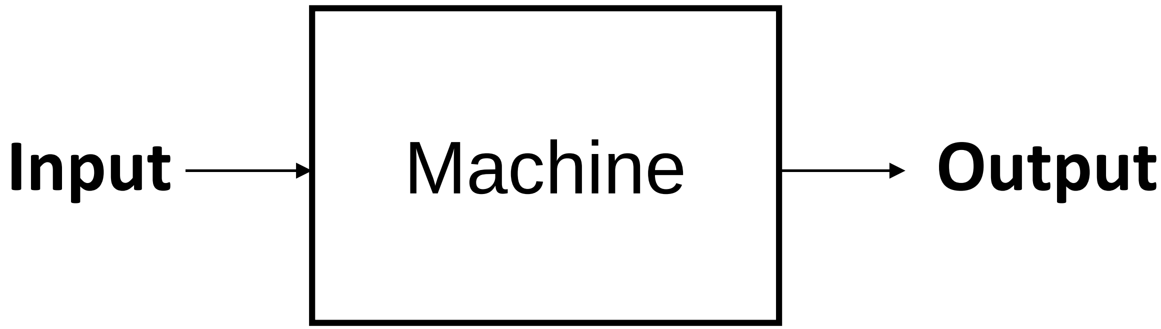
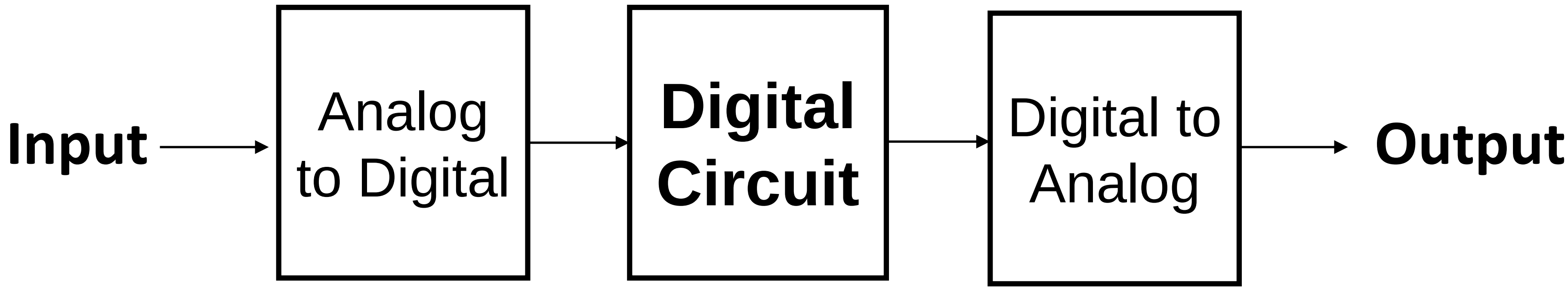
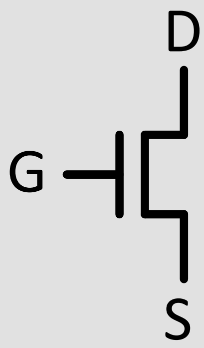
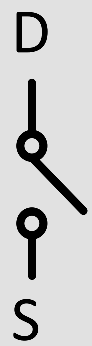
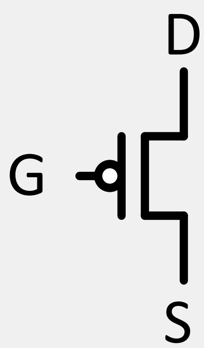
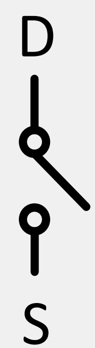
Role of Digital Circuit

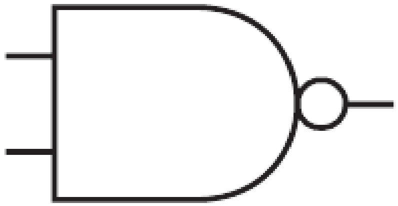




Revisit of MOSFET Switch Operation

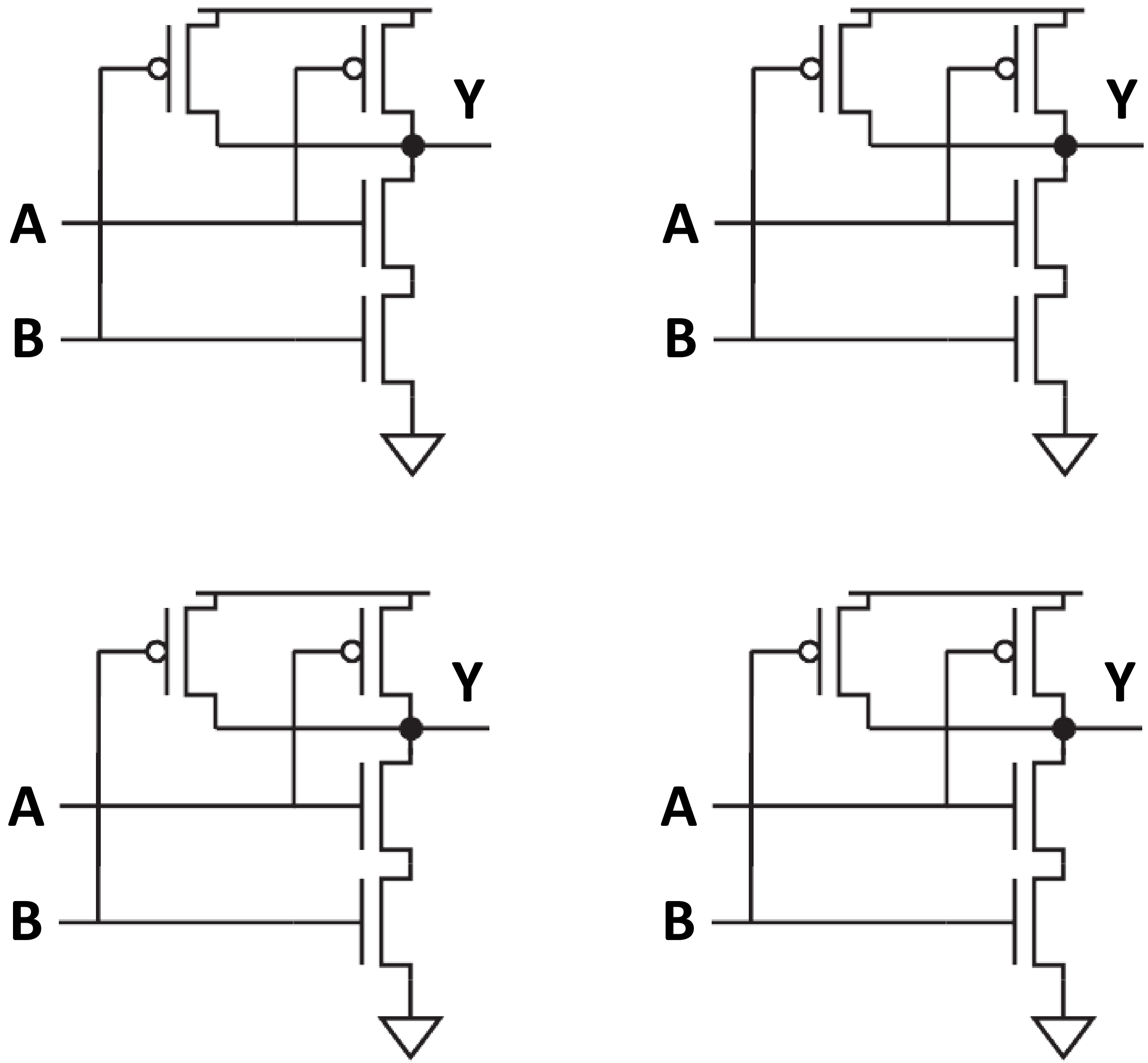
	Symbol	G = 0	G = 1
NMOSFET			
PMOSFET			

Realization of NAND2 Operation



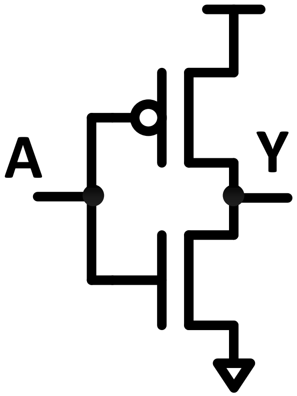
A	B	Y
0	0	1
0	1	1
1	0	1
1	1	0

"1" → 3V
"0" → 0V

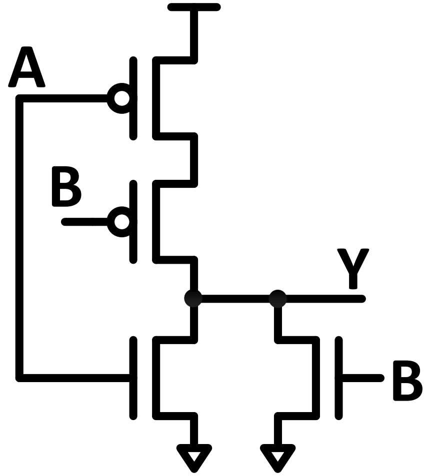


Inverter & NOR2

A	Y
0	1
1	0

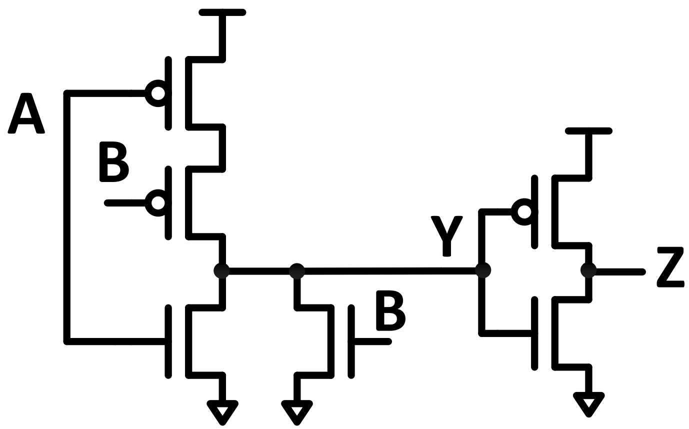


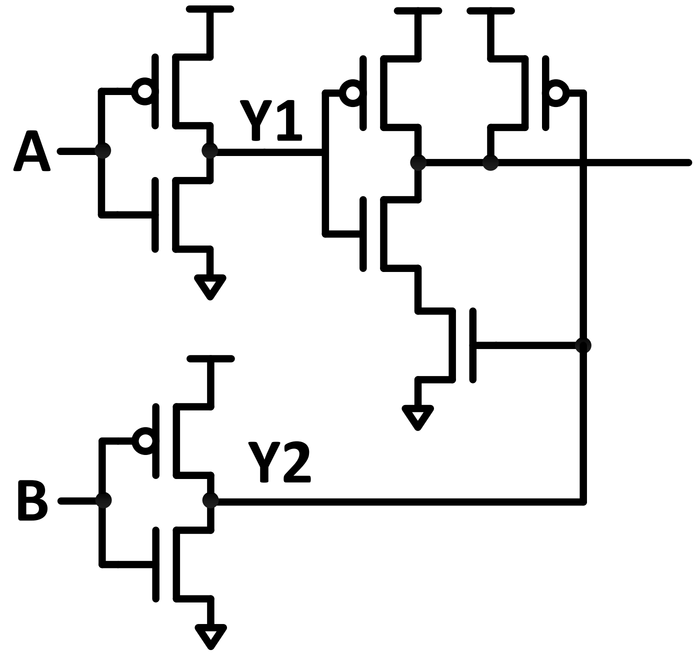
A	B	Y
0	0	1
0	1	0
1	0	0
1	1	0



Question: Which is Faster?

