Lecture 01: Metal-Oxide-Semiconductor Field Effect Transistor (MOSFET)

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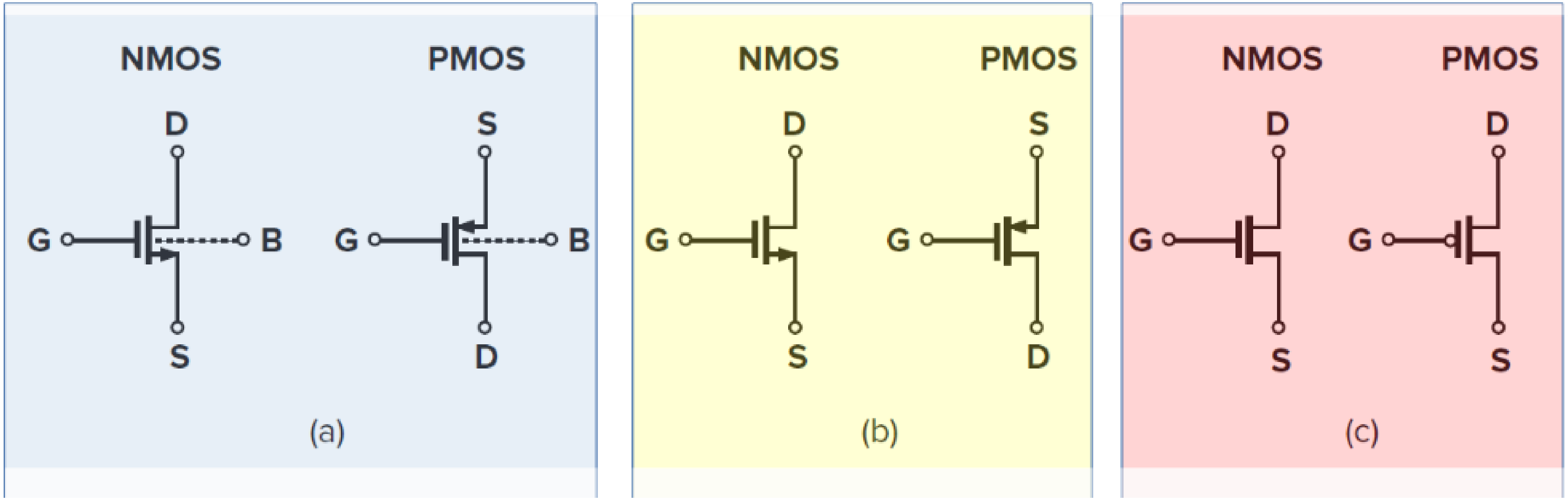
Outline

Remember this is an overview*

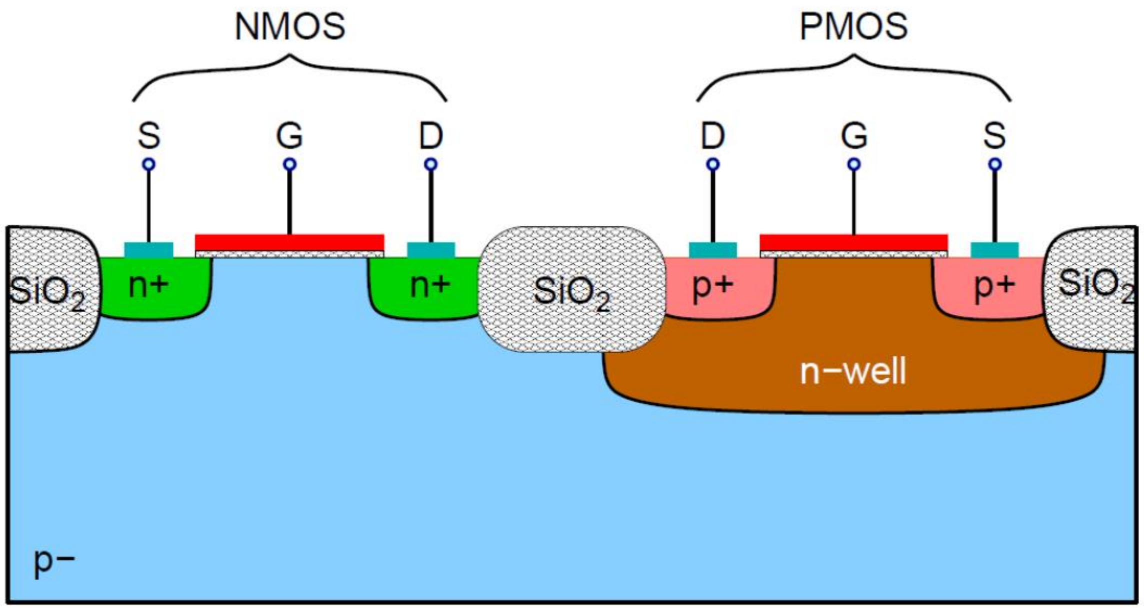
- Introduction
- Basic Operation
- Regions
  - Triode
  - Saturation
- Summary

MOSFET Circuits Symbols

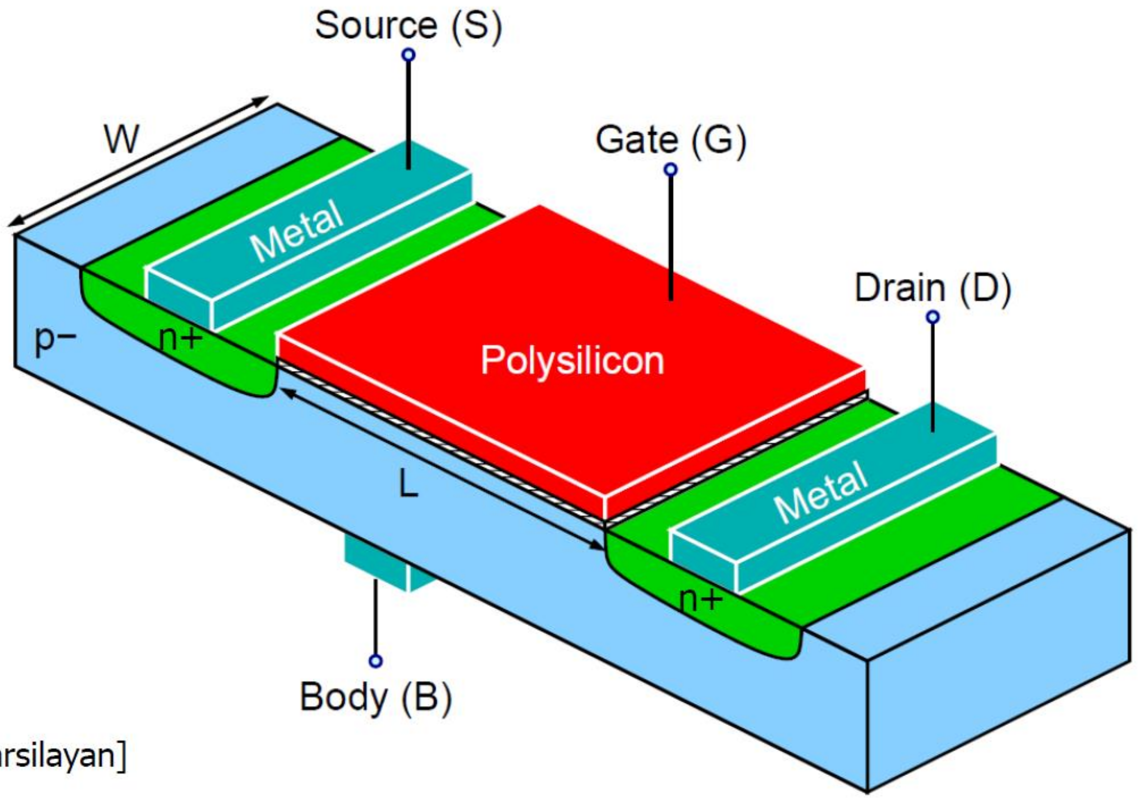


- MOSFETs are 4-terminal devices: Drain, Gate, Source, and Body (or Bulk)
- Body terminal generally has small impact in normal operation.
- Two complementary types: **NMOS** and **PMOS**

MOSFET Physical Structure



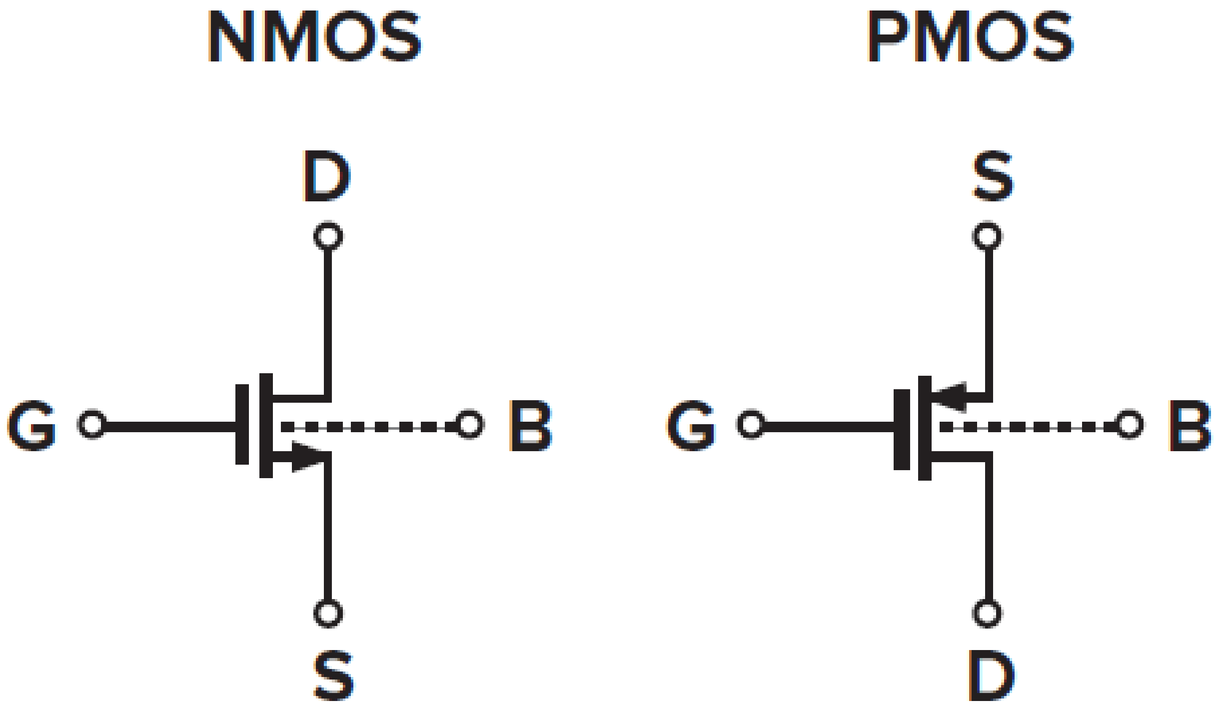
[Karsilayan]



