EE105 – Fall 2015
Microelectronic Devices and Circuits

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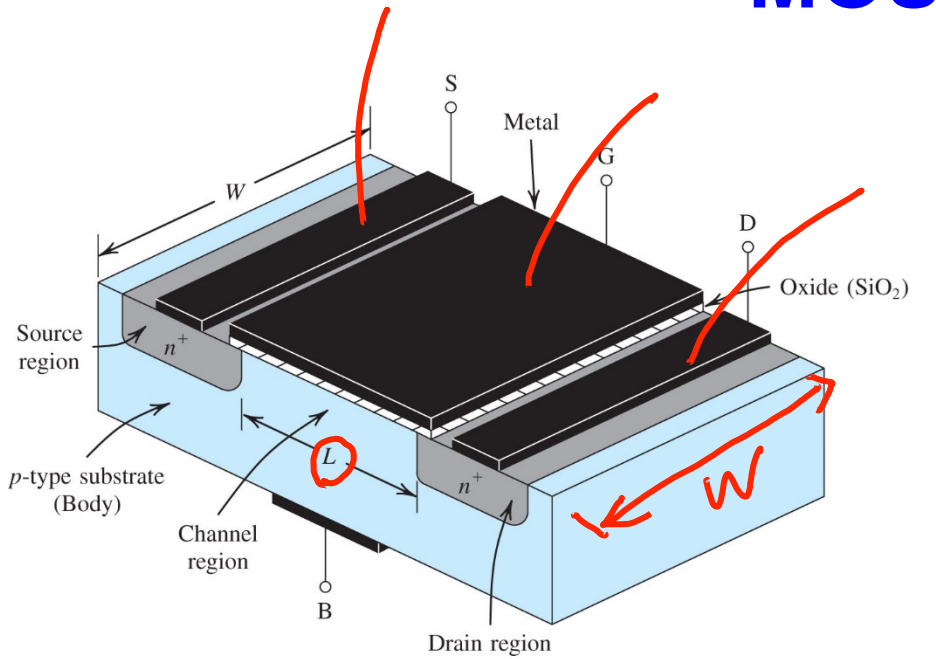
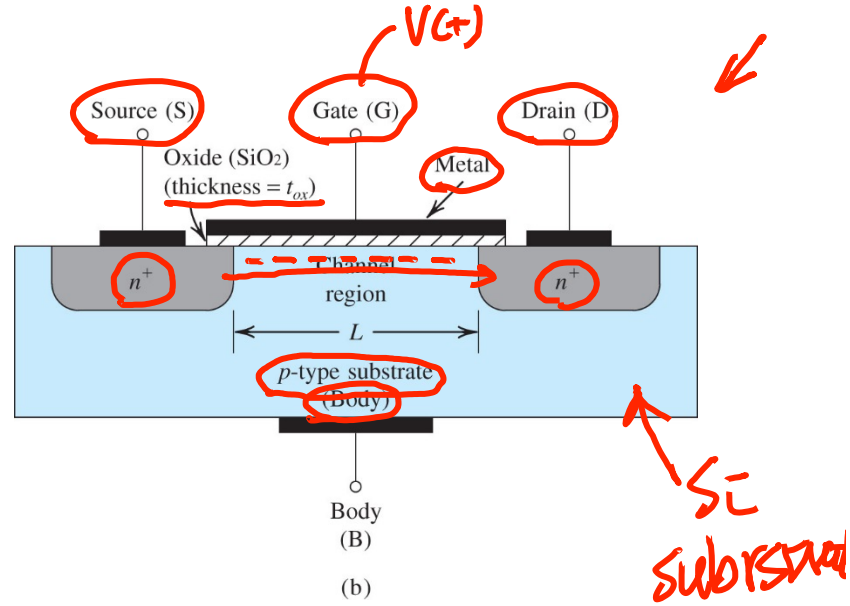
MOSFET

Metal-Oxide-Semiconductor



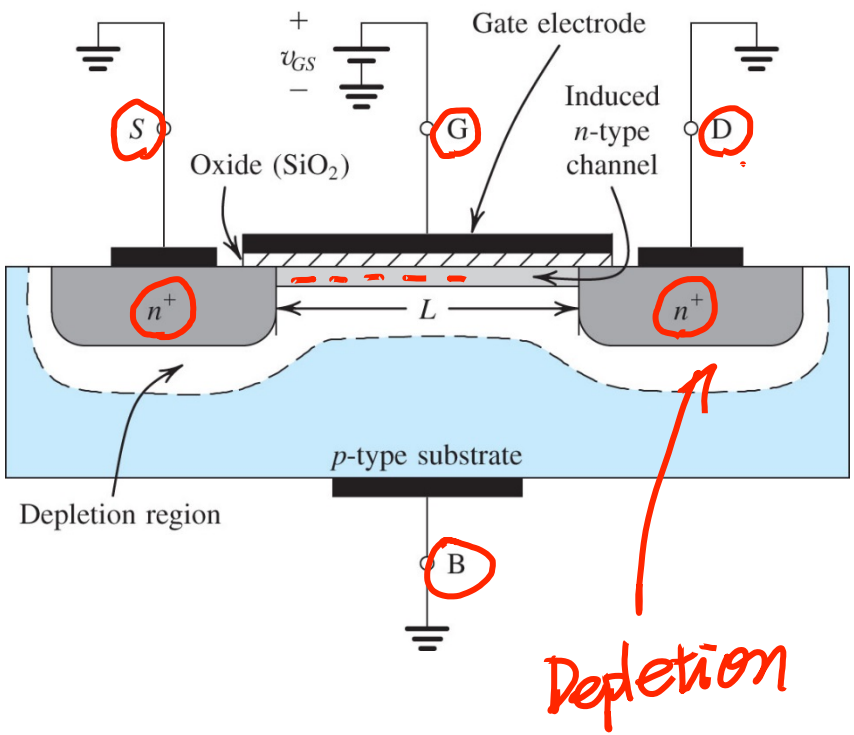
(a)