- Suppose that you want to achieve OR2 operation, Z = A+B





- How about power? Area?
- Is there any other better design in terms of PPA?

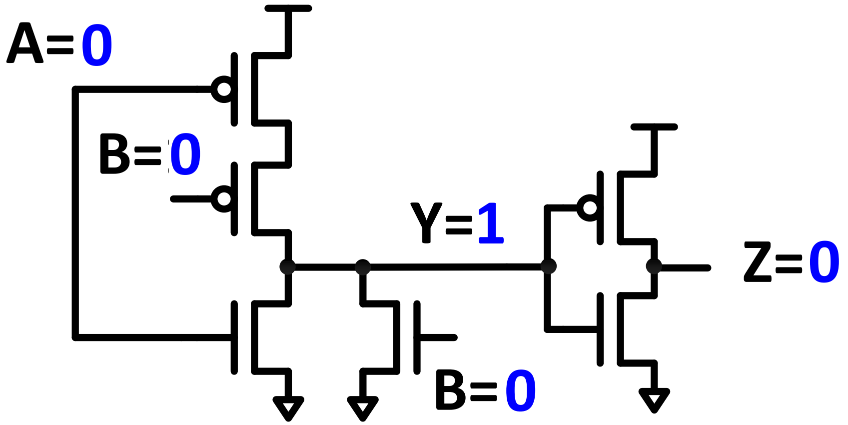
MOSFET Backgrounds

Hanwool Jeong

hwjeong@kw.ac.kr

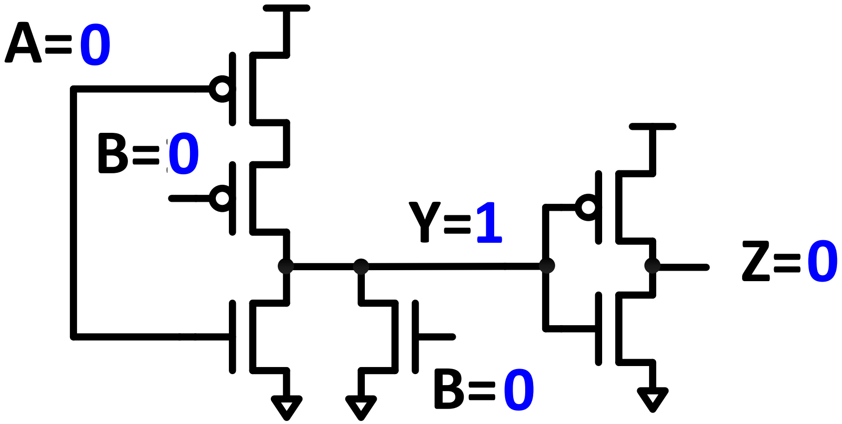
How Speed is Determined

- Delay in a digital circuit
  ➔ Time required for signal propagation in terms of voltage change



- Why do we need a finite “time” for signal propagation?

Voltage Change



- Charge moves and voltage changes ➔ Takes time! How much?
- Or, how can we speed up the circuit?
    1) More charge moves per time
    2) Even with smaller charge, voltage can be easily changed
- Have you heard of two following things?
    1) Relation between charge move vs. time
    2) Relation between charge vs. Voltage change

We Should Know Current & Capacitor

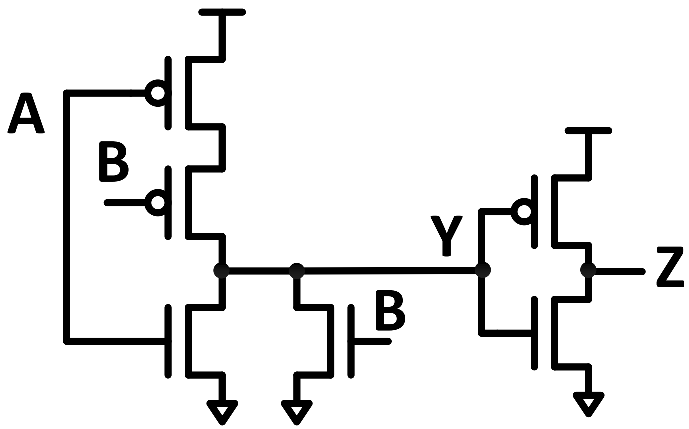
- Definition of current

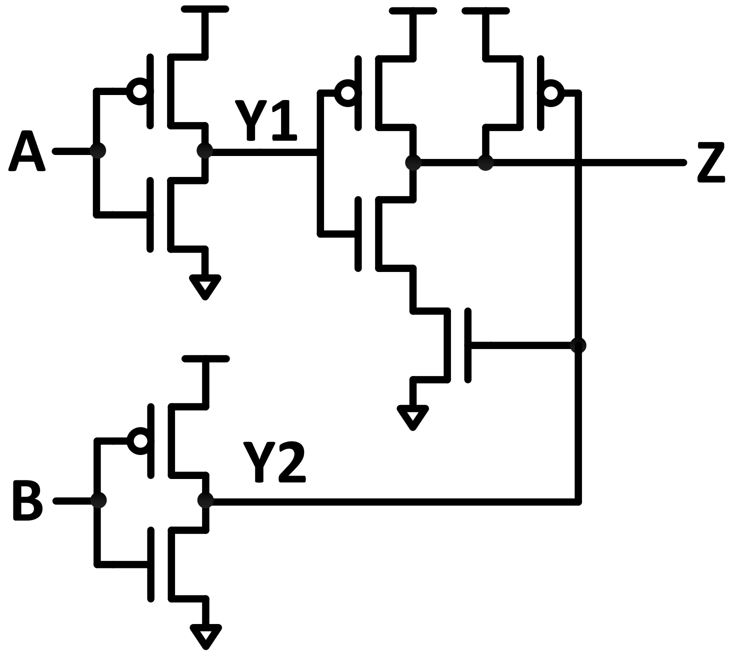
- Definition of a capacitor

- Then how can we determine the speed?

Now We See What We Should Focus

- Current and capacitor in digital circuit

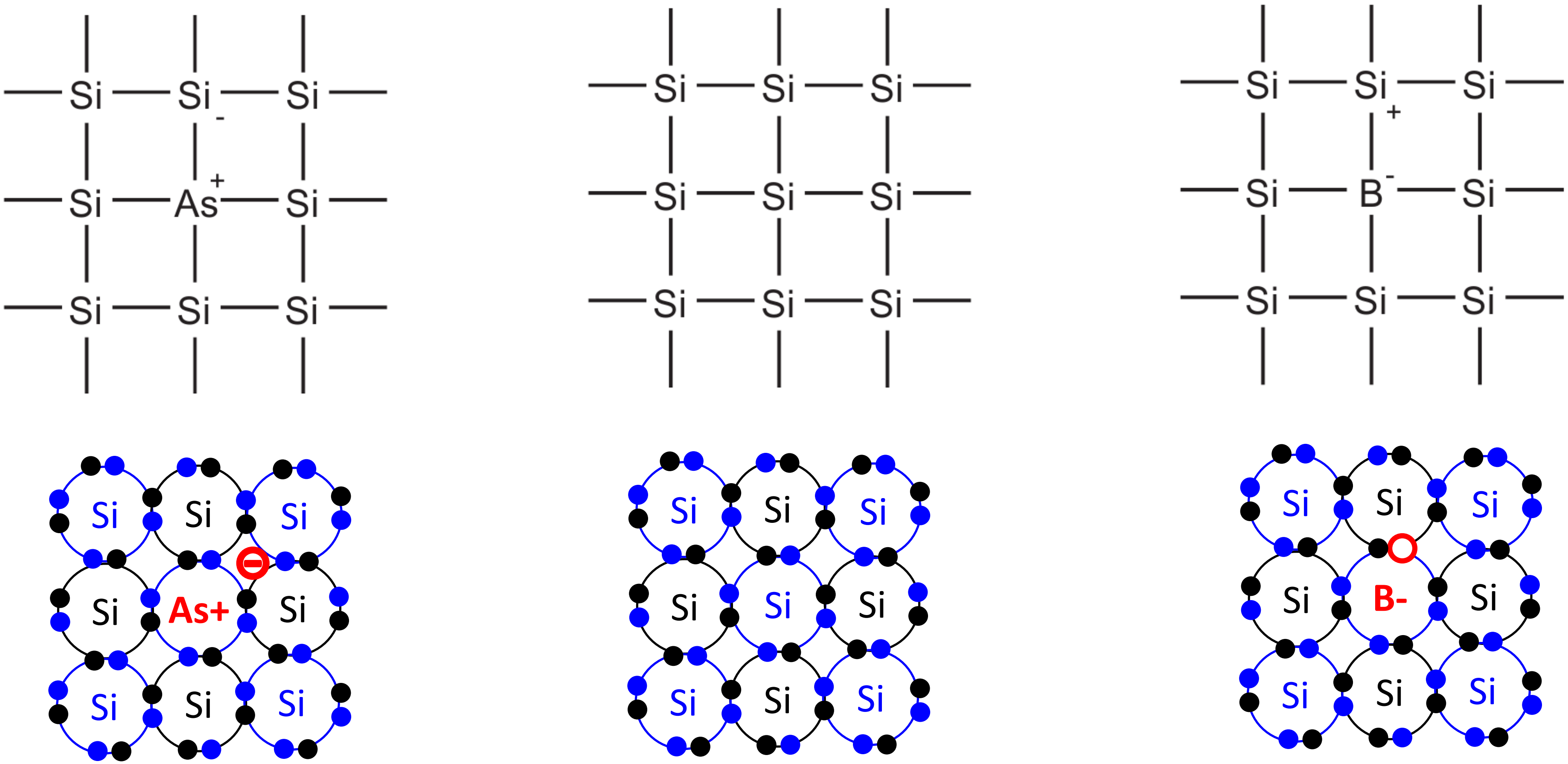




Quaitative Respect;
Structure & Operation of MOSFET

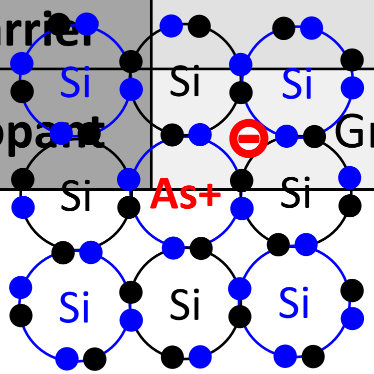
Silicon As a Semiconductor Material

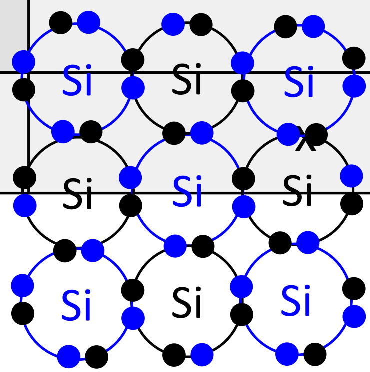
- Representative Material for Integrated Circuits
- Group IV ➔ Covalent bonds with four adjacent atoms