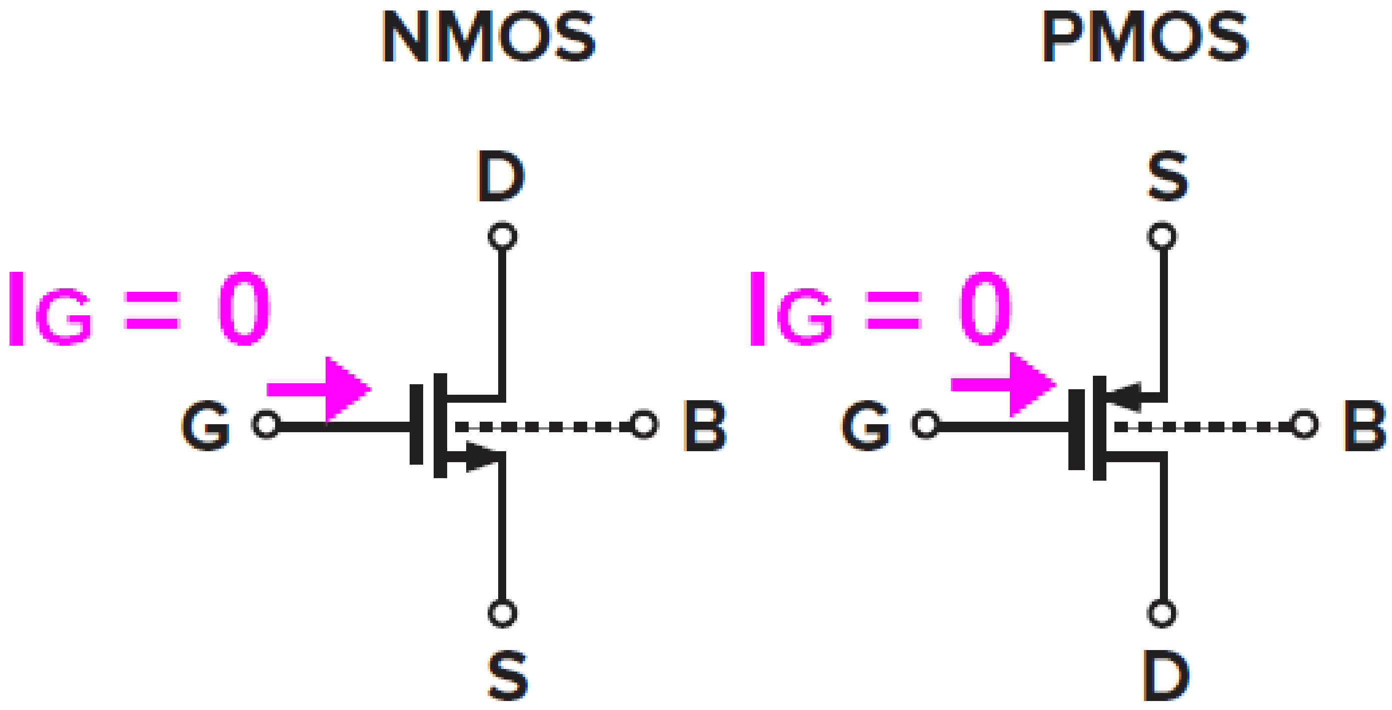
[Karsilayan]

- MOSFET is a symmetrical device (integrated)

MOSFET – Initial Thoughts



MOSFET – Initial Thoughts



- The current flowing through Gate terminal can be considered equal to zero.

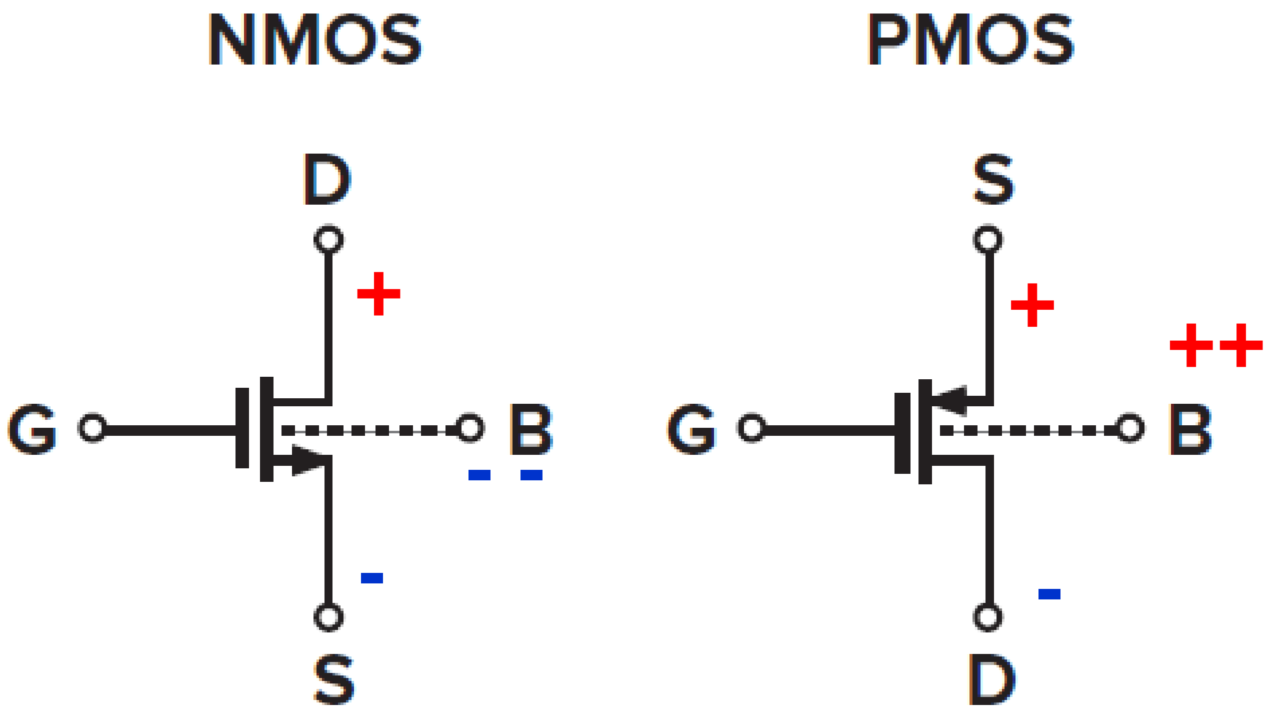
MOSFET – Initial Thoughts

In NMOS:

Drain more + than source.
Bulk (body) must be connected to the most - terminal in the circuit (or source).

In PMOS:

Source is more + than drain.
Bulk (body) must be connected to the most + terminal in the circuit (or source).



MOSFET – Initial Thoughts

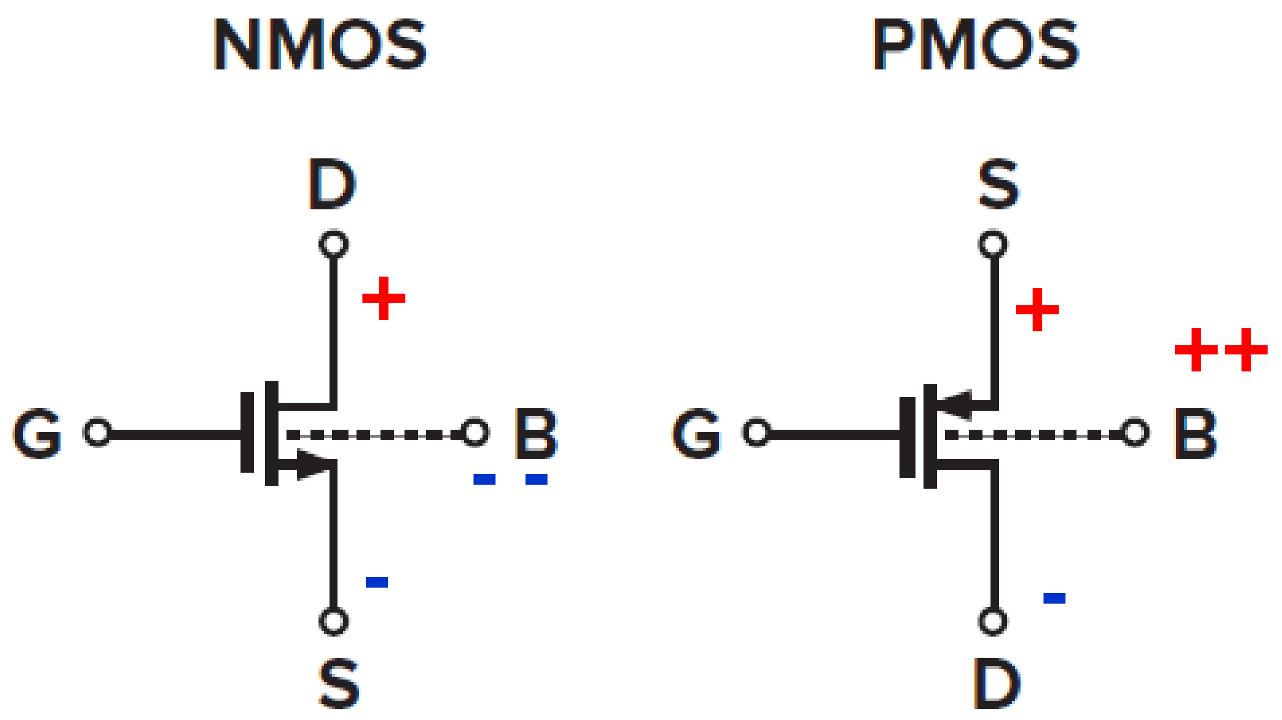
<u>In NMOS:</u>

Drain more + than source.
Bulk (body) must be connected to the most - terminal in the circuit (or source).

