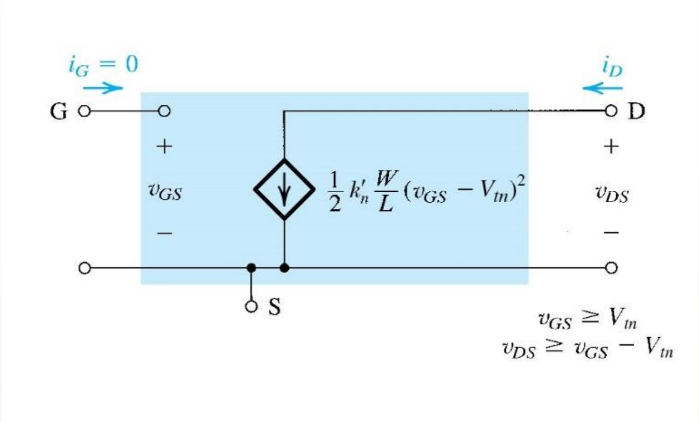
The $i_D - v_{GS}$ characteristic

- Shown here is the $i_D - v_{GS}$ characteristic of an NMOS transistor operating in saturation.
- If we want to plot i_D vs. v_{OV}, we simply shift the origin to the point $v_{GS} = V_{tn}$



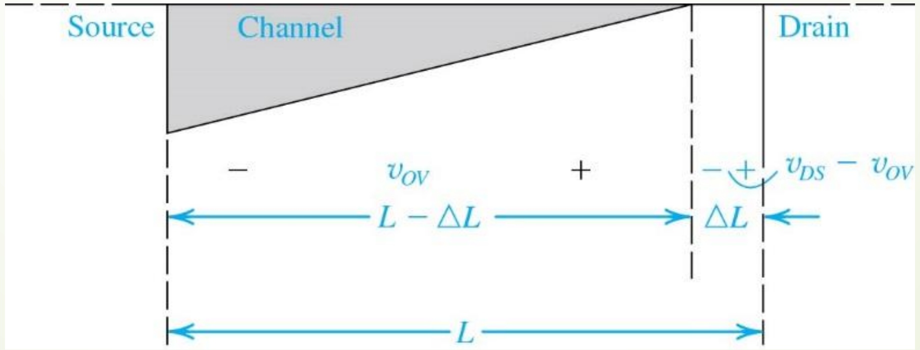
Large-signal equivalent circuit model

- The view of the MOSFET in the saturation region as a voltage-controlled current source is illustrated by the equivalent-circuit model shown.
  - Known as the **large-signal equivalent circuit**
- The current source here is ideal, with an infinite output resistance representing the independence, in saturation, of i_D from v_{DS}.



Finite output resistance in saturation

- The previous model assumed that when operating in saturation, an increase Δv_{DS} in the drain-to-source voltage causes zero change in the drain current.
- In reality, increasing v_{DS} beyond v_{OV} does affect the channel.
  - As v_{DS} is increased, the channel pinch-off point moves slightly away from the drain, toward the source.