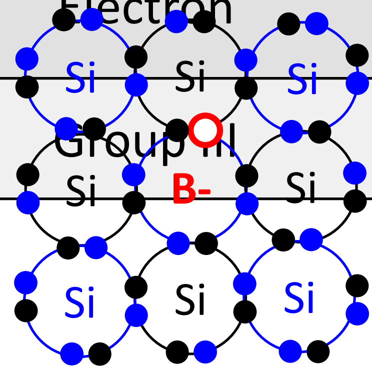


N-type vs. P-type Semiconductor

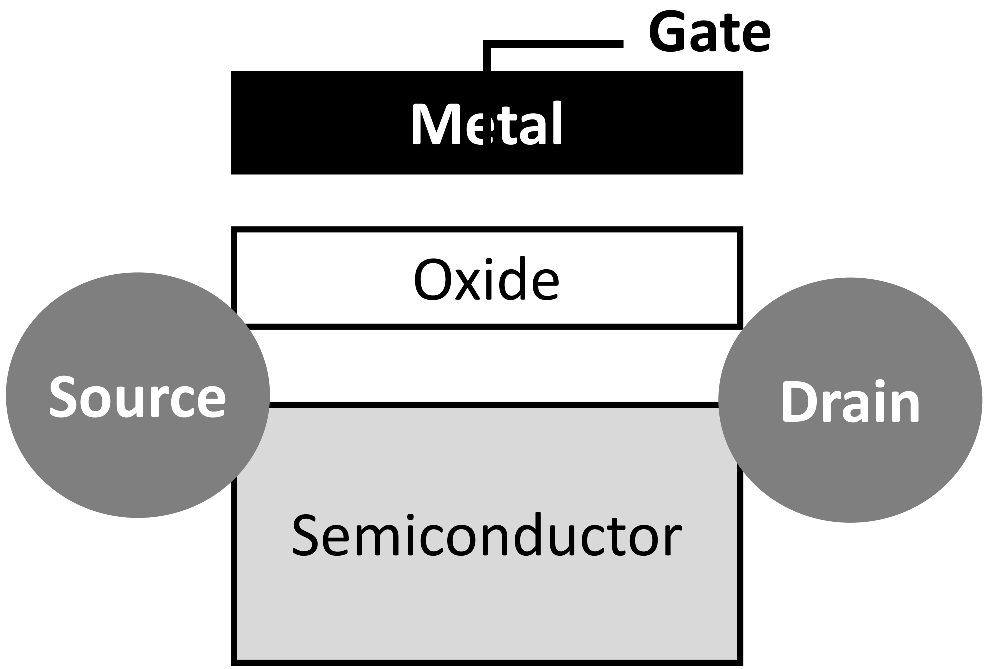
	N-type (Extrinsic)	Intrinsic	P-type (Extrinsic)
Structure			
Majority Carrier	Electron	Hole density = Electron density	Hole
Minority Carrier	Hole		Electron
Dopant	Group VI	X	Group III







MOSFET; Semiconducting Device

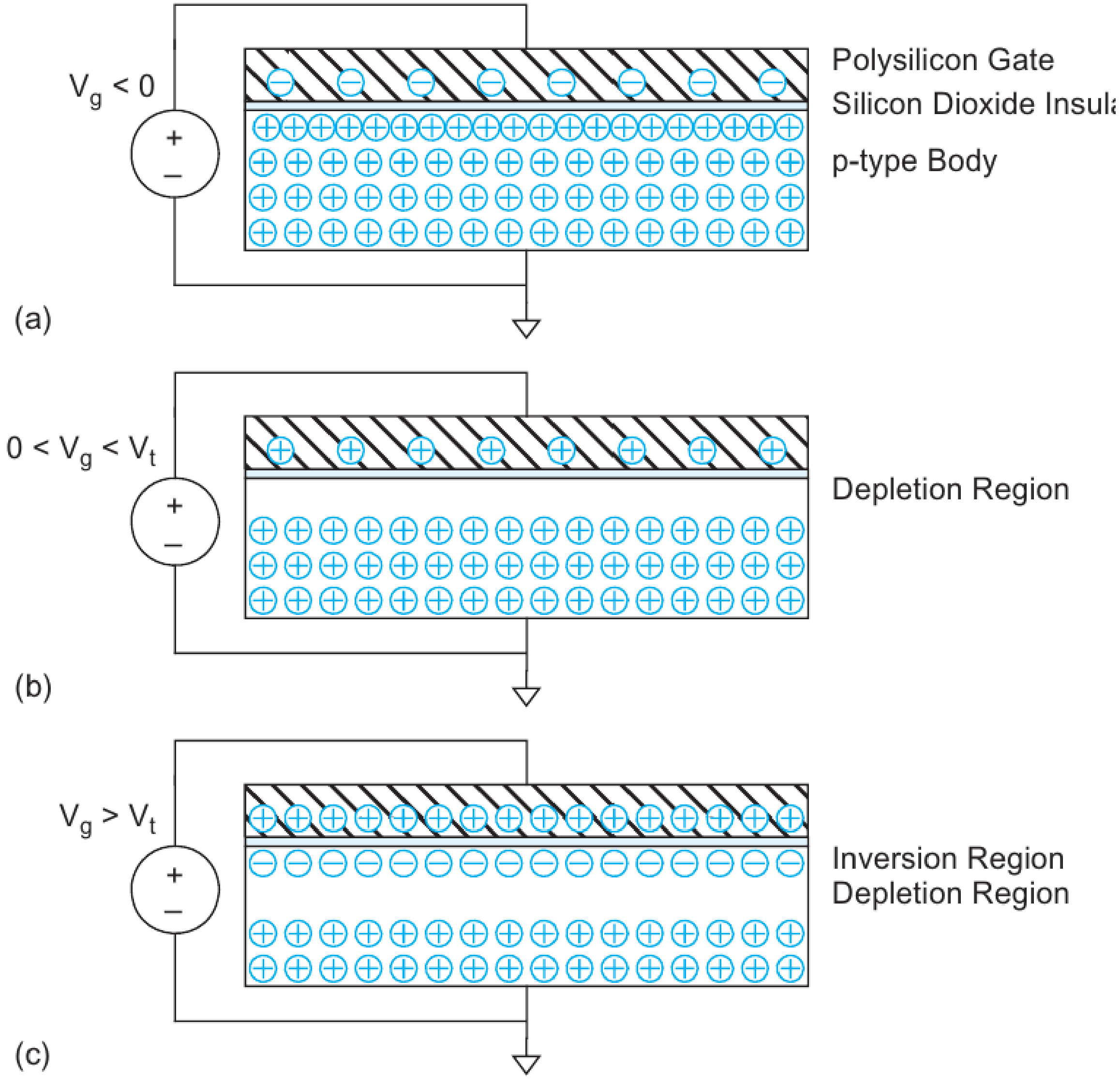


- nMOS : Majority carriers are electrons
- pMOS : Majority carriers are holes
- Current flow is controlled by gate voltage

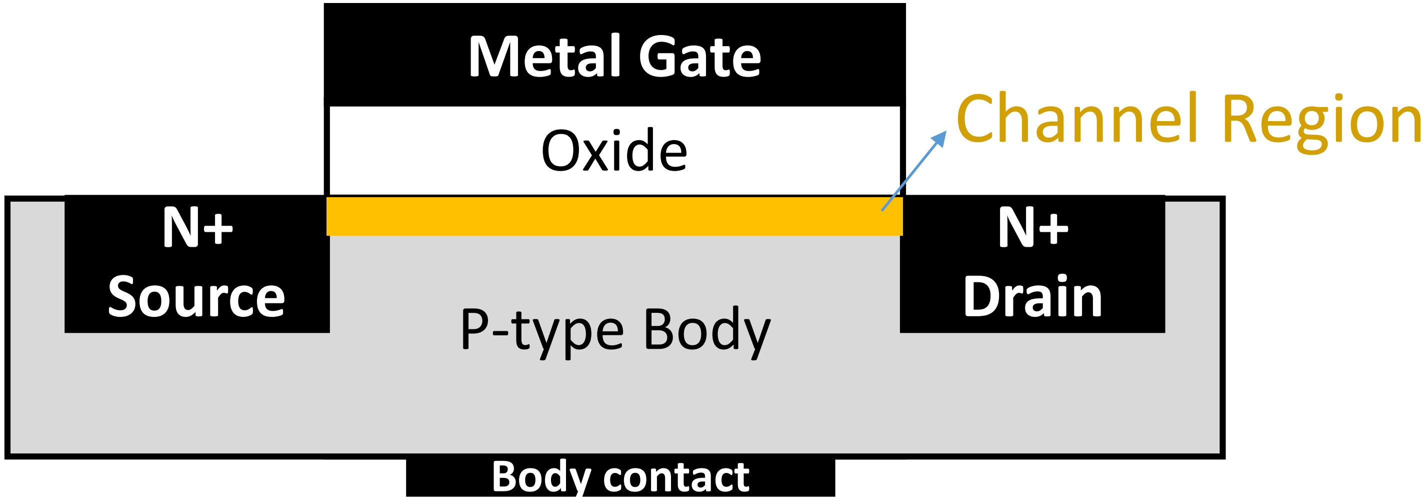
P-type Body MOS

- Accumulation
- Depletion
- Inversion

V_t : Threshold voltage



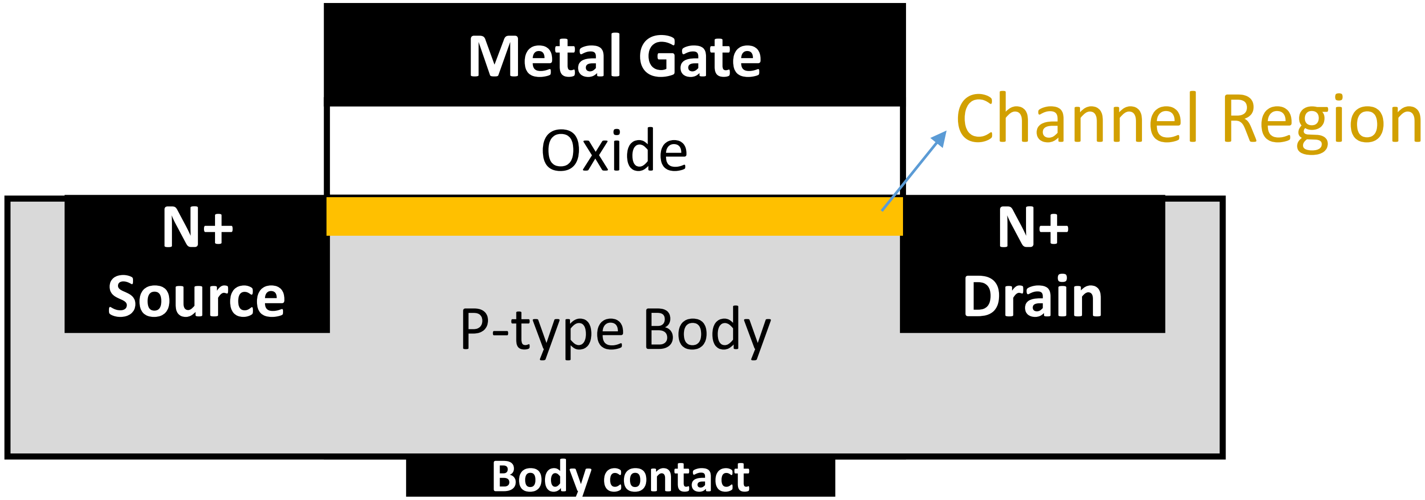
Now We Will Incorporate Source & Drain



- Source and drain are heavily doped silicon
  ➔ You can consider it as conductor
- Channel potential matters.