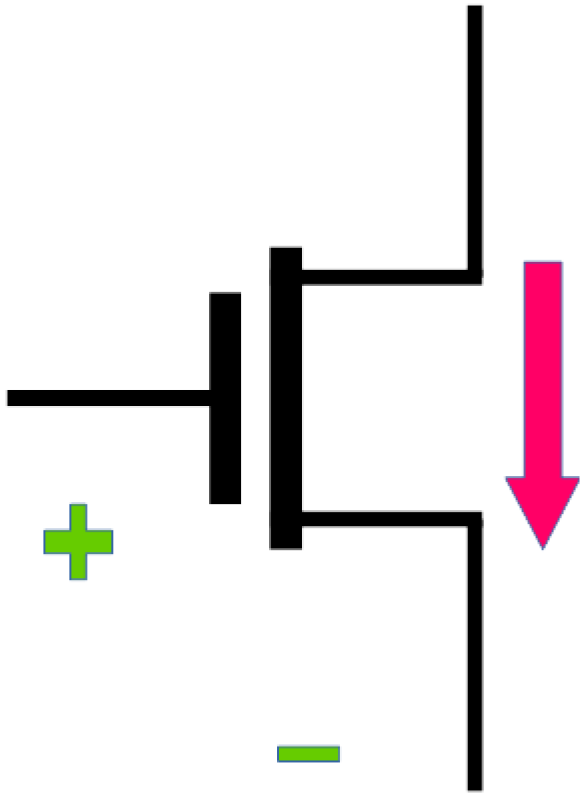
<u>In PMOS:</u>

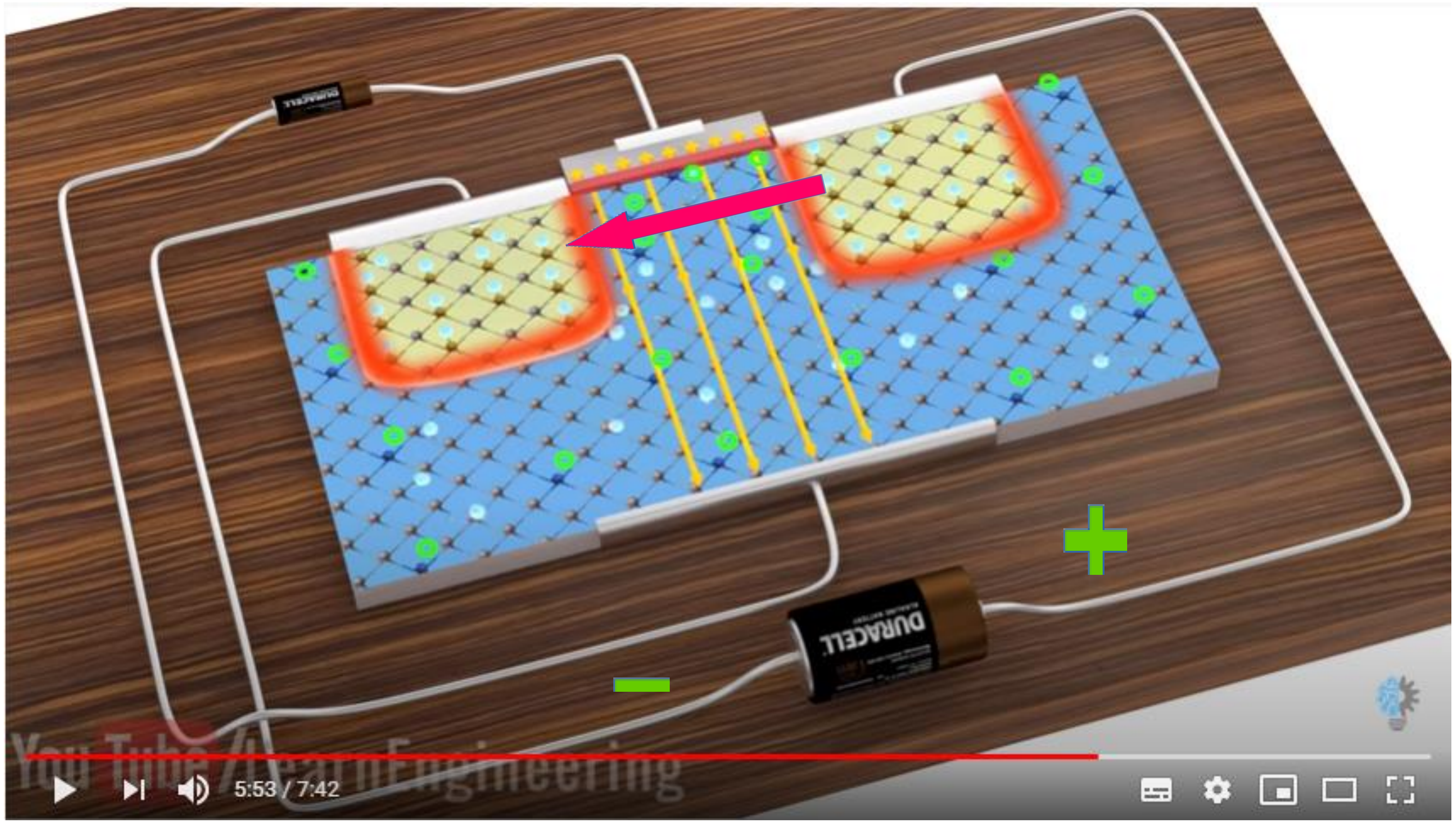
Source is more + than drain.
Bulk (body) must be connected to the most + terminal in the circuit (or source).

Bulk also can be connected to source □ Why?