(b)

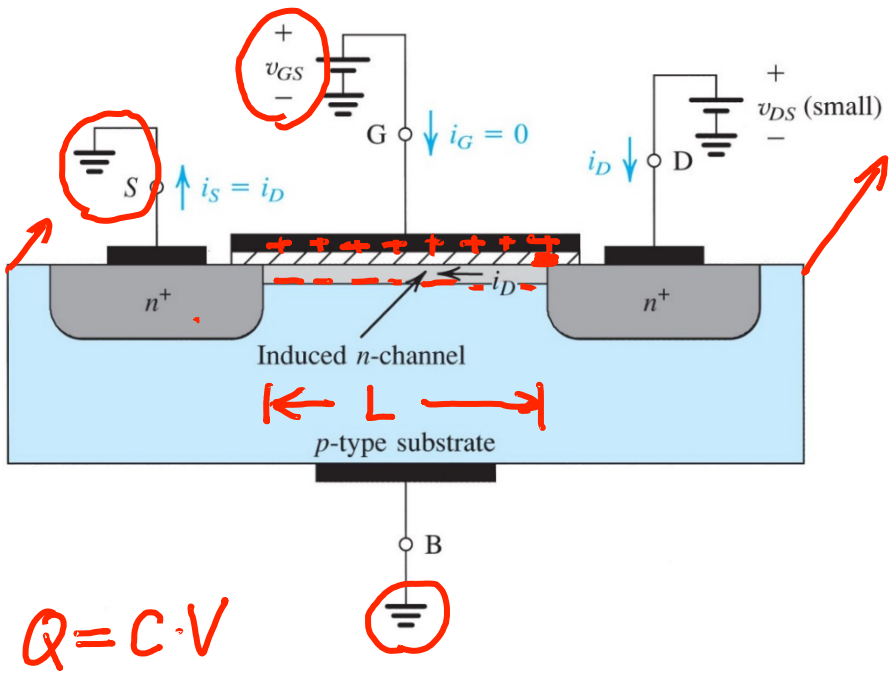
- **MOSFET: metal-oxide-semiconductor field effect transistor**
- **Typically**
  - **Channel length: L ~ 10 nm to 0.35 μm,**
  - **Channel width: W ~ 0.05 μm to 100 μm,**
  - **Oxide thickness: t_{ox} ~ 1 to 10 nm**

NMOSFET (or simply NMOS)

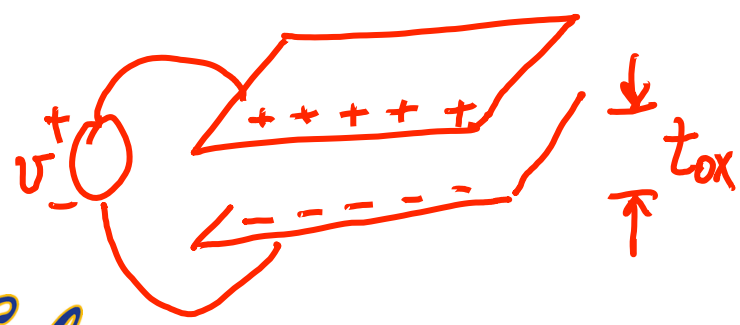


- N-channel MOSFET
  - Current conducted by electrons
- 3 terminal device
  - Source (S): n+ (heavily n-type)
  - Drain (D): n+
  - Gate (G): metal deposited on insulator above channel
- Substrate (called "Body") is a 4th terminal
  - Substrate is p-doped
- Electrons is induced in channel when a positive gate voltage is applied
- Electrons moves from Source to Drain
  - Current flows from D to S

Creating a "Channel" for Current Flow



$Q = C \cdot V$



MOS is a capacitor across an insulator (oxide)

When a positive voltage is applied at Gate, electrons are induced under the gate.

At "thresold", sufficient number of electrons form a "channel" between Source and Drain, forming a conductive channel.