$V_g \uparrow$ ➔ Channel region becomes more attractive to electron
V_s or $V_d \uparrow$ ➔ Channel region becomes less attractive to electron

Revisit of Turn-On Point



$V_{GS} > V_t$: Turn on

$V_{GS} < V_t$: Turn off

Meaning of Threshold Voltage

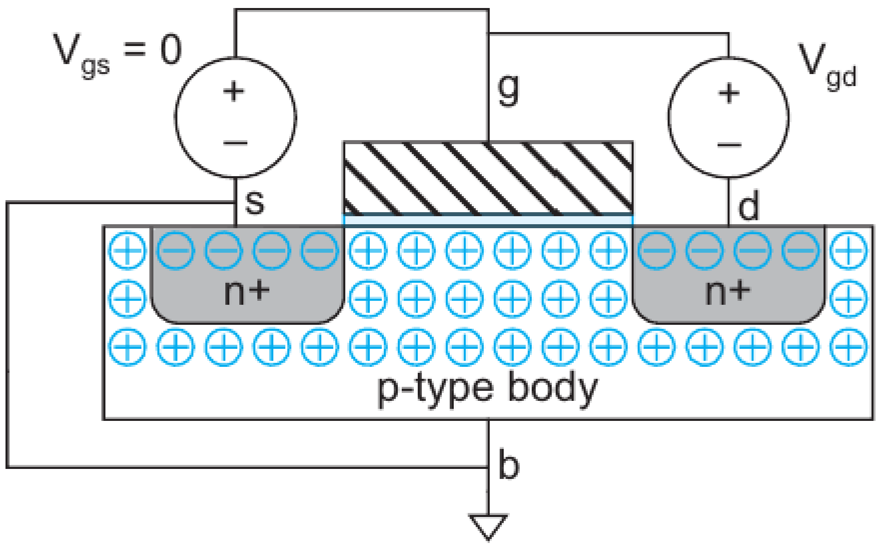
- The minimum V_{GS} that is needed to create a conducting path between the source and drain terminals.
- Effectively, you can consider it as "**voltage drop across MOS**" ➔ Electron feels "$\mathbf{V_G – V_t}$" instead of "$\mathbf{V_G}$" at channel region.
- Sometimes, $V_{GS} – V_t$ is defined as overdrive voltage V_{ov} as

$$V_{ov} = V_{GS} - V_t$$

- Can you describe turn-on and turn-off of nMOSFET with V_{ov}?

nMOSFET; Cutoff

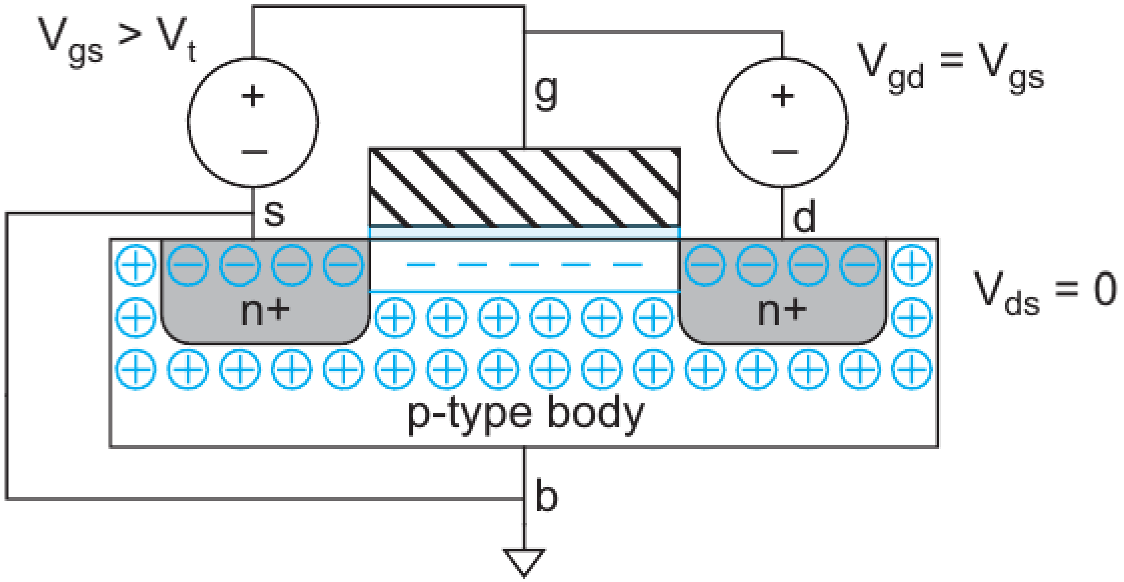
- $V_{GS} < V_t$ or $V_{ov} < 0$



Cutoff:
No Channel
$I_{ds} = 0$

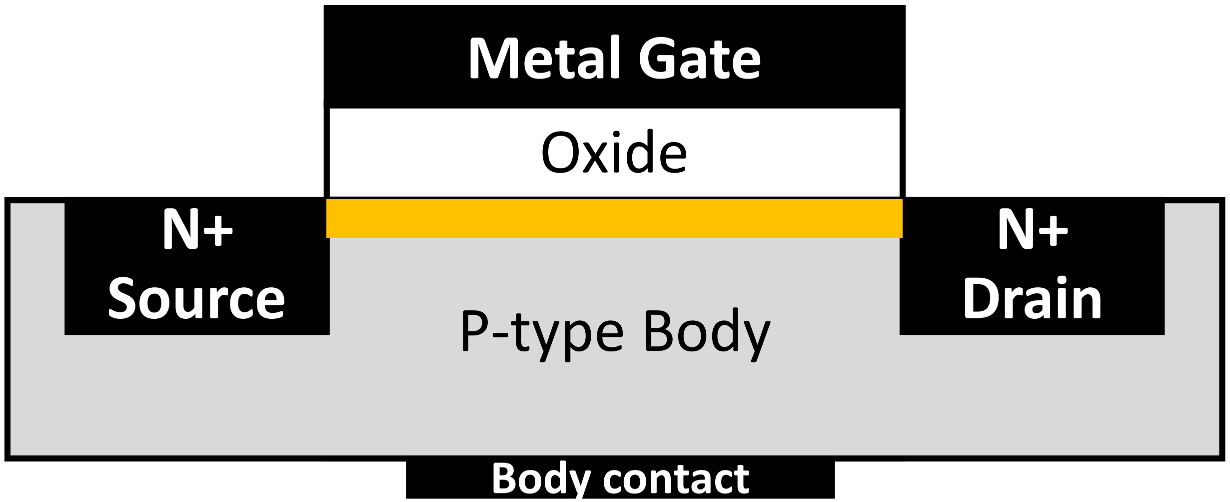
nMOSFET; Turn-on with V_{DS} = 0

- What if V_{DS} becomes larger?



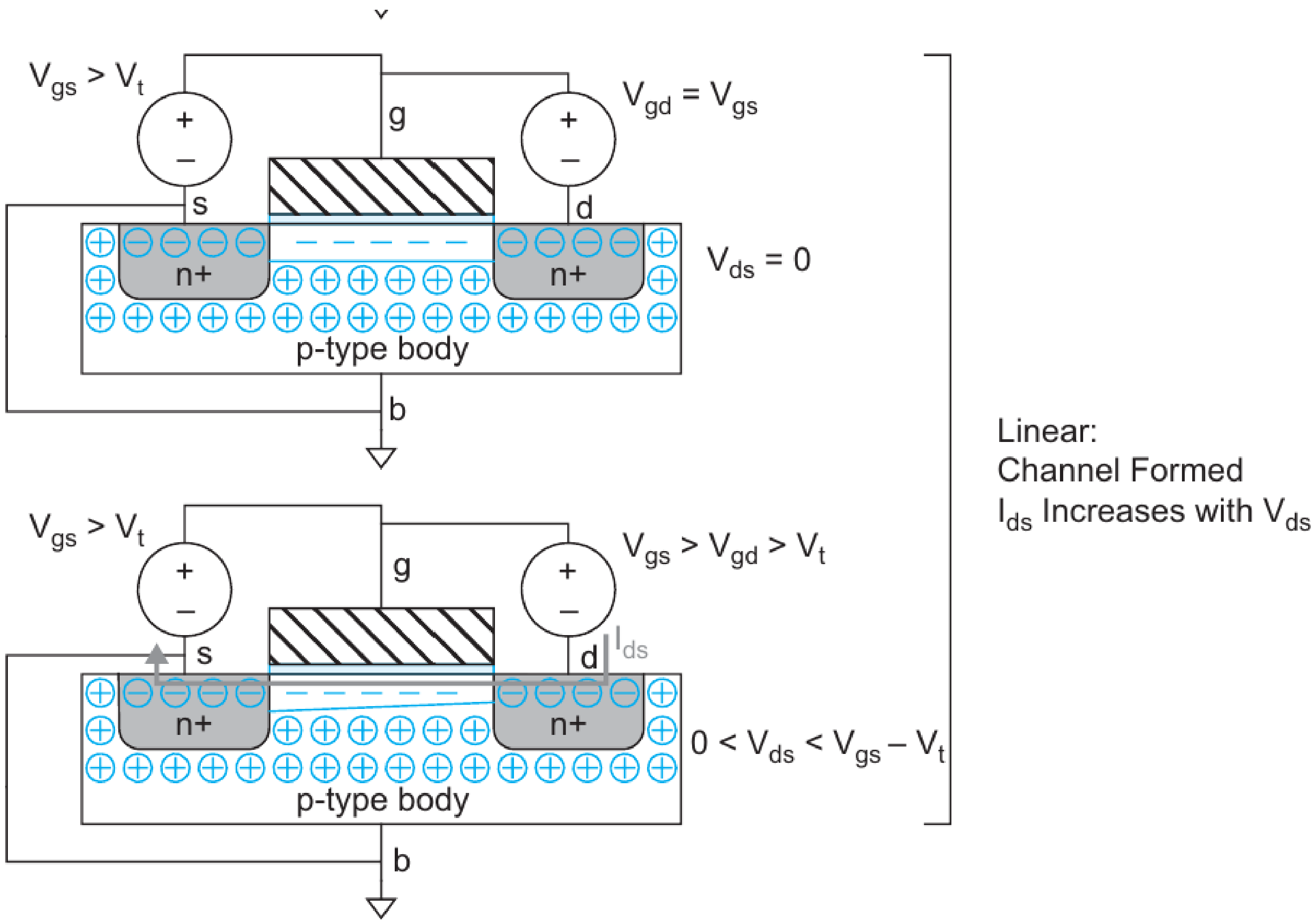
Effect of Drain Voltage on Channel Region

- $V_g \uparrow$ ➔ Channel region becomes more attractive to electron
- V_s or $V_D \uparrow$ ➔ Channel region becomes less attractive to electron