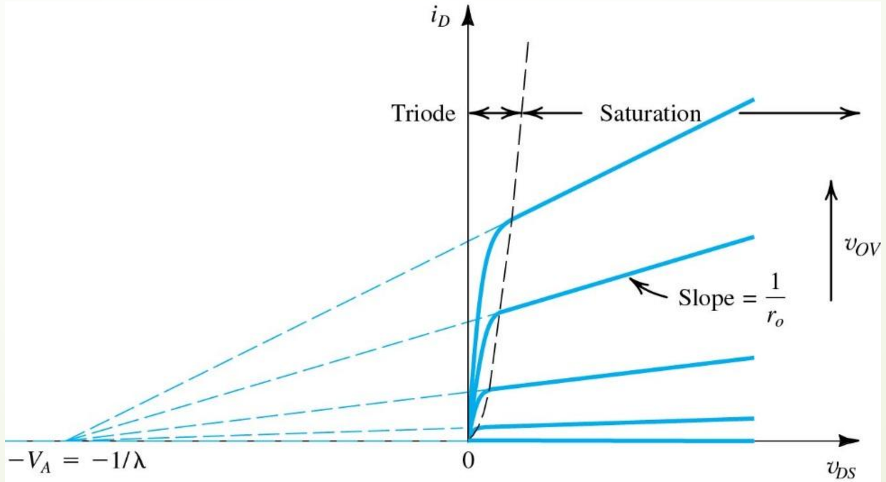


Finite output resistance in saturation

- The voltage across the channel remains constant at v_{OV} and the additional voltage applied to the drain appears as a voltage drop across the narrow depletion region between the end of the channel and the drain region.
- The channel length is in effect reduced from L to $L - \Delta L$
  - This phenomenon is known as **channel-length modulation.**
- We account for this effect in the expression for i_D by including a factor $(1 + \lambda v_{DS})$
  - $i_D = \frac{1}{2} k_n' \left(\frac{W}{L}\right) (v_{GS} - V_{tn})^2 (1 + \lambda v_{DS})$
  - Here λ is a device parameter whose units are reciprocal volts (V^{-1}).
  - The value of λ depends on both the process technology and the channel length L.

Finite output resistance in saturation

- The figure shows a set of $i_D - v_{DS}$ characteristics showing the effect of channel-length modulation.
- The observed linear dependence of i_D on v_{DS} in the saturation region is represented in the equation by the factor $(1 + \lambda v_{DS})$.



Finite output resistance in saturation

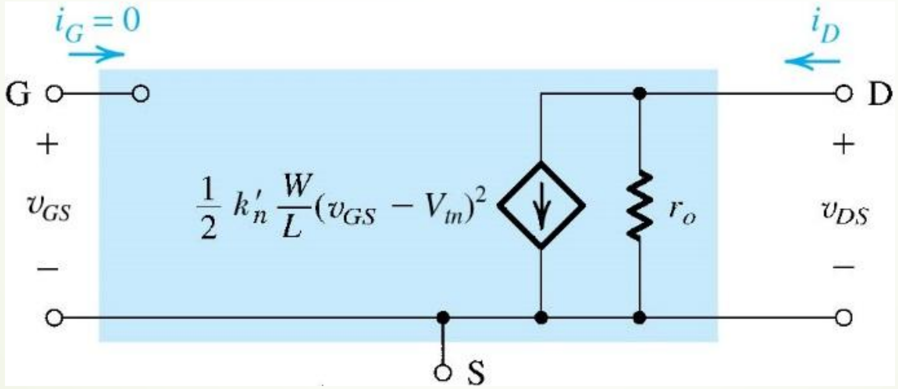
- When the straight-line $i_D - v_{DS}$ characteristics are extrapolated, they intersect the v_{DS} axis at the point $v_{DS} = -V_A$, where V_A is a positive voltage.
- The equation for drain current indicates that $i_D = 0$ at $v_{DS} = -1/\lambda$.
- Then it follows that $V_A = \frac{1}{\lambda}$
- V_A is a device parameter with dimensions of V, and for a given process, V_A is proportional to the channel length L that the designer selects for the MOSFET.
- We can express this as $V_A = V_A' L$
  - V_A' is entirely process-technology dependent having the dimensions of volts per micron.
  - Typical values for V_A' are in the range of $5\ V/\mu m$ to $50\ V/\mu m$.

Finite output resistance in saturation

- The output resistance of the current source representing i_D in saturation is no longer infinite. We define the output resistance as
  - $r_o = \left[\frac{\partial i_D}{\partial v_{DS}}\right]^{-1}_{vGS\ constant}$
- Using the equation for i_D results in
  - $r_o = \left[\lambda \frac{k_n'}{2} \frac{W}{L} (v_{GS} - V_{tn})^2\right]^{-1}$
- This can be written as $r_o = \frac{1}{\lambda i_D'} = \frac{V_A}{i_D'}$
- Note that i_D' is the drain current without channel-length modulation
- $i_D' = \frac{1}{2} k_n' \frac{W}{L} (v_{GS} - V_{tn})^2$

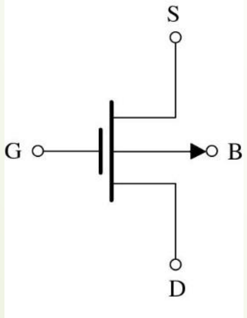
Large-signal equivalent circuit model

- The figure shows the large-signal, equivalent-circuit model of the *n*-channel MOSFET in saturation, incorporating the output resistance r_o.