Total charge in the channel:

$$|Q| = C_{ox} \cdot WL \cdot (v_{GS} - V_t)$$ ← Process control

where $C_{ox} = \dfrac{\varepsilon_{ox}}{t_{ox}}$ is oxide capacitance

per unit area

$\varepsilon_{ox} = 3.9\varepsilon_0 = 3.9 \times (8.854 \times 10^{-12}\ \text{F/m})$

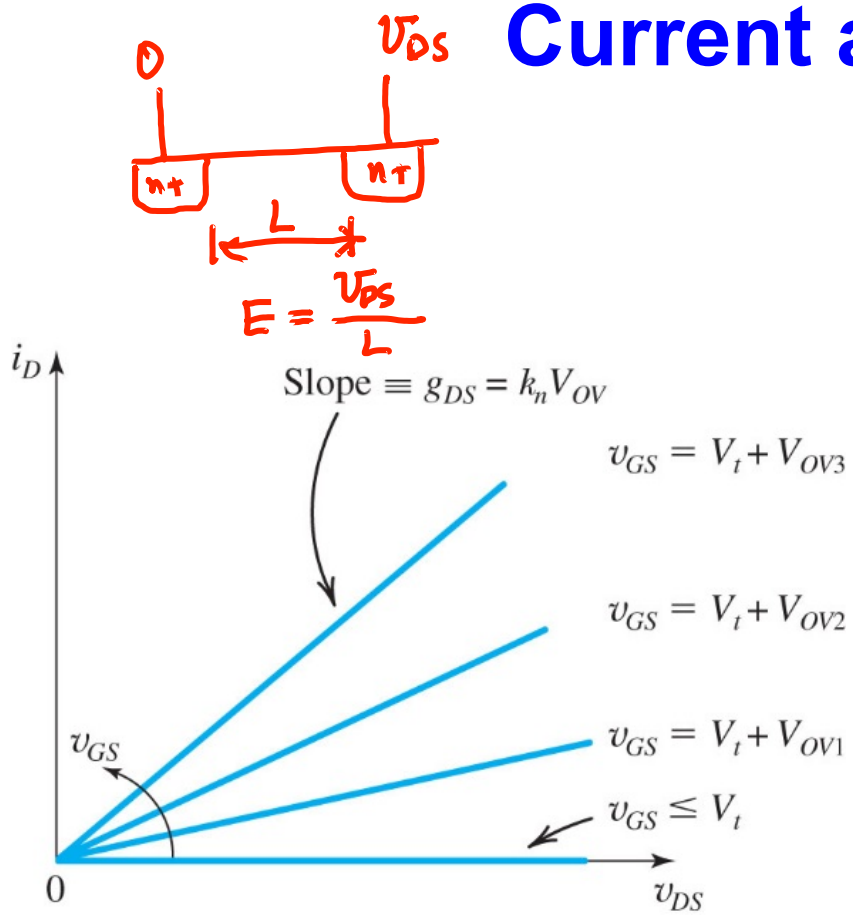
W : gate width

L : gate length

V_t : Threshold voltage

$\boxed{v_{GS} - V_t \equiv v_{OV}}$ is called "Overdrive Voltage"

Current at Small v_{DS}



When $v_{OV} = v_{GS} - V_t > 0$, a channel is formed between Source and Drain.

Linear charge density in channel:

$$\frac{|Q|}{L} = C_{ox} W \cdot v_{OV}$$

Electric field along the channel

$$|E| = \frac{v_{DS}}{L}$$

Drain current = charge density x velocity:

$$i_D = \frac{|Q|}{L} v_n = \frac{|Q|}{L} \mu_n |E| = C_{ox} W \cdot v_{OV} \mu_n \frac{v_{DS}}{L}$$