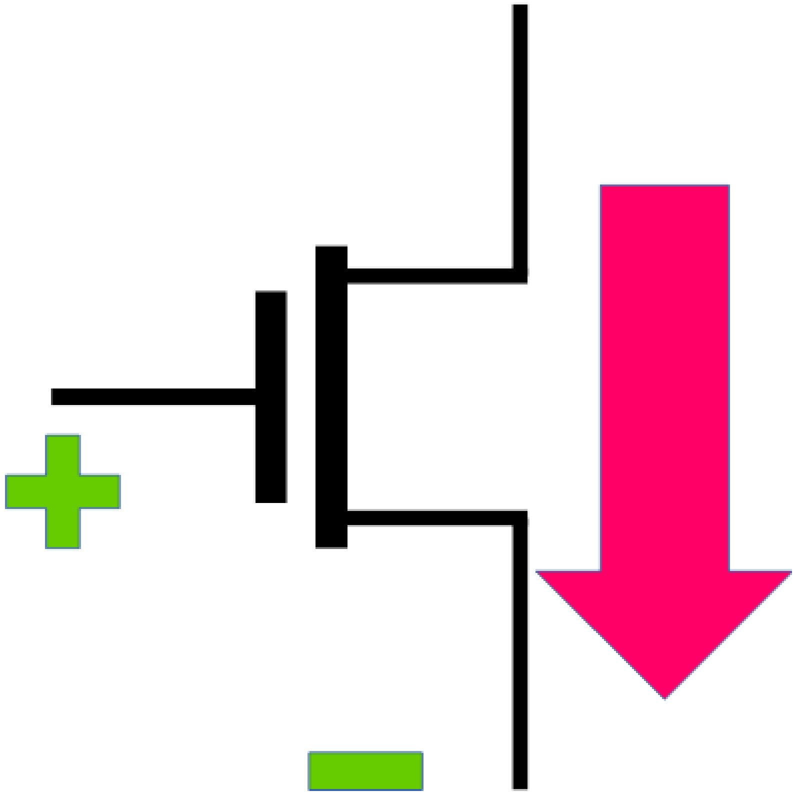
MOSFET – Initial Thoughts

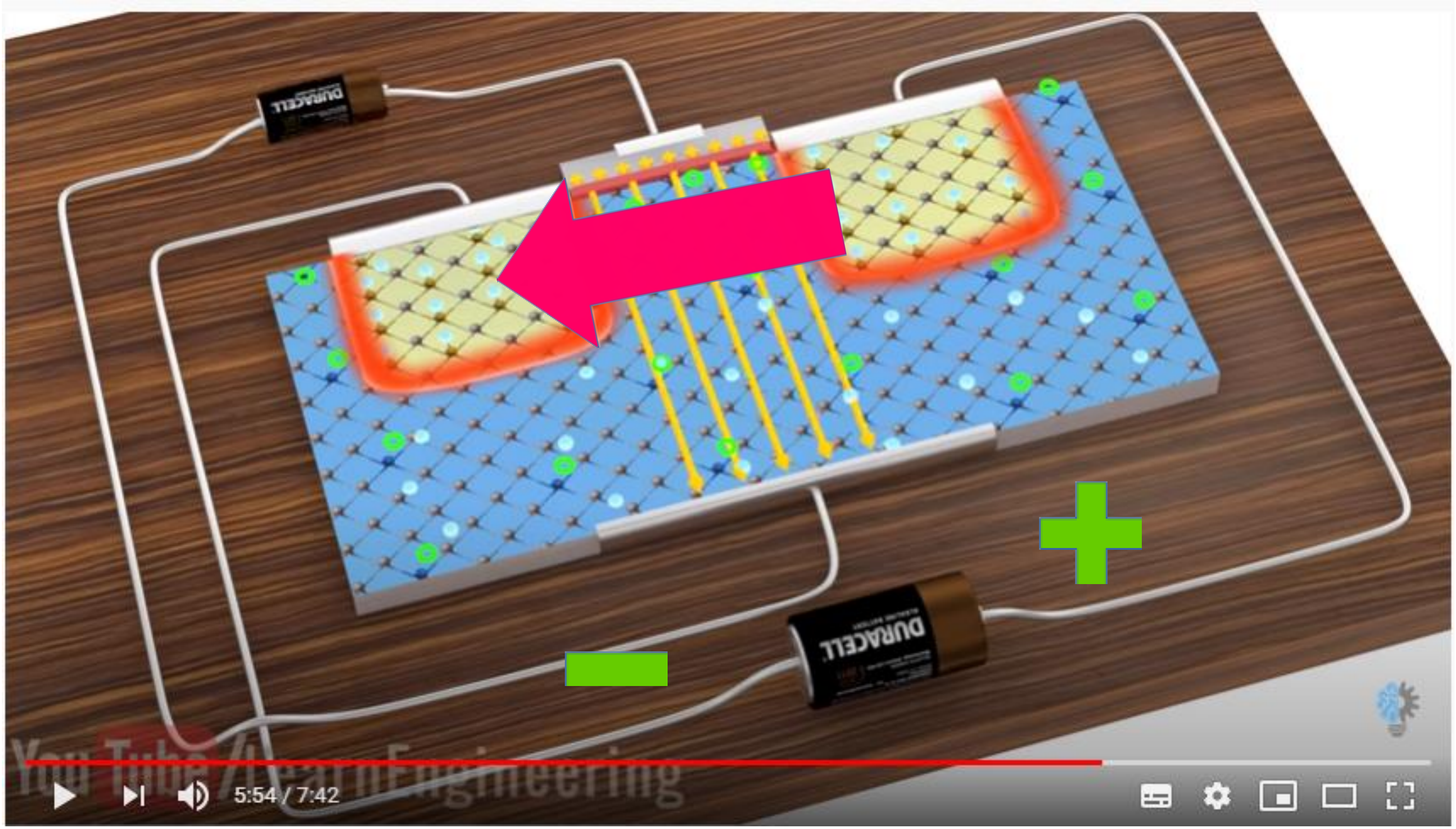




- MOSFET is ON
- In red the conventional current (positive charge)

MOSFET – Initial Thoughts

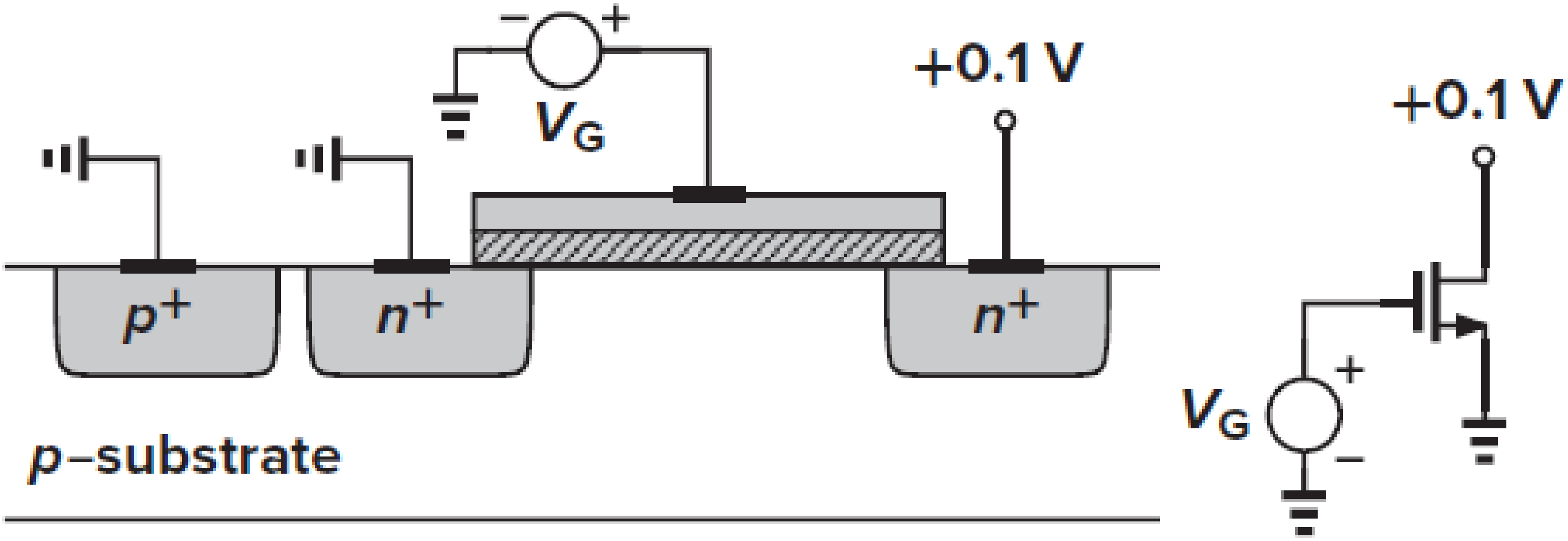




- MOSFET is ON
- In red the conventional current (positive charge)

MOSFET – I/V Characteristics: NMOS

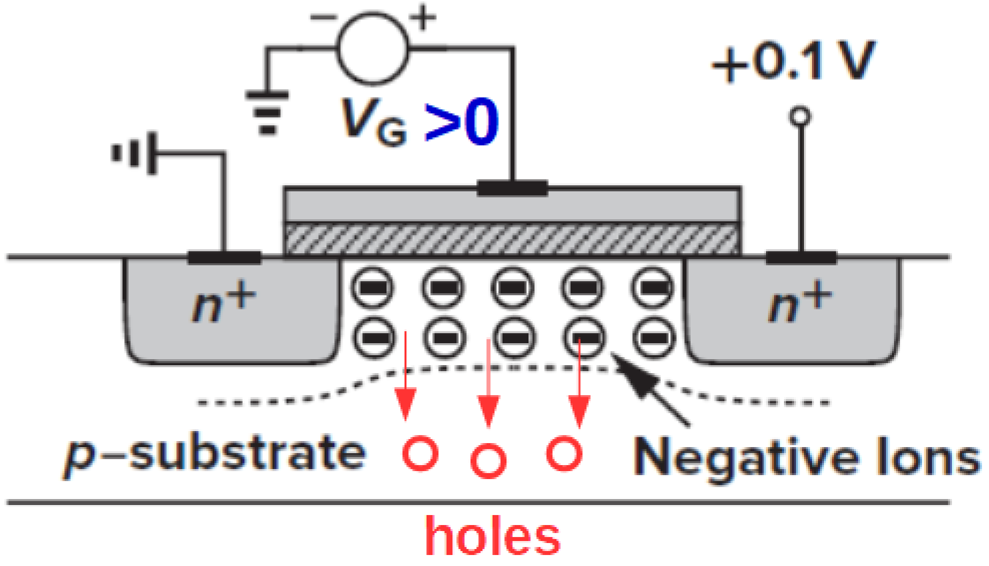
- **The Threshold Voltage**

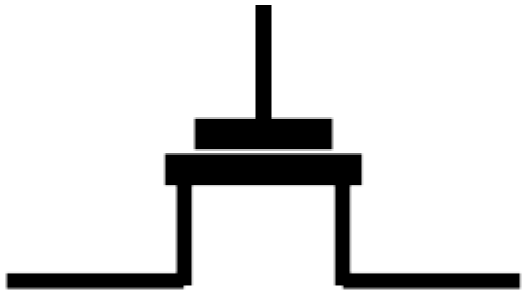


- We need to TURN ON the device □ **If VG = 0**, there is no current flowing through the device (Between which terminals?)

MOSFET – I/V Characteristics: NMOS

- **The Threshold Voltage**

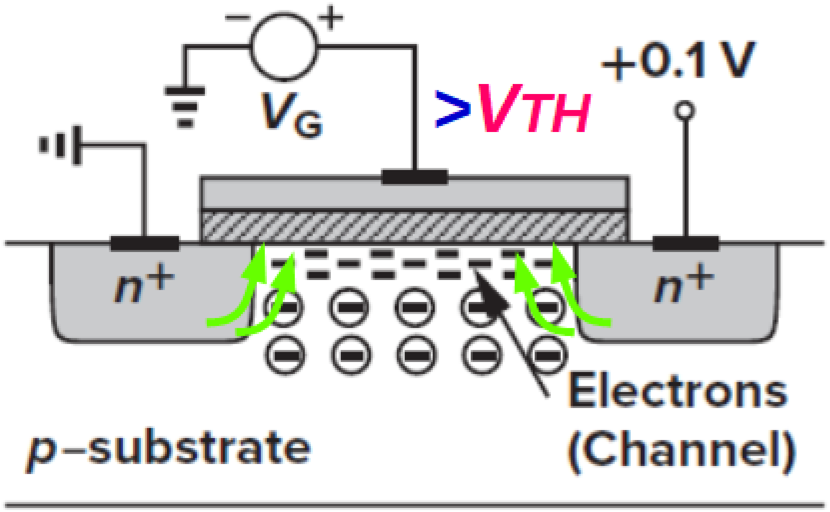


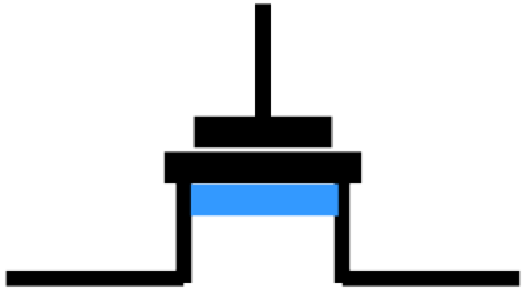


- As **VG becomes more positive**, the holes in the *p*-substrate are repelled from the gate area, leaving negative ions behind so as to mirror the charge on the gate. **No current flows!**