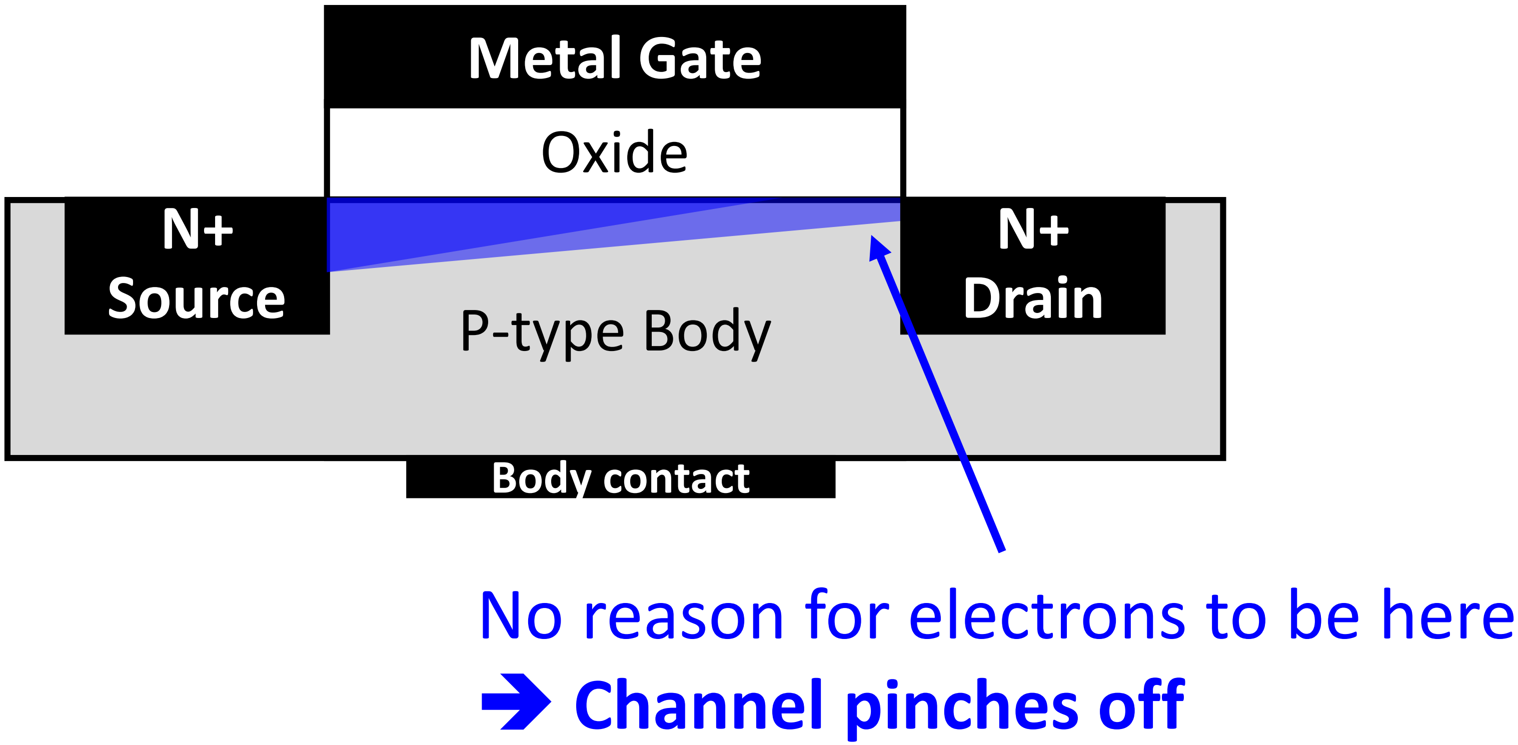
nMOSFET; Linear

- Note that the shape of channel changes according to V_{DS}



Channel Pinch-off

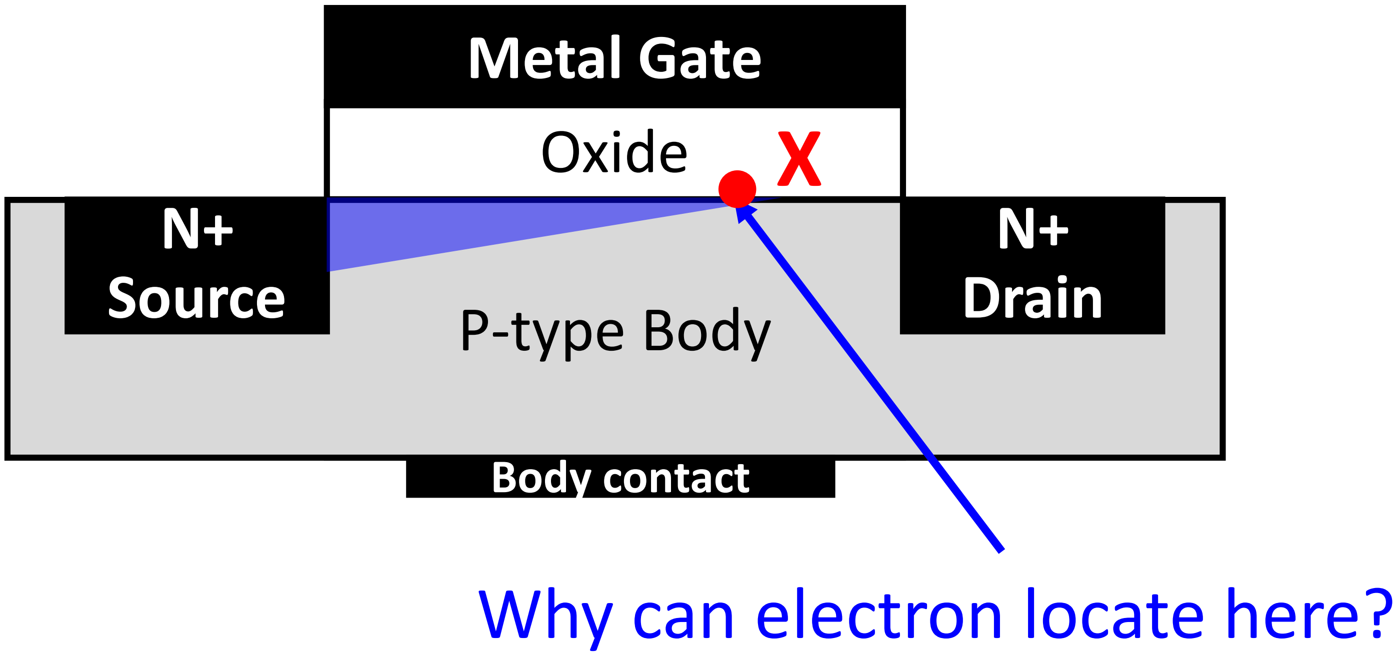
- Electron attraction by Gate **vs.** Electron attraction of Drain
- What if $V_D > V_{GS} - V_t$



Why Can Electron be There?

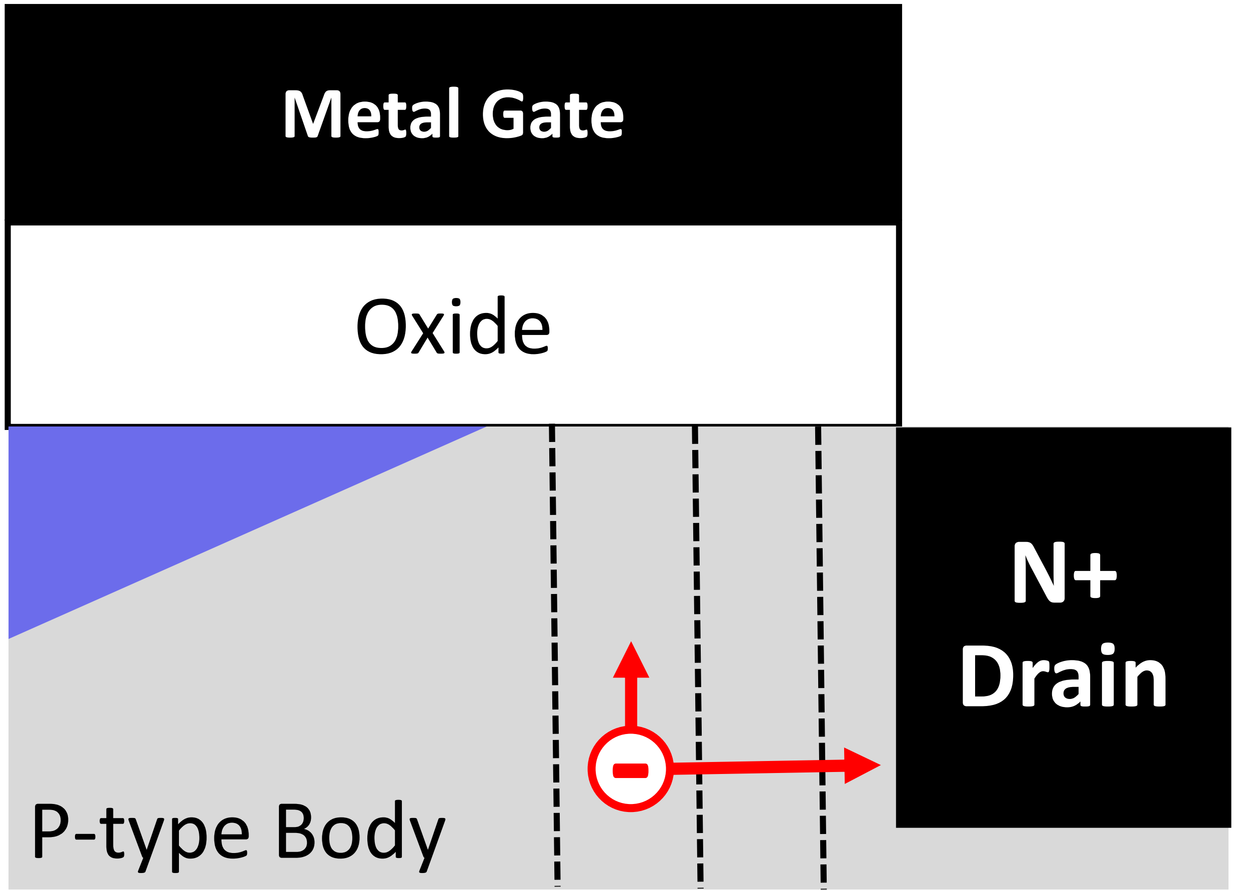
- Why can electron be point X while it cannot exist right side?