$$i_D = \left(\mu_n C_{ox} \frac{W}{L}\right) v_{OV} v_{DS}$$

aspect ratio of FET

At small v_{DS}, the transistor is like a gate-controlled variable resistor

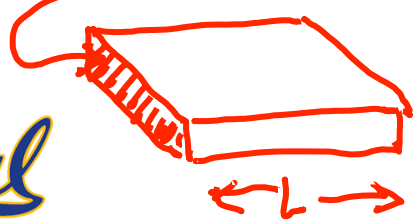
$J = n q v_n$

$\frac{Q}{L} = \frac{C_{ox} W \cdot L \cdot v_{OV}}{L}$

$I = J \cdot \text{area} = (n q \cdot \text{area}) v_n$

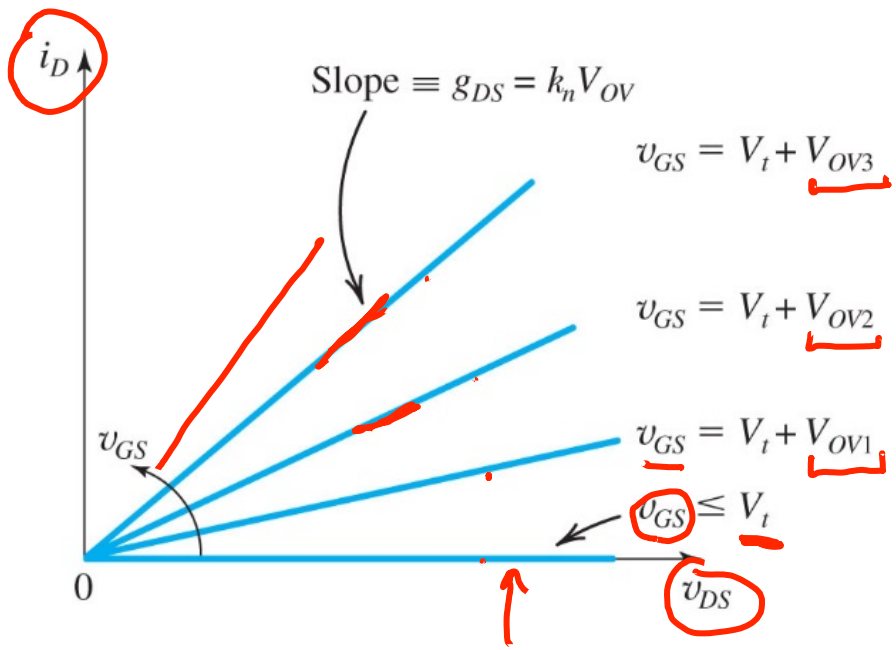
$Q = (n q \cdot \text{area} \cdot L)$

volume



$\rightarrow i_D$

Current at Small v_{DS}



$$i_D = (\mu_n C_{ox}) \frac{W}{L} v_{OV} v_{DS}$$

$$= k_n' \frac{W}{L} v_{OV} v_{DS}$$

$$= k_n v_{OV} v_{DS}$$

where

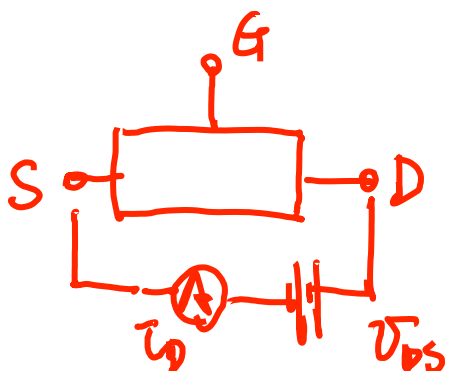
$k_n' = \mu_n C_{ox}$: process transconducance paramter

$k_n = \left(\mu_n C_{ox} \frac{W}{L}\right)$: MOSFET transconductance parameter

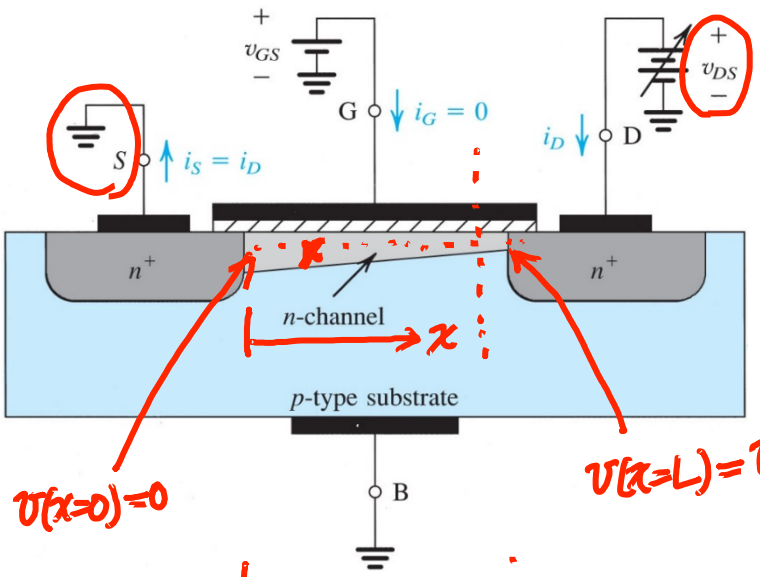
MOSFET behaves like a linear resistor

$$r_{DS} = \frac{v_{DS}}{i_D} = \frac{1}{k_n v_{OV}}$$

Resistance value can be changed by gate voltage (overdrive voltage)



Triode Region ($v_{DS} < v_{OV}$)



As v_{DS} increases, the potential in the channel is no longer a constant. Assume the channel is $v(x)$:

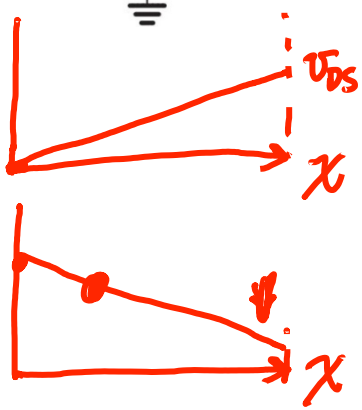
$$i_D = \left[C_{ox}W\left(v_{GS} - v(x) - V_t\right)\right]v_n(x) = i_D(x) = i_D$$

$$v_n(x) = \mu_n\left|E(x)\right| = \mu_n\frac{dv(x)}{dx}$$

Note: i_D is still constant along the channel (think Kirchhoff's Current Law)

Integrate along the channel

$$\int_{x=0}^{x=L} i_D\,dx = \int_{x=0}^{x=L}\left(C_{ox}W\left(v_{GS} - v(x) - V_t\right)\mu_n\frac{dv(x)}{dx}\right)dx$$