MOSFET – I/V Characteristics: NMOS

- **The Threshold Voltage**

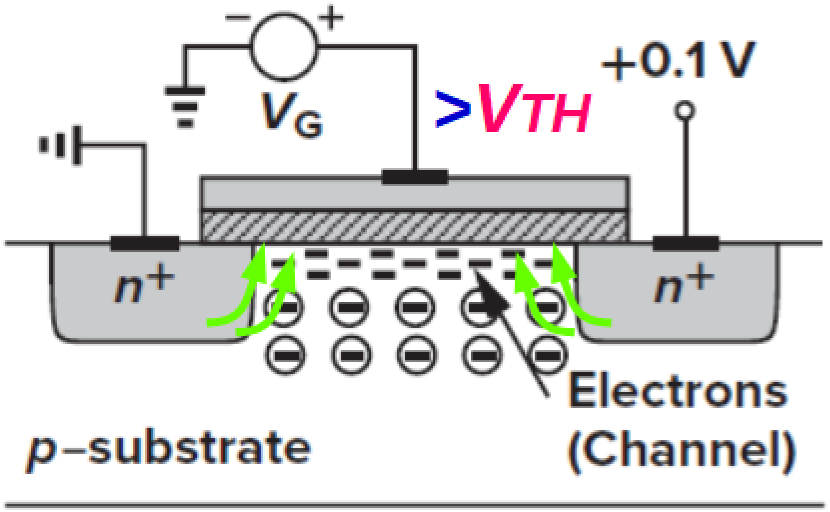


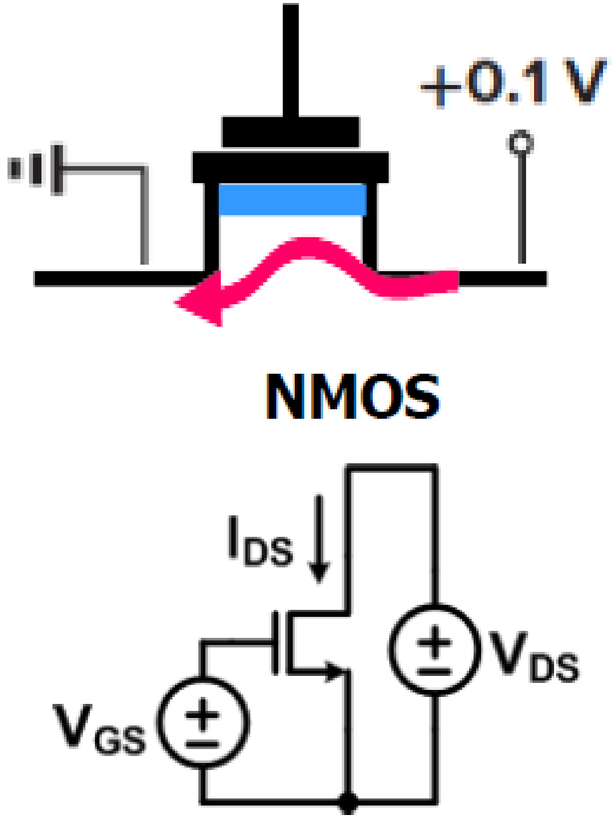


When **VG becomes a sufficient positive value**, electrons flow from the diffusions and create a "**channel interface**". This value is the ***"threshold voltage" → VTH***

MOSFET – I/V Characteristics: NMOS

- **The Threshold Voltage**





- **Now a current flow is possible!!!**
- **Check the convention**

MOSFET – I/V Characteristics: NMOS

$$I = Q_d \cdot v$$

$$Q_d = WC_{ox}(V_{GS} - V_{TH})$$

$$Q_d(x) = WC_{ox}[V_{GS} - V(x) - V_{TH}]$$

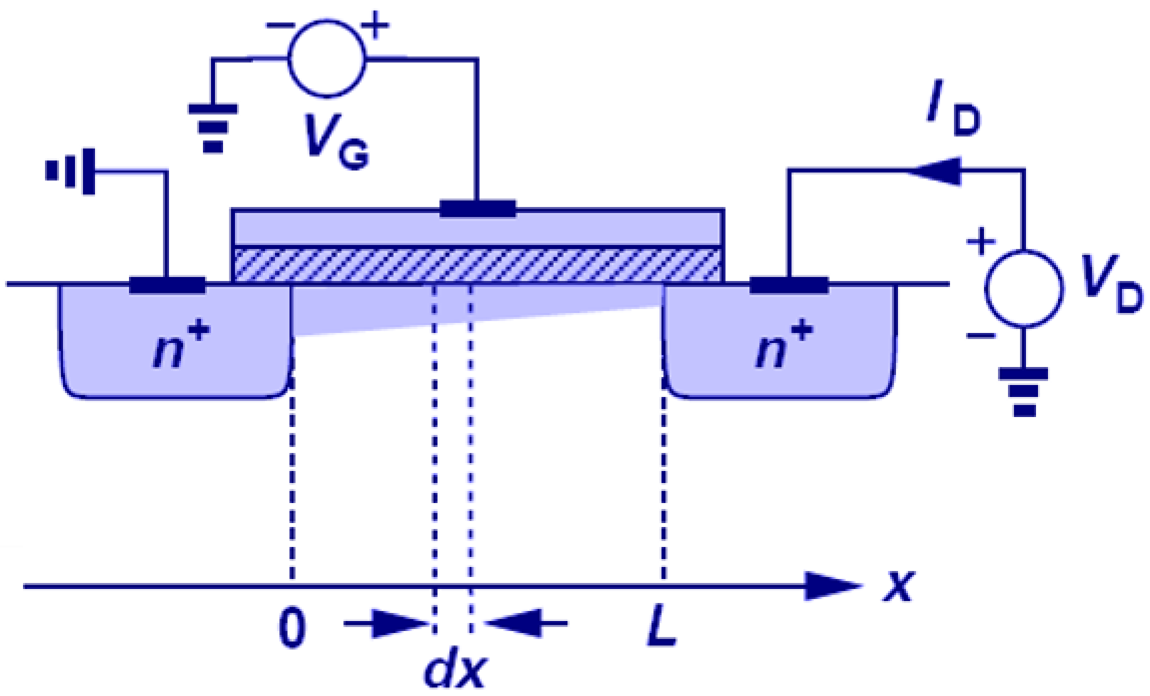
$$I_D = -WC_{ox}[V_{GS} - V(x) - V_{TH}]v$$

$$v = -\mu_n E \qquad = +\mu_n \frac{dV}{dx},$$

$$I_D = WC_{ox}[V_{GS} - V(x) - V_{TH}]\mu_n \frac{dV(x)}{dx}$$

$$\int_{x=0}^{L} I_D dx = \int_{V=0}^{V_{DS}} WC_{ox}\mu_n[V_{GS} - V(x) - V_{TH}]dV$$

$$\boxed{I_D = \mu_n C_{ox}\frac{W}{L}\left[(V_{GS} - V_{TH})V_{DS} - \frac{1}{2}V_{DS}^2\right]}$$

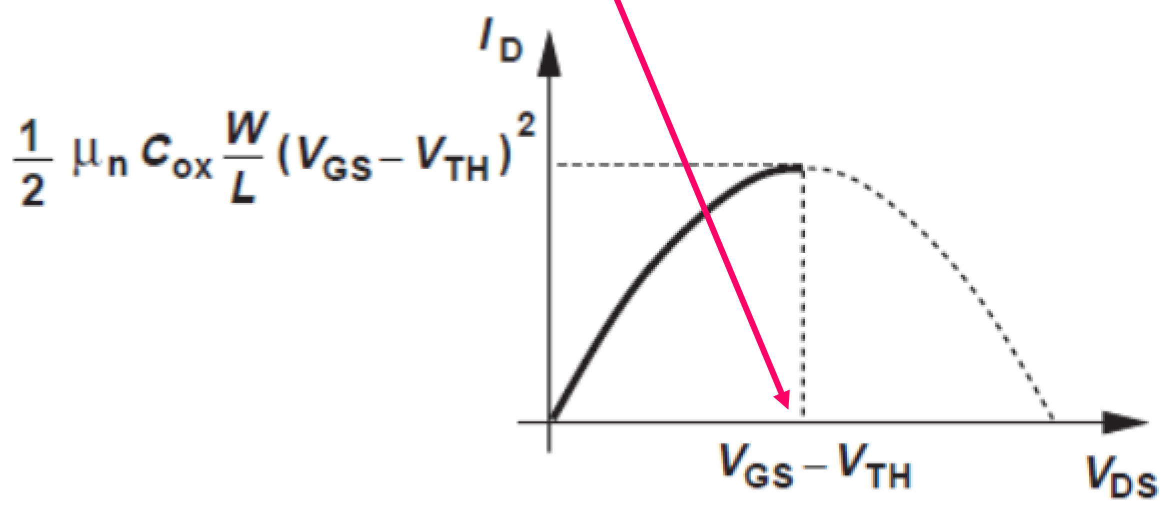


$$\boxed{Q(x) = WC_{ox}[V_{GS} - V(x) - V_{TH}]}$$

[Razavi]