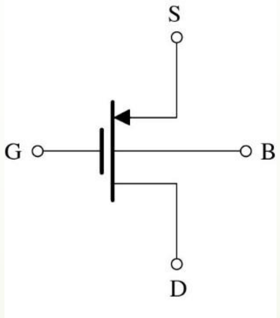


Characteristics of the *p*-channel MOSFET

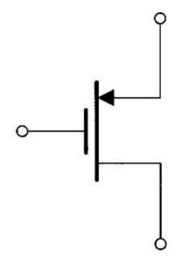
- The circuit symbol for the p-channel enhancement-type MOSFET is shown in part (a).
- In part (b) is shown the modified circuit symbol with an arrowhead pointing in the normal direction of current flow.
- In part (c) we see the simplified circuit symbol when the source is connected to the substrate (body).



(a)

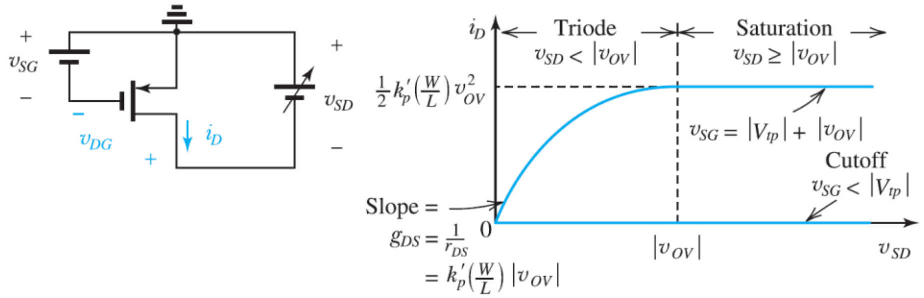


(b)


(c)

Characteristics of the *p*-channel MOSFET

Table 5.2 Regions of Operation of the Enhancement PMOS Transistor



- $v_{SG} < |V_{tp}|$: no channel; transistor in cutoff; $i_D = 0$
- $v_{SG} = |V_{tp}| + |v_{OV}|$: a channel is induced; transistor operates in the triode region or in the saturation region depending on whether the channel is continuous or pinched off at the drain end;

Triode Region

Continuous channel, obtained by:

$$v_{DG} > |V_{tp}|$$

or equivalently

$$v_{SD} < |v_{OV}|$$

Then

$$i_D = k_p'\left(\frac{W}{L}\right)\left[(v_{SG} - |V_{tp}|)v_{SD} - \frac{1}{2}v_{SD}^2\right]$$

or equivalently

$$i_D = k_p'\left(\frac{W}{L}\right)\left(|v_{OV}| - \frac{1}{2}v_{SD}\right)v_{SD}$$

Saturation Region

Pinched-off channel, obtained by:

$$v_{DG} \leq |V_{tp}|$$

or equivalently

$$v_{SD} \geq |v_{OV}|$$

Then

$$i_D = \frac{1}{2}k_p'\left(\frac{W}{L}\right)(v_{SG} - |V_{tp}|)^2$$

or equivalently

$$i_D = \frac{1}{2}k_p'\left(\frac{W}{L}\right)v_{OV}^2$$

Characteristics of the *p*-channel MOSFET

- While V_{tp} is negative, we use $|V_{tp}|$
- The voltages v_{SG} and v_{SD} are positive.
- The PMOS devices also are affected by the channel-length modulation effect
- The drain current can be expressed as
  - $i_D = \frac{1}{2}k_p'\left(\frac{W}{L}\right)\left(v_{SG} - |V_{tp}|\right)^2(1 + |\lambda|v_{SD})$
- Or equivalently
  - $i_D = \frac{1}{2}k_p'\left(\frac{W}{L}\right)\left(v_{SG} - |V_{tp}|\right)^2\left(1 + \frac{v_{SD}}{|V_A|}\right)$

Characteristics of the *p*-channel MOSFET

- To turn on a PMOS transistor, the gate voltage has to be made lower than the source voltage by at least $|V_{tp}|$.
- To operate in the triode region, the drain voltage has to exceed that of the gate by at least $|V_{tp}|$. Otherwise, the PMOS device operates in saturation.