$\frac{Q}{\text{area}} = C_{ox} * (v_{GS} - v(x) - V_t)$

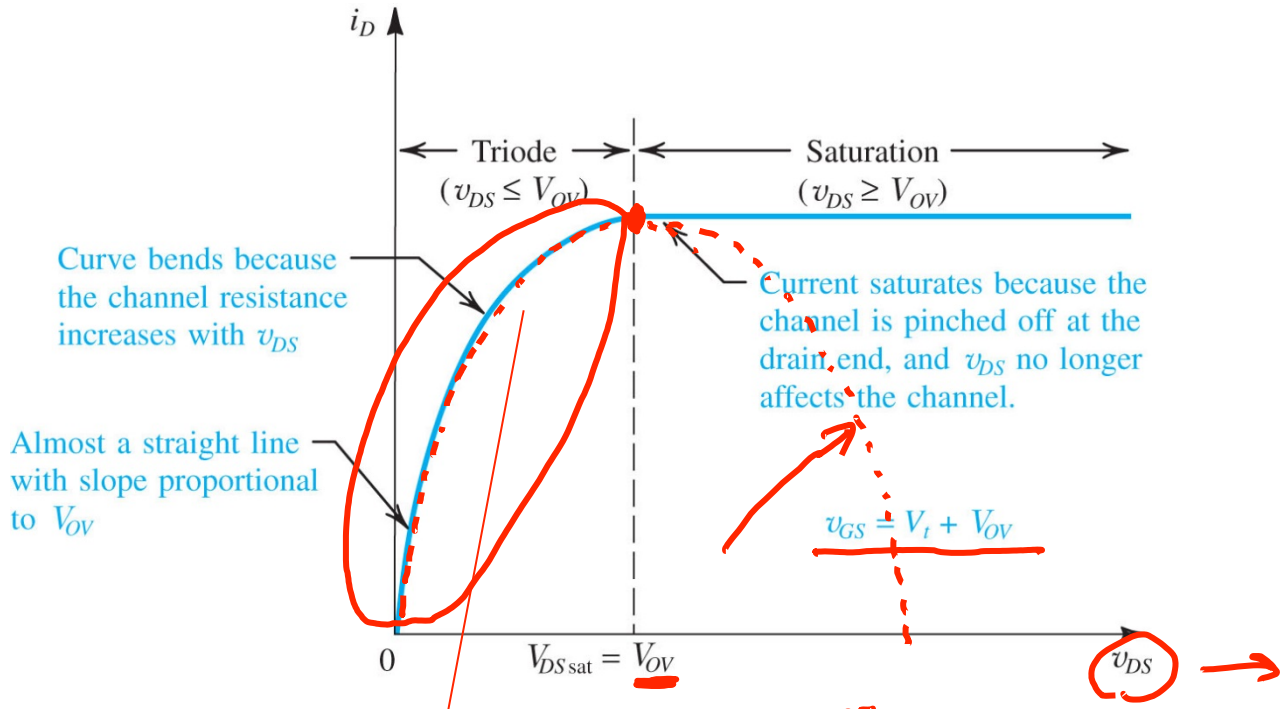
Change of variable on right-hand side: $x \rightarrow v$

$$i_D L = \int_{v=0}^{v=v_{DS}}\left(C_{ox}W\left(v_{OV} - v\right)\mu_n\right)dv \qquad \int v\,dv = \frac{1}{2}v^2$$

$$\Longrightarrow \quad i_D = \mu_n C_{ox}\left(\frac{W}{L}\right)\left(v_{OV}v_{DS} - \frac{1}{2}v_{DS}^2\right)$$

$\rightarrow \mu_n C_{ox}\left(\frac{W}{L}\right) v_{OV} v_{DS}$ when v_{DS} small

Triode Region ($v_{DS} < v_{OV}$)



$$\frac{v_{OV}}{2\times\left(\frac{1}{2}\right)} = v_{OV}$$

When $0 \le v_{DS} \le v_{OV}$

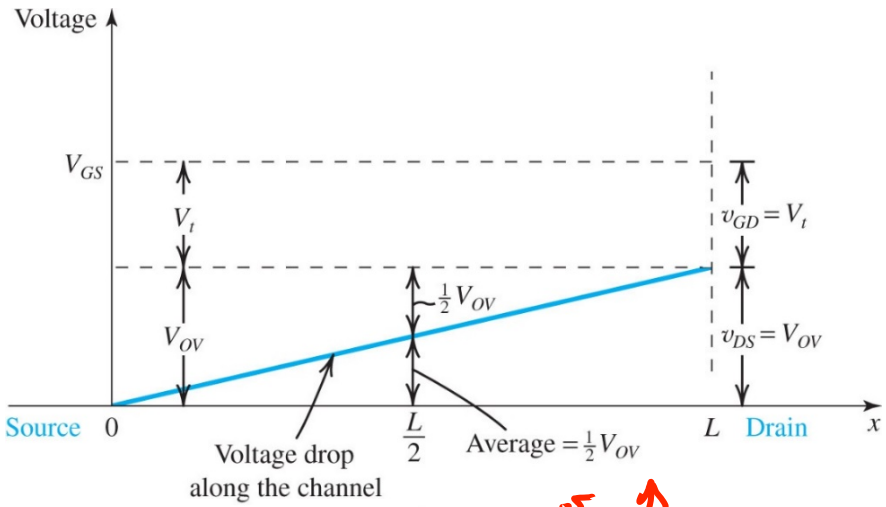
$$i_D = \mu_n C_{ox}\left(\frac{W}{L}\right)\left(v_{OV}v_{DS} - \frac{1}{2}v_{DS}^2\right)$$

This is called the "Triode Region"