➔Because at the right of X, drain is more attractive



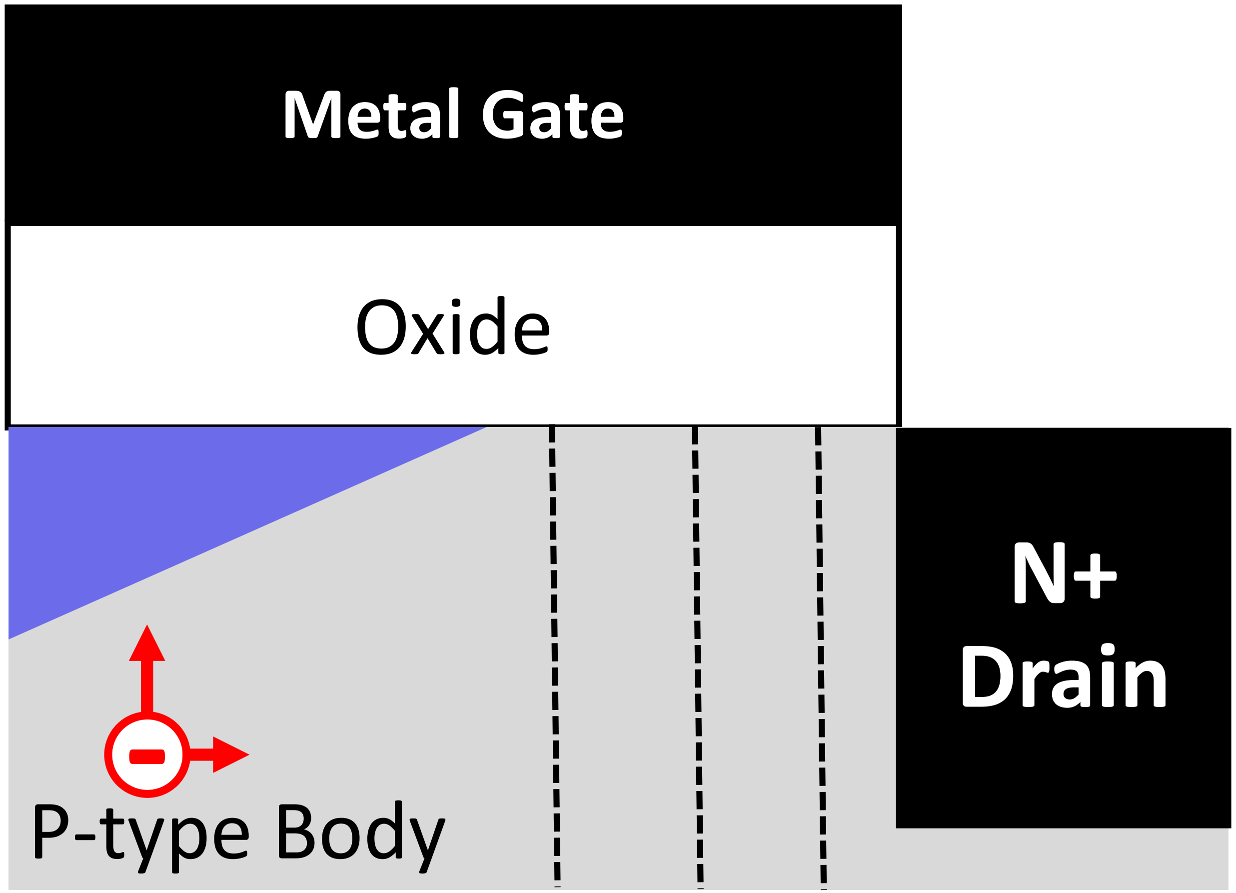
If Electron Will At Right Side of X

- V_{GS} = 2V, V_t = 0.5V, V_{DS} = 5V
- Potential formed by **V_{DS}** > V_{GS} - V_t



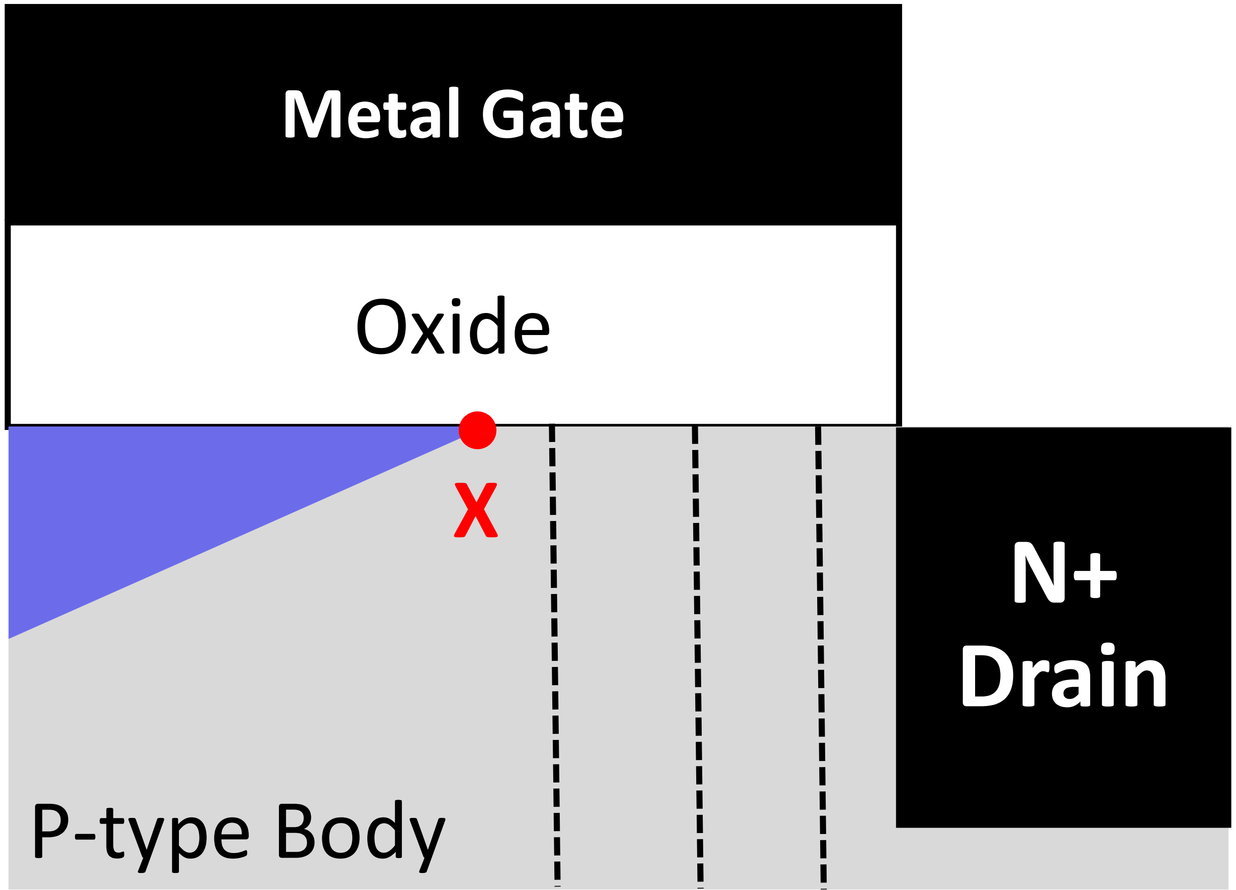
If Electron Will At Left Side of X

- V_{GS} = 2V, V_t = 0.5V, V_{DS} = 5V
- Potential formed by V_{DS} < **V_{GS} - V_t**

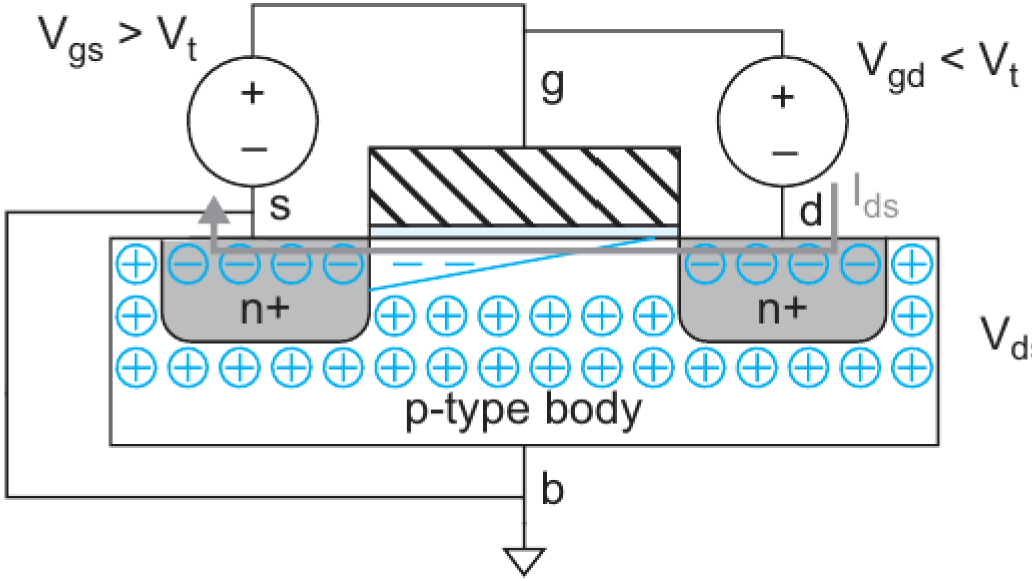


At Point X

- V_{GS} = 2V, V_t = 0.5V, V_{DS} = 5V
- Potential formed by $V_{DS} = V_{GS} - V_t$. That is, $V_X = V_{GS} - V_t$



nMOSFET; Saturation



$V_{ds} > V_{gs} - V_t$

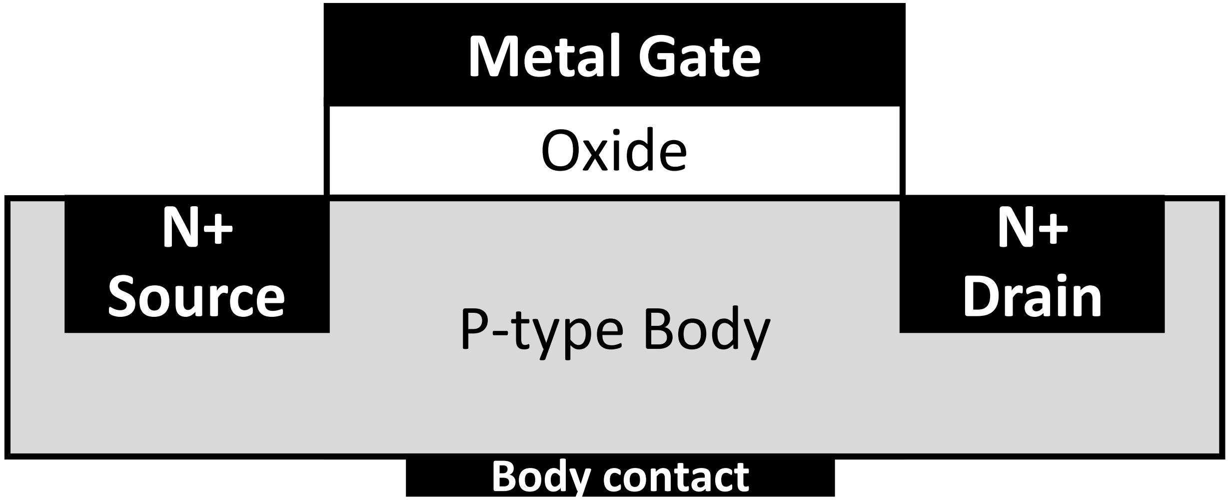
Saturation:
Channel Pinched Off
I_{ds} Independent of V_{ds}

Three nMOSFET Operation Modes

- $V_{GS} < V_t$: Cut off
- $V_{GS} > V_t$ and $V_{DS} < V_{GS} - V_t$: Linear
- $V_{GS} > V_t$ and $V_{DS} < V_{GS} - V_t$: Saturation