MOSFET – I/V Characteristics: NMOS

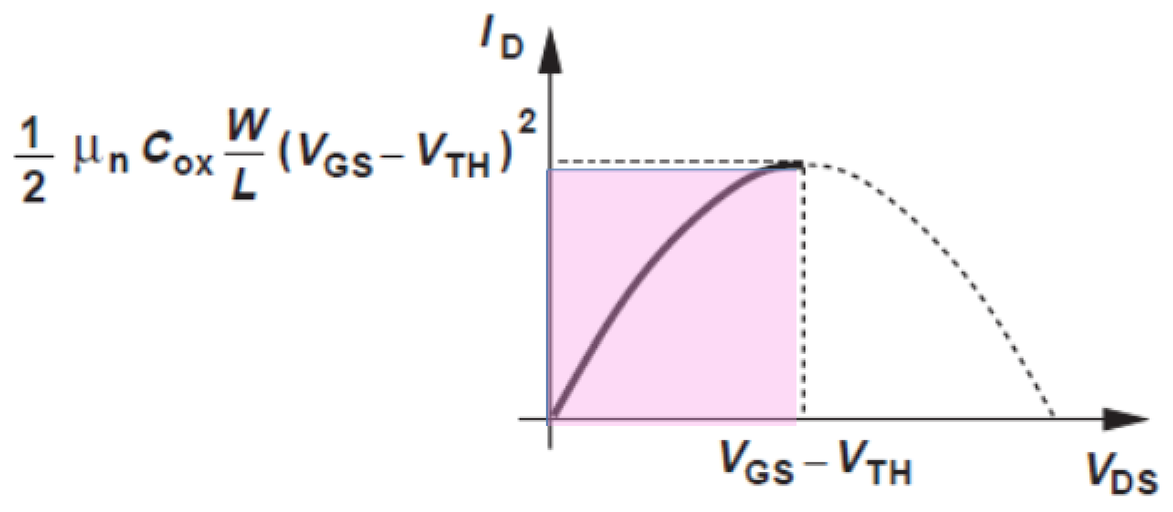
- Maximum current happens at **(V_{GS}-V_{TH}),** called the "overdrive voltage"



$$I_{D,max} = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS}-V_{TH})^2$$

MOSFET – I/V Characteristics: NMOS

- Maximum current happens at **(V_{GS}-V_{TH})**, called the "overdrive voltage"

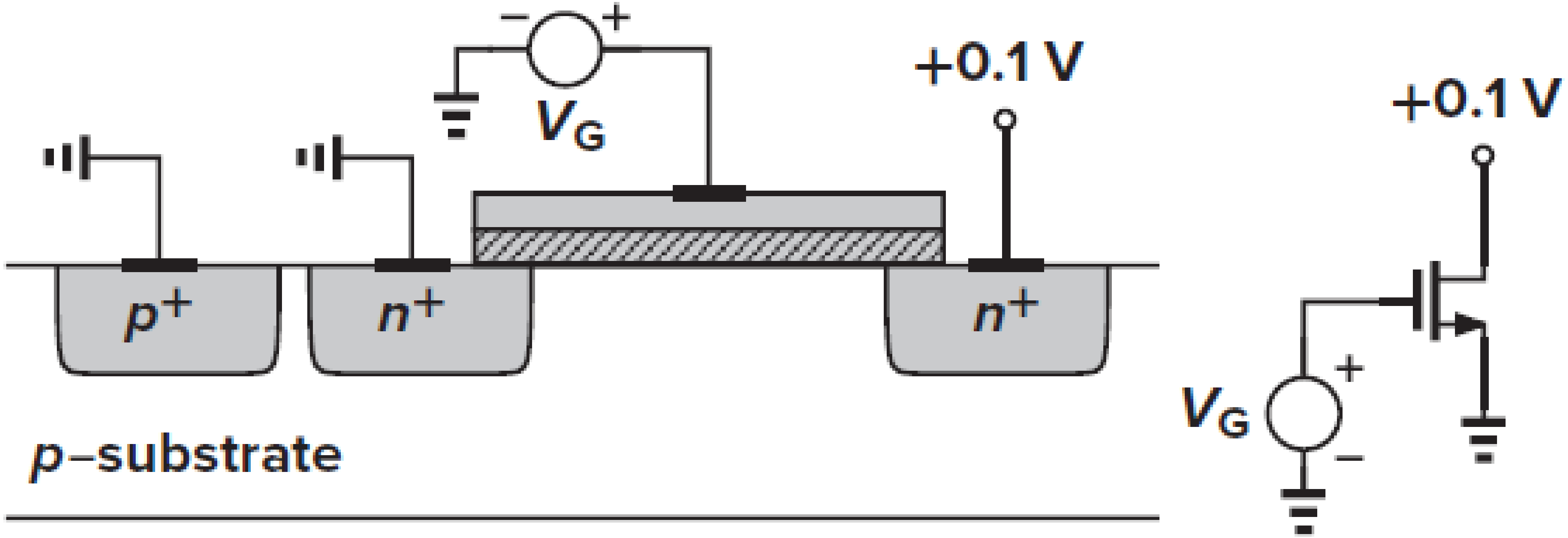


$$I_{D,max} = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS}-V_{TH})^2$$

This is known as the TRIODE region

MOSFET – Triode Region

- MOSFET looks like a controllable resistance

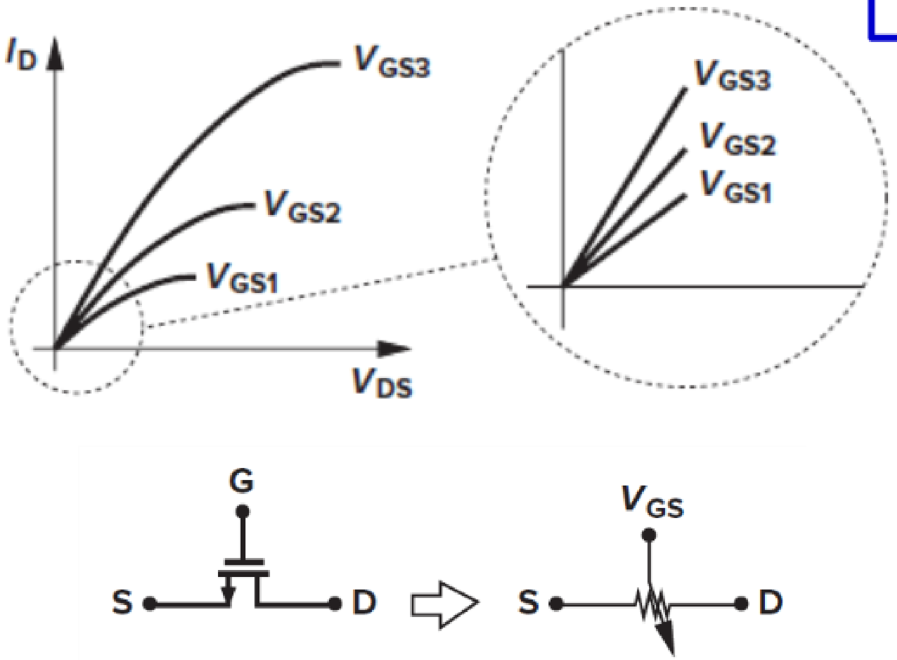


MOSFET – Triode Region

- For low V_{DS} values, the channel is still homogeneous
- For higher V_{DS} values, the behavior becomes more and more nonlinear

MOSFET – Triode Region

- For low V_{DS} values, the channel is still homogeneous



$$I_D = \mu_n C_{ox}\frac{W}{L}\left[(V_{GS}-V_{TH})V_{DS}-\frac{1}{2}V_{DS}^2\right]$$

$V_{DS} << 2(V_{GS}-V_{TH})$

$$I_D \approx \mu_n C_{ox}\frac{W}{L}(V_{GS}-V_{TH})V_{DS}$$

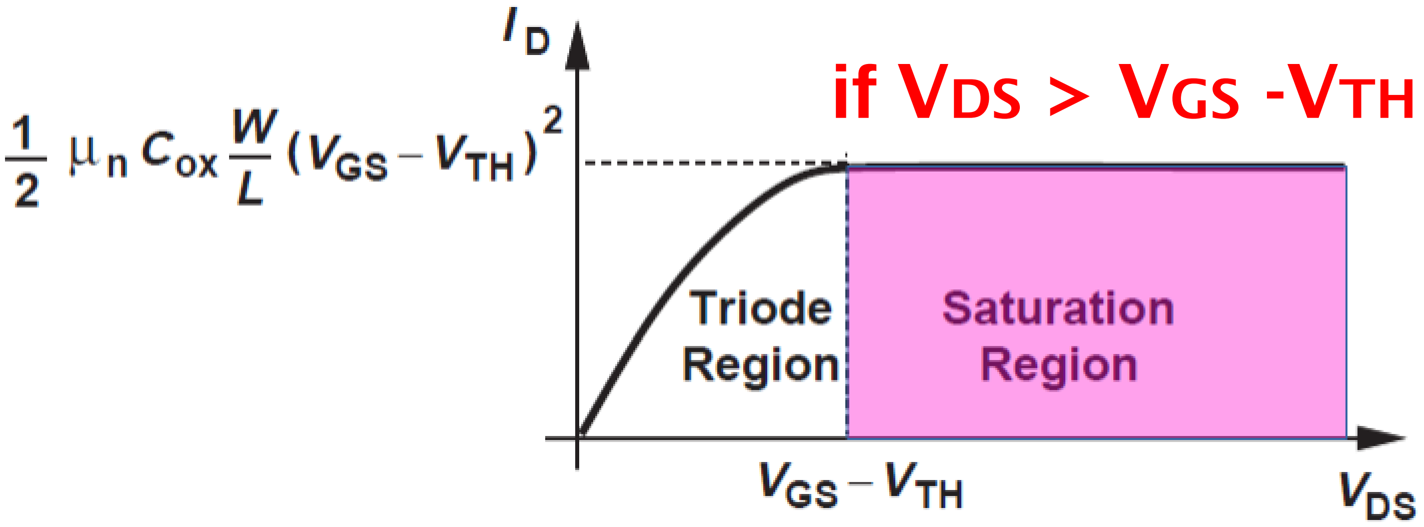
$$R_{on} = \frac{1}{\mu_n C_{ox}\frac{W}{L}(V_{GS}-V_{TH})}$$

MOSFET – Triode Region

- For low V_{DS} values, the channel is still homogeneous
- For higher V_{DS} values, the behavior becomes more and more nonlinear