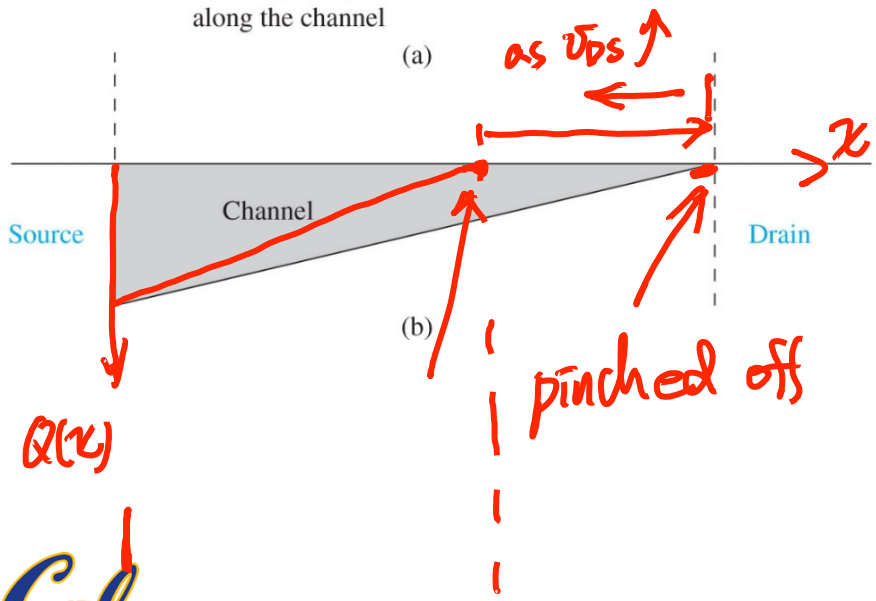
Pinch-Off

$\Rightarrow Q = C_{ox}(v_{GS} - v(x) - V_t) = 0$ when $v(x) = v_{DS} = v_{GS} - V_t = v_{OV}$

$x = L,\ v(x) = v_{DS}$



(a)



(b)

The channel potential at the drain side is v_{DS}.

When $v_{DS} = v_{OV}$, the local charge density there

$$\frac{|Q|}{\text{area}} = C_{ox}\left(v_{GS} - v_{DS} - V_t\right) = C_{ox}\left(v_{OV} - v_{DS}\right) = 0$$

So the channel is "pinched off" near the Drain.

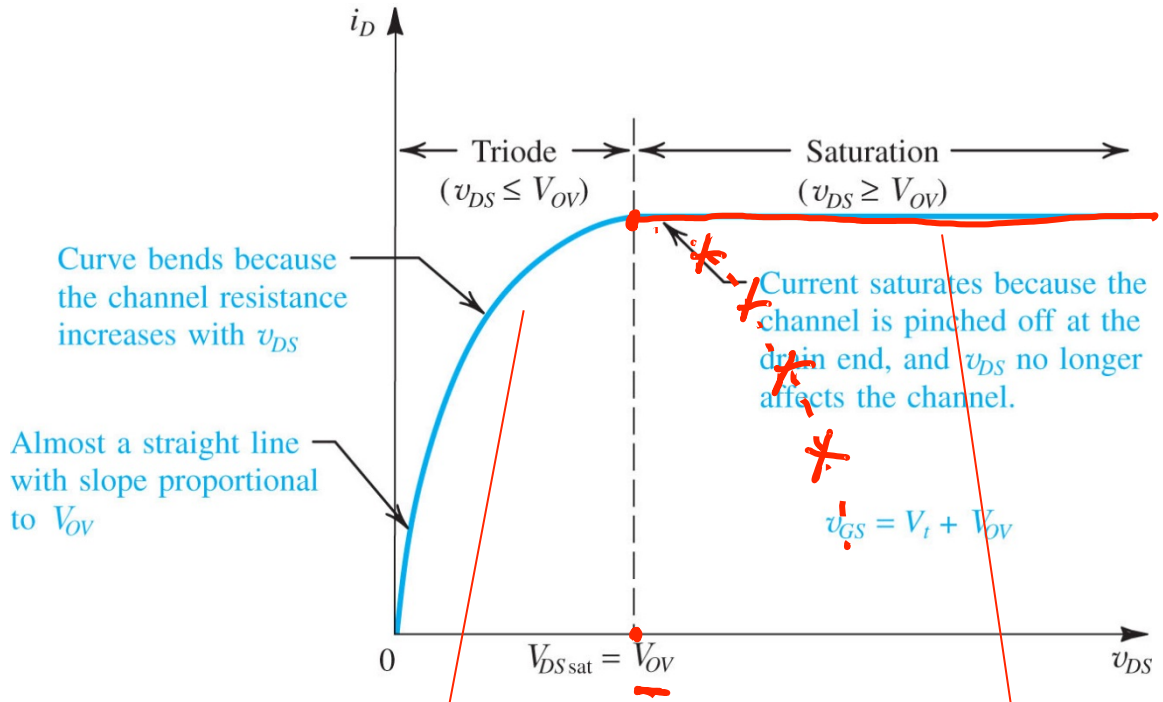
Once the channel is pinched off, the drain current remains constant:

$$i_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}v_{OV}^2$$

This region, $v_{DS} > v_{OV}$, is called "Saturation"

what happens when $v_{DS} > v_{OV}$

Saturation Region ($v_{DS} > v_{OV}$)



When $0 \le v_{DS} \le v_{OV}$

$$i_D = \mu_n C_{ox} \frac{W}{L}\left(v_{OV} v_{DS} - \frac{1}{2} v_{DS}^2\right)$$

This is called the "Triode Region"