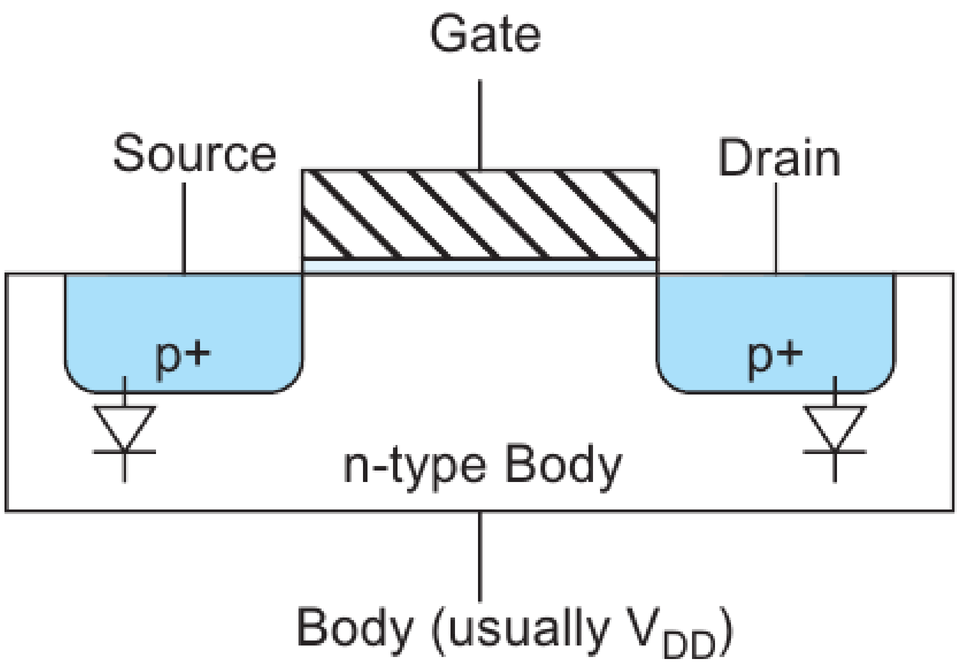
P-N Junction & Body Bias in nMOSFET

- For reverse bias, body is usually connected to lowest potential in nMOSFET



pMOSFET

- pMOSFET operates in the opposite fashion.
- The n-type body is tied to a high potential so the junctions

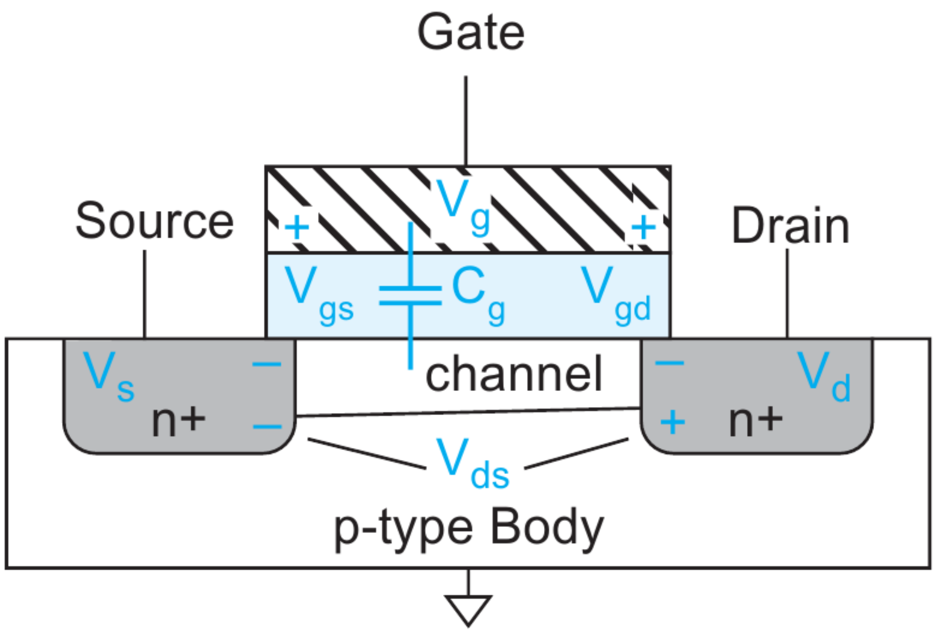


Quantitative Respect;
I-V Characteristic of MOSFET

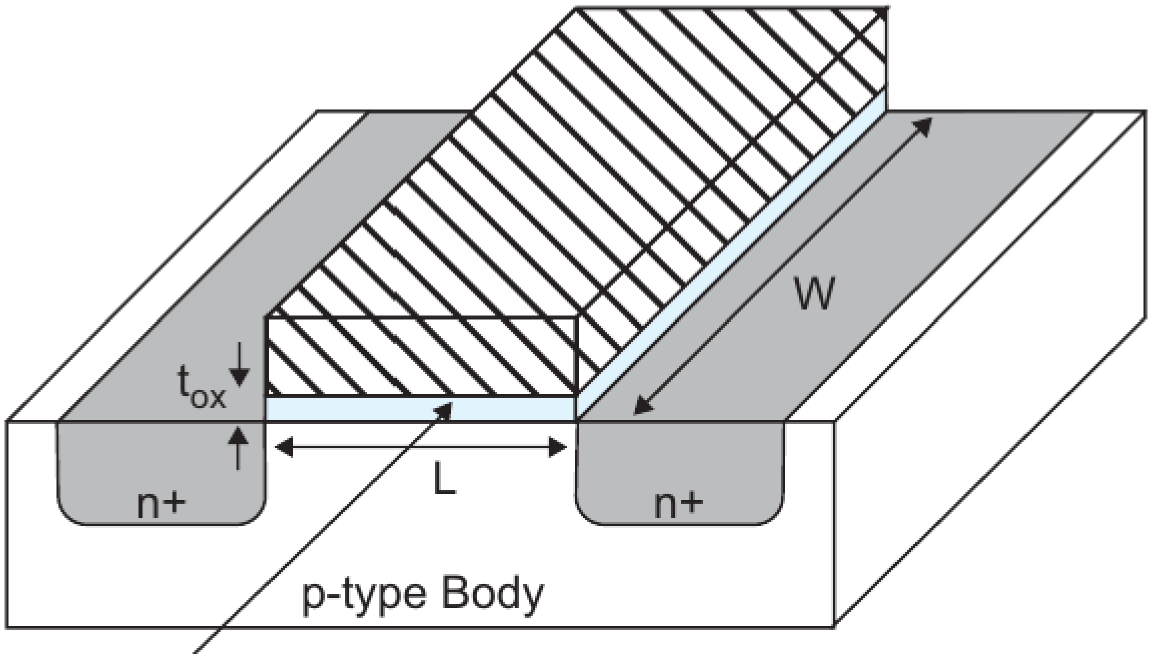
Drain Current Derivation

- Starting from the current definition $I_{DS} = Q/t$
- How can we derive Q in MOSFET?
  ➔ Charge in channel region, $Q_{channel} = CV$.
    ✓Cap? ➔ Gate capacitance, C_g
    ✓Voltage? ➔ Gate-to-channel voltage (V_{gc}) with MOS V-drop, V_t
- That is,

$$Q_{channel} = C_g(V_{gc} - V_t)$$

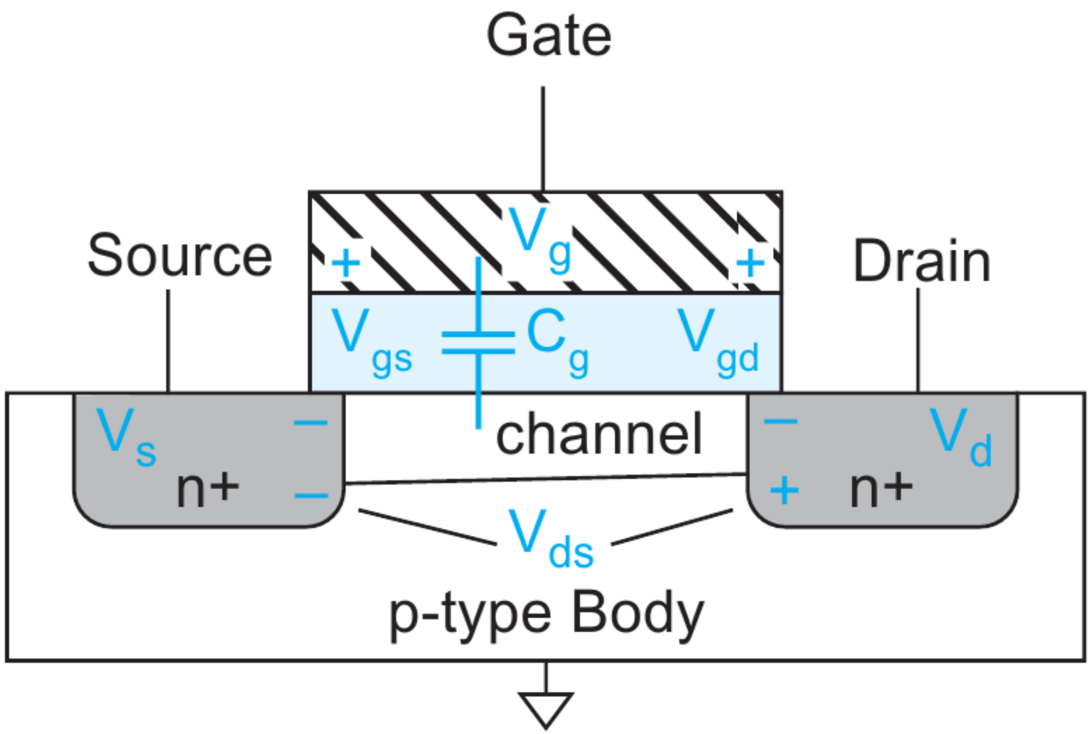


Gate Capacitance



$$C_g = k_{ox}\varepsilon_0 \frac{WL}{t_{ox}} = \varepsilon_{ox}\frac{WL}{t_{ox}} = C_{ox}WL$$

V_{gc}



$$V_{gc} = (V_{gs} + V_{gd})/2 = V_{gs} - V_{ds}/2$$

I_{DS} So Far

$Q_{channel} = C_g(V_{gc} - V_t)$

$= C_{ox}LW\,(V_{GS} - V_{DS}/2 - V_t)$

$I_{DS} = C_{ox}LW\,(^1/_t)(V_{GS} - V_{DS}/2 - V_t)$

Time?

- Voltage is noting but potential energy for unit charge
- Potential energy forms an electric field (=force for unit charge)

Electric-Field = Voltage/Distance

- In our case, Electric-field = V_{DS}/L
- Can we use F = ma?
  ➔ **No,** electrons only can be accelerated between collisions.
- Thus, over time, they move at the drift velocity (v) proportional to Electric-field, formulated by

$$v = \mu E$$

where μ is called mobility.

I_{DS}

$Q_{channel} = C_g(V_{GC} - V_t)$

$= C_{ox}LW\,(V_{GS} - V_{DS}/2 - V_t)$

$I_{DS} = C_{ox}LW\,({}^{1}/_{t})(V_{GS} - V_{DS}/2 - V_t)$

$t = L / v$

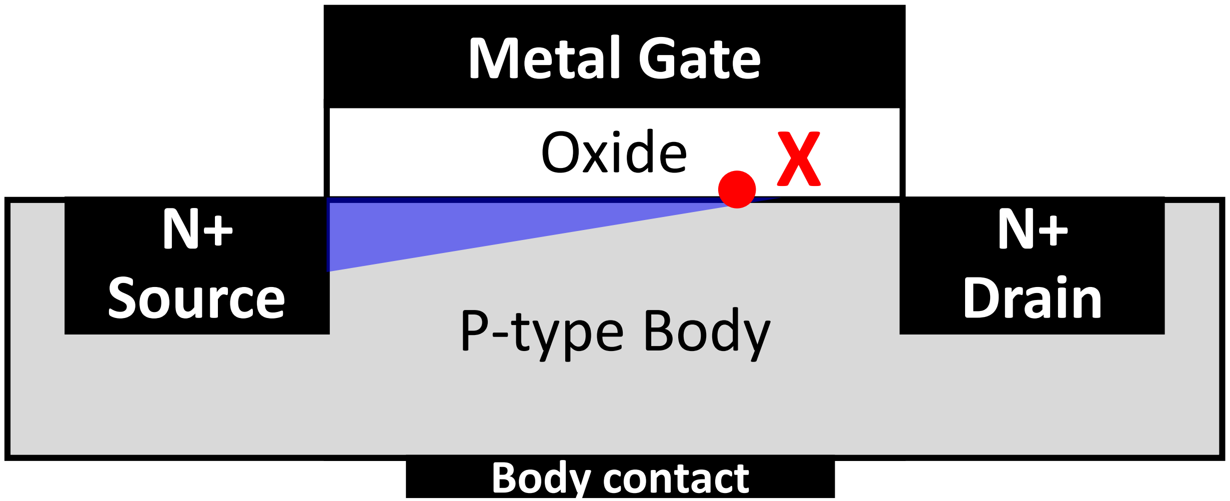
$= L / \mu E$

$= L^2 / \mu V_{DS}$

$$\mathbf{I_{DS} = \mu C_{ox}\frac{W}{L}(V_{GS} - V_{DS}/2 - V_t)V_{DS}}$$

How About Channel Pinch-off?