MOSFET – Saturation Region

- For higher V_{DS} values, the behavior becomes more and more nonlinear

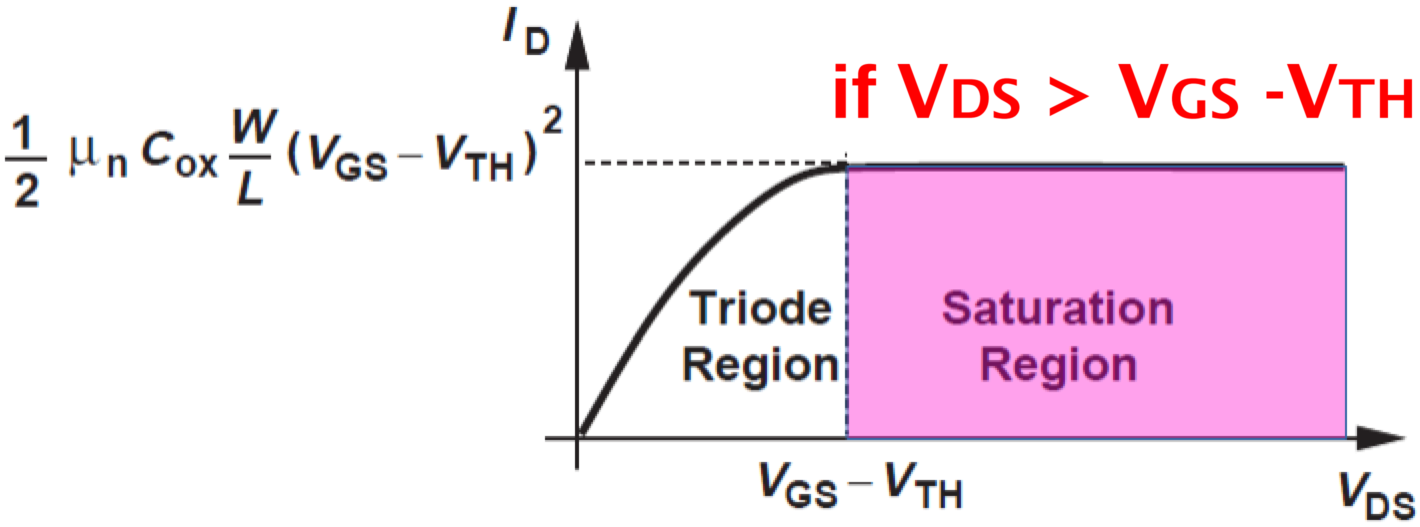


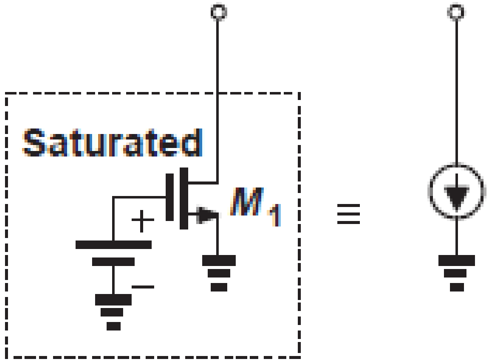
$$\boxed{I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L_1}(V_{GS} - V_{TH})^2}$$

MOSFET – Saturation Region

- For higher **V_{DS}** values, the behavior becomes more and more nonlinear

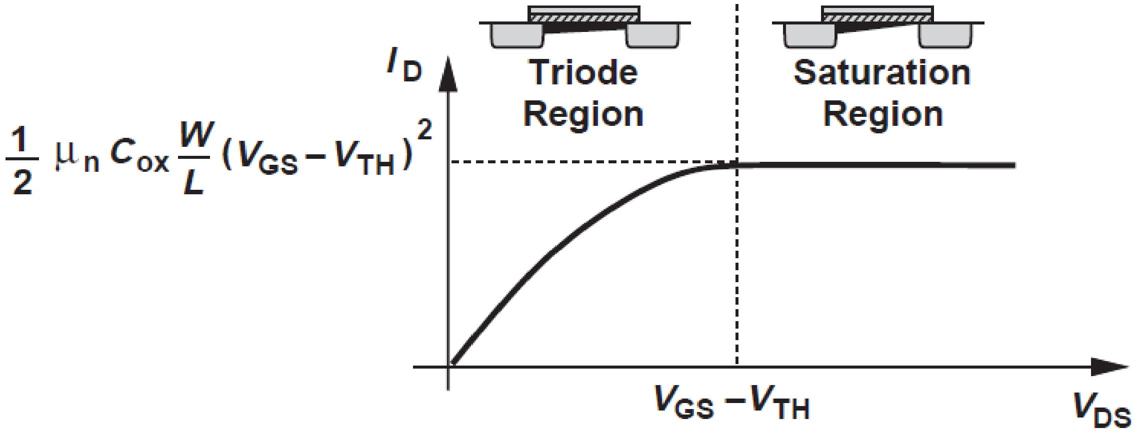
if V_{DS} > V_{GS} -V_{TH}





$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L_1}(V_{GS}-V_{TH})^2$$

MOSFET – 1st Arrival: Summary



TURN ON the Device

$V_{GS} > V_{TH}$

Triode Region

- $V_{DS} < V_{GS} - V_{TH}$
- I_D depends on V_{GS} and V_{DS}

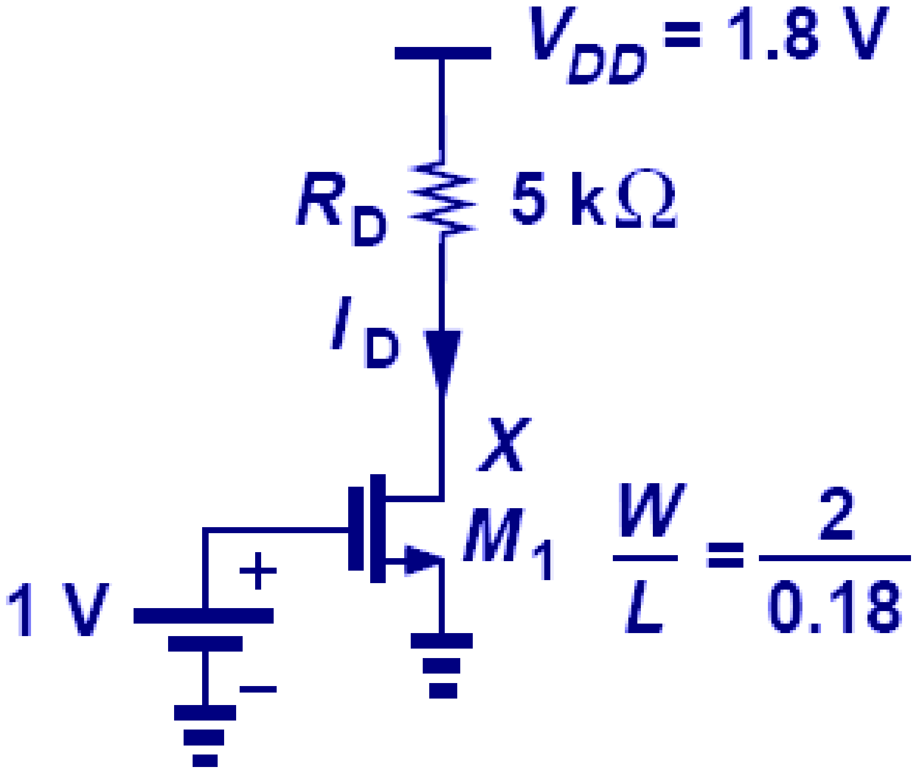
$$I_D = \mu_n C_{ox}\frac{W}{L}\left[(V_{GS}-V_{TH})V_{DS} - \frac{1}{2}V_{DS}^2\right]$$

Saturation Region

- $V_{DS} \geq V_{GS} - V_{TH}$
- I_D depends on V_{GS} (mostly)

$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L_1}(V_{GS}-V_{TH})^2$$

Let’s Practice!



Calculate the bias current of M1. Assume.

$\mu_n C_{ox}$ = 100uA/V^2

V_{TH} = 0.4V

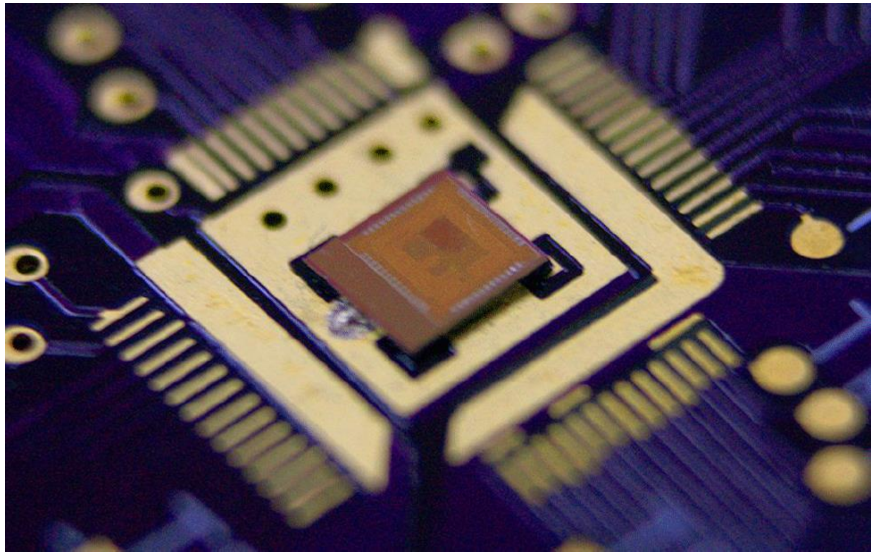
What is the operation region?

How can check our answers?