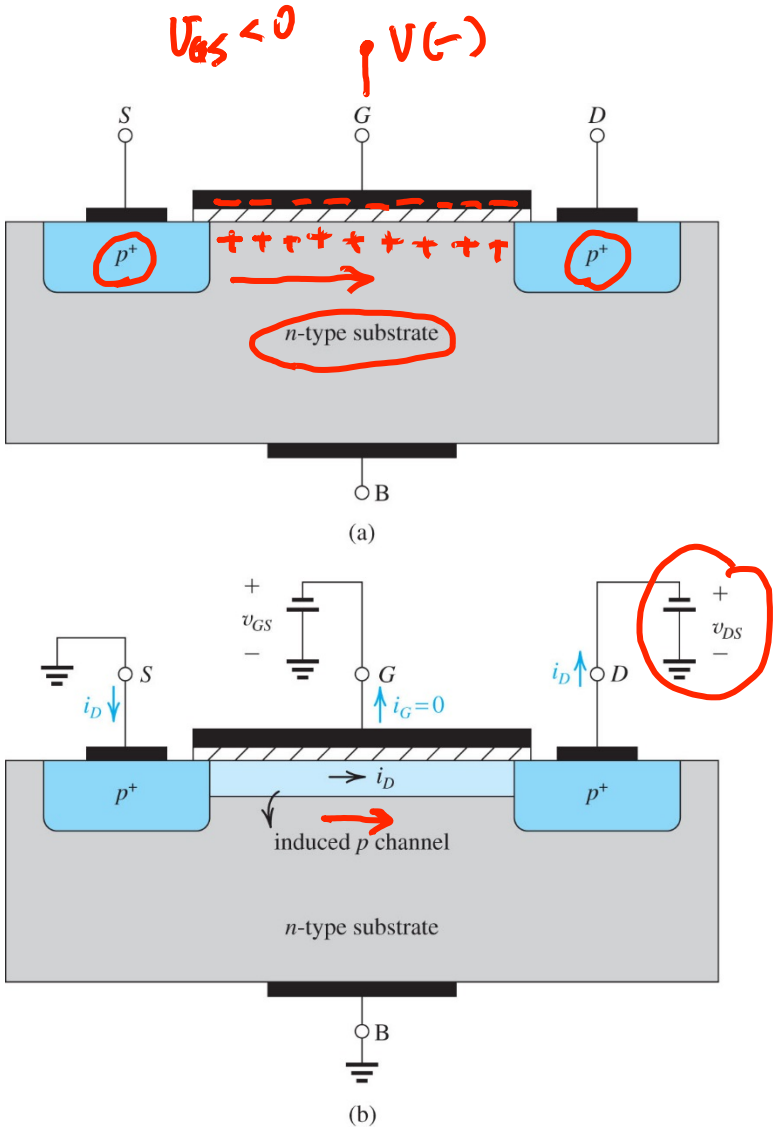
$i_{D,max} = \frac{1}{2} \mu_n C_{ox} \left(\frac{W}{L}\right)$ $\quad v_{DS} = v_{OV}$

When $v_{DS} > v_{OV}$,

$$\boxed{i_D = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} v_{OV}^2}$$

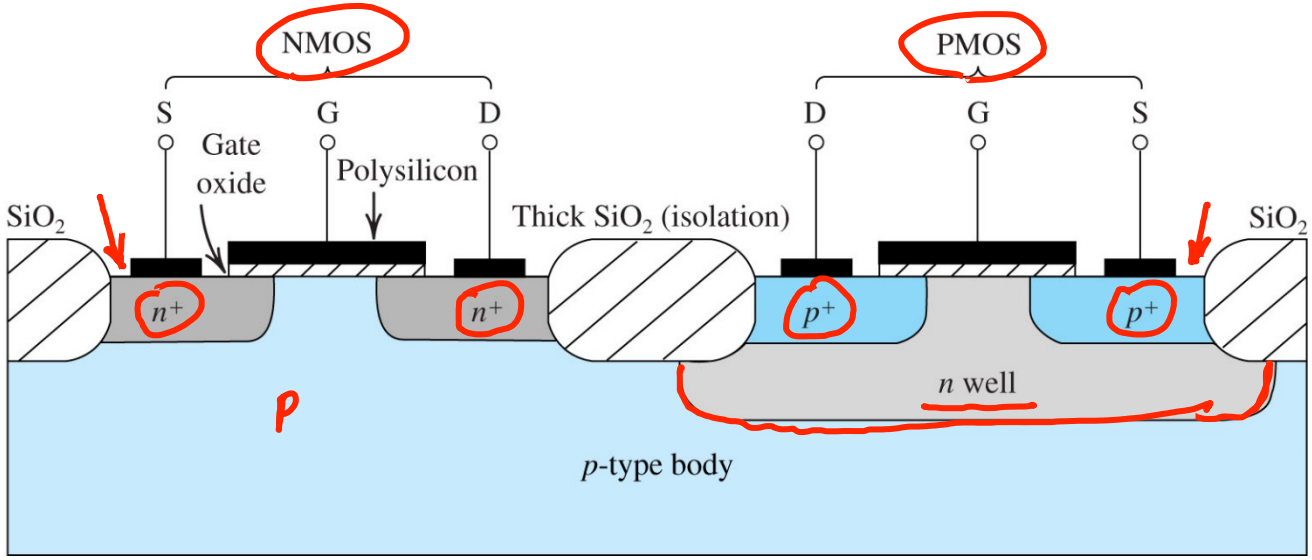
This is called "Saturation Region"