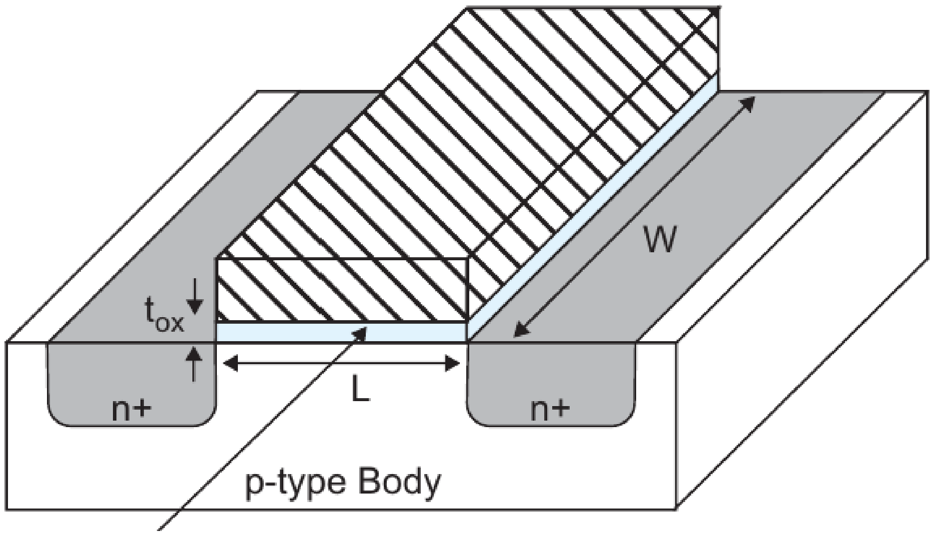
- When $V_{ds} > V_{gs} - V_t$, $v = \mu E$ does not hold any more and current is not dependent on V_{DS}.
- As $V_X = V_{GS} - V_t$, we can insert $V_{GS} - V_t$ into V_{DS} of the previously derived equation.



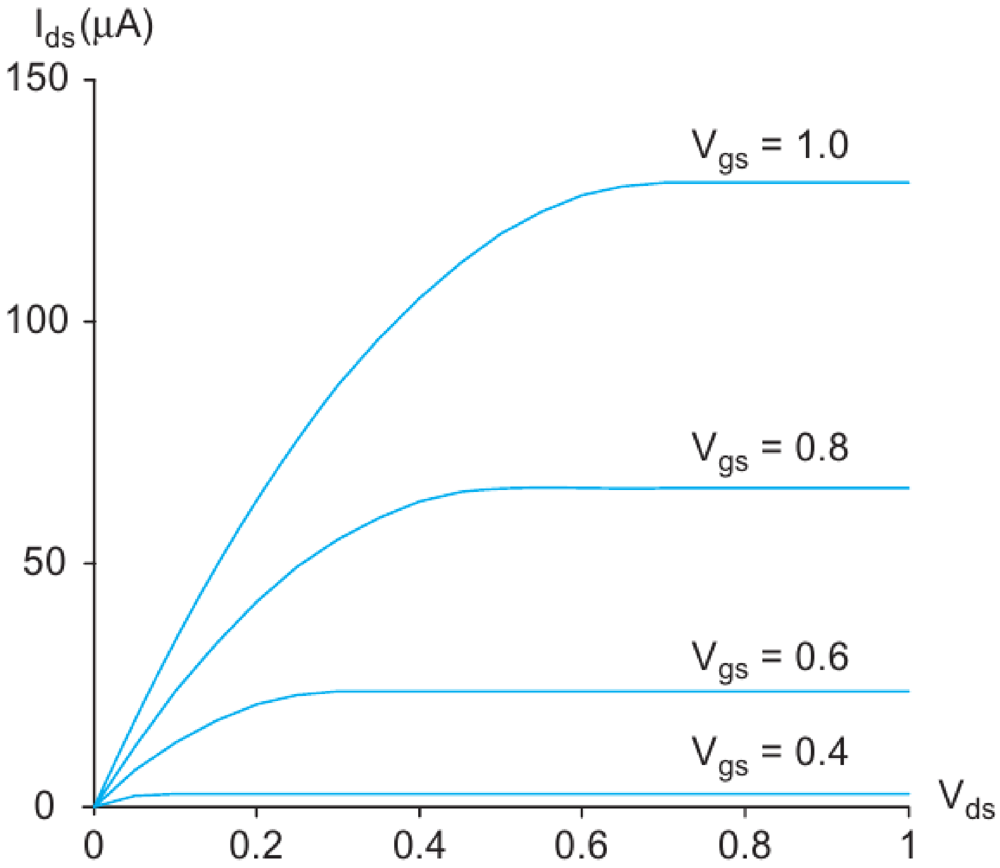
I_{DS} in Three Region

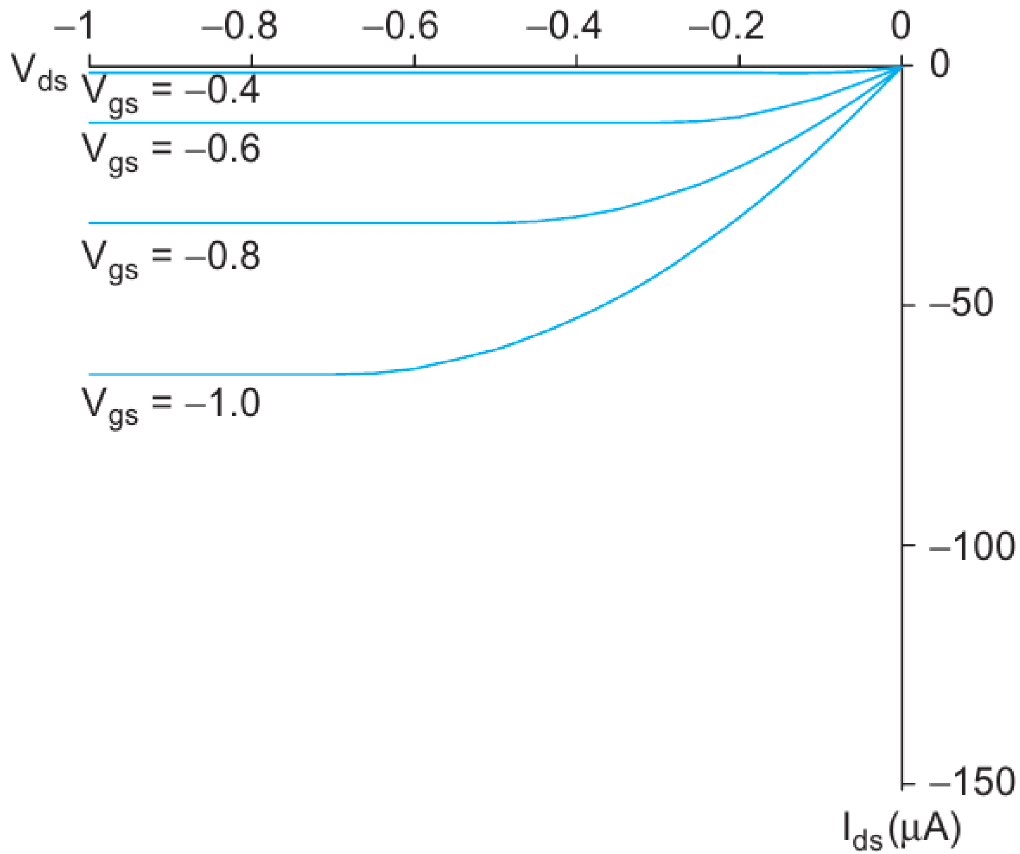
- Defining $\beta = \mu C_{ox}(W/L)$,

$$I_{ds} = \begin{cases} 0 & V_{gs} < V_t & \text{Cutoff} \\ \beta\left(V_{GT} - V_{ds}/2\right)V_{ds} & V_{ds} < V_{\text{dsat}} & \text{Linear} \\ \dfrac{\beta}{2}V_{GT}^2 & V_{ds} > V_{\text{dsat}} & \text{Saturation} \end{cases}$$



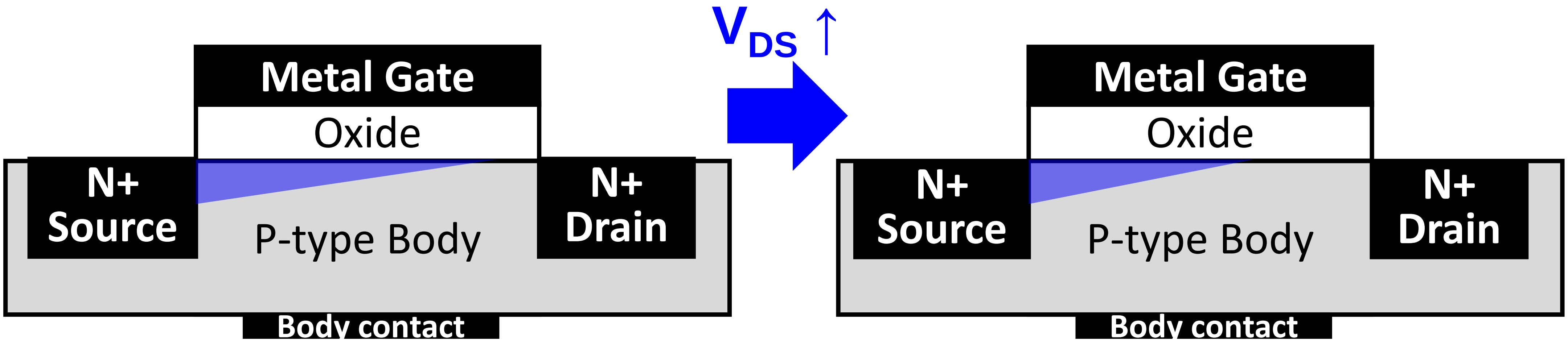
I-V Curve in nMOSFET and pMOSFET





V_{DS} vs. L

- **Effective channel length becomes smaller** as V_{DS} is larger and pinched off length is larger
- This effect is called “channel length modulation.”
- I_{DS} is not independent to V_{DS} even if $V_{DS} > V_{GS} - V_t$.



I_{DS} Model w/ Channel Length Modulation

- V_{DS} dependent form is added to the saturation current expression.

$$I_{ds} = \begin