Homework

- PMOS Case Study
- Complementary Reading Hand Notes
- Think and choose the best question you have after homework and prepare it for the next class

Thanks



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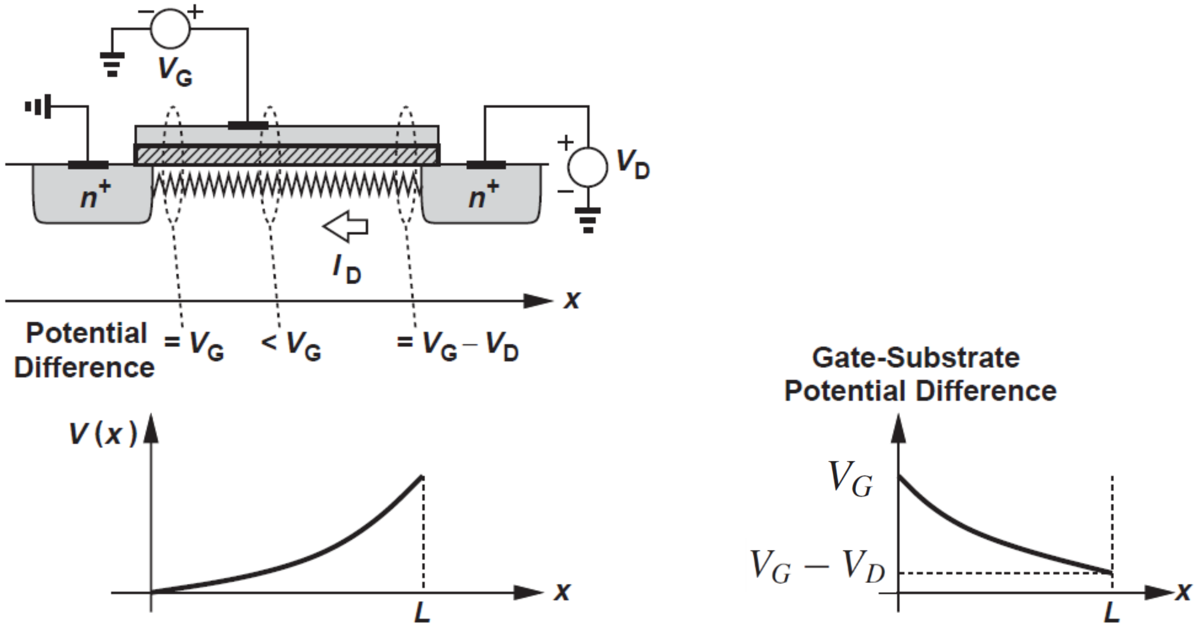
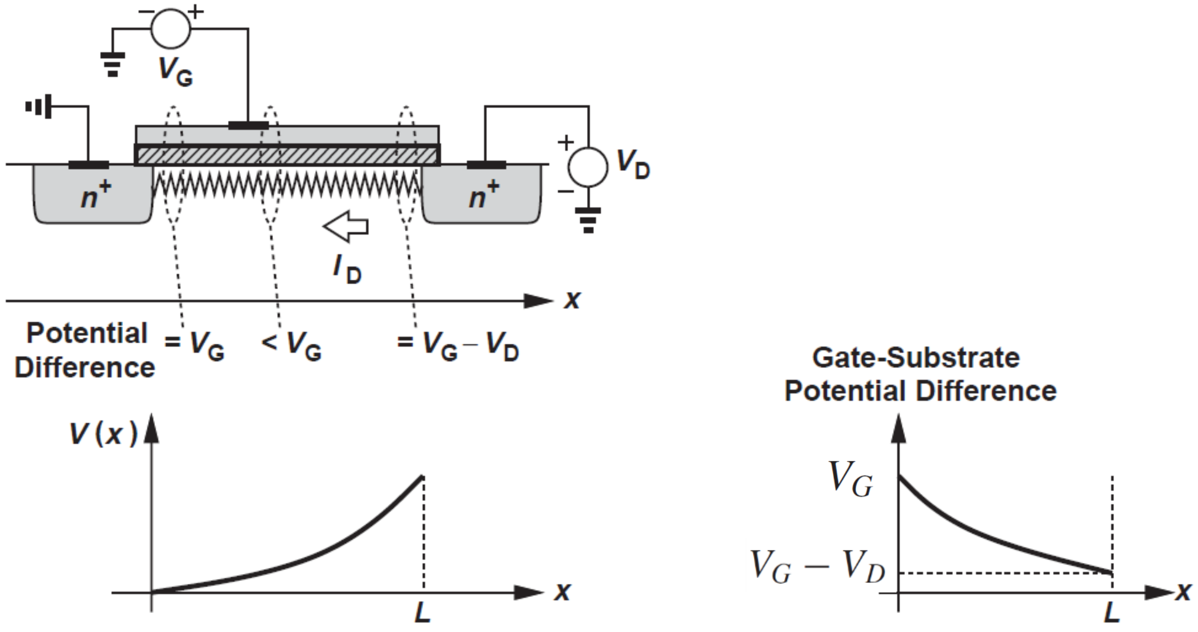
Appendix

- Saturation occurs due to a phenomenon known as **Channel Pinch-Off.** Let's try to understand!



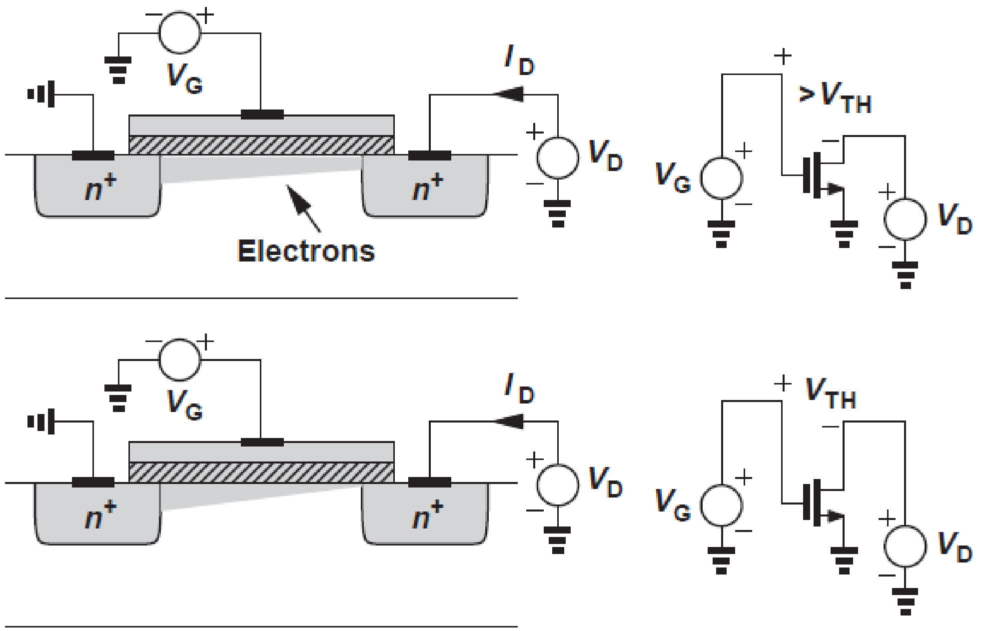
Why this happen?

- Saturation occurs due to a phenomenon known as **Channel Pinch-Off.** Let's try to understand!



MOS I/V Characteristics

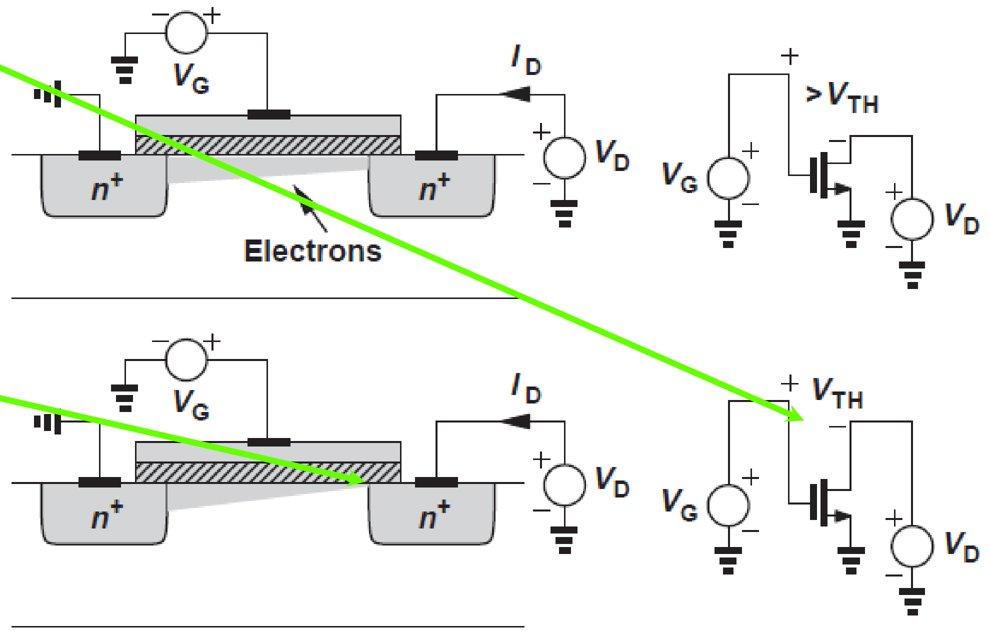
- Density of electrons falls to a minimum at x=L
- If drain voltage is high enough to produce
- **$V_G - V_D < V_{TH}$**, then the channel ceases to exist near the drain



MOS I/V Characteristics

- Density of electrons falls to a minimum at x=L
- If drain voltage is high enough to produce
- **$V_G - V_D < V_{TH}$**, then the channel ceases to exist near the drain

We say at this point that channel is "pinched off"



The saturation current

- The current integral has to be adjusted

$$\int_{x=0}^{x=L_1} I_D \, dx = \int_{V(x)=0}^{V(x)=V_{GS}-V_{TH}} \mu_n C_{ox} W [V_{GS} - V(x) - V_{TH}] \, dV.$$

$$\boxed{I_D = \frac{1}{2} \mu_n C_{ox} \frac{W}{L_1} (V_{GS} - V_{TH})^2}$$

This is the saturation current