PMOSFET (or simply PMOS)



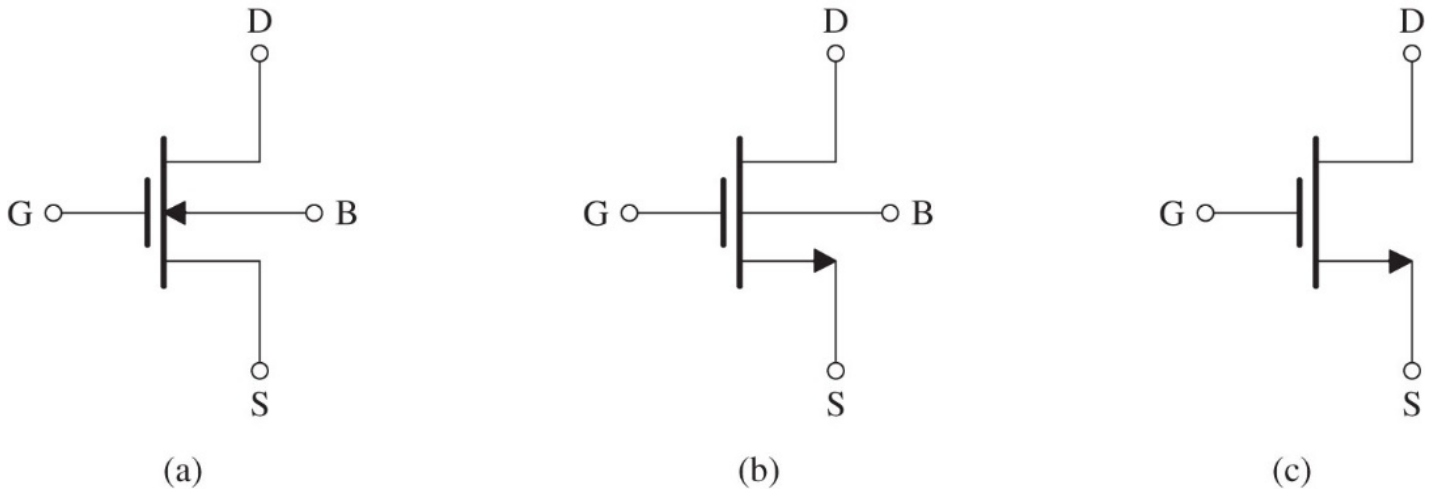
- **P-channel MOSFET**
  - **Current conducted by holes**
- **3 terminal device**
  - **Source (S): p+ (heavily p-type)**
  - **Drain (D): p+**
  - **Gate (G): metal deposited on insulator above channel**
- **Substrate (called "Body") is a 4th terminal**
  - **Substrate is n-doped**
- **Holes is induced in channel when a negative gate voltage is applied**
- **Holes moves from Source to Drain**
  - **Current flows from S to D**

CMOS
(Complementary MOS)



- CMOS is the prevalent IC technology today
- Since NMOS and PMOS are formed on oppositely doped substrates, one of the transistor needs to be placed in a "well"
- PMOS is placed in an "n well" here.
- Alternatively, NMOS can be placed in p well

Circuit Symbol for NMOS

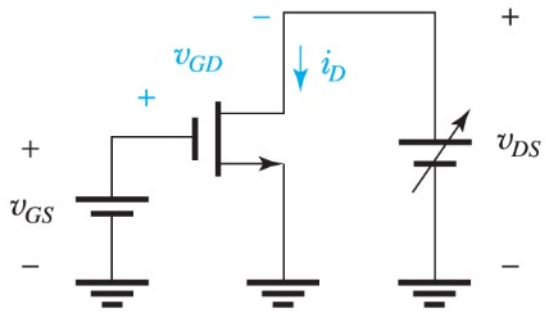


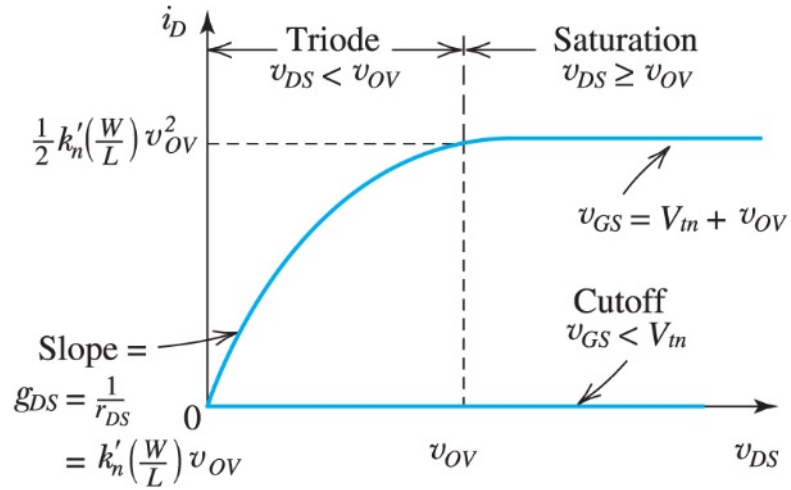
4 terminal including Body (Arrow pointing to channel indicating substrate is p-type)

Modified circuit symbol with arrow on source (Arrow indicating direction of current flow)

Simplified circuit symbol with body connected to source (or when the effect of the body on device operation is unimportant)

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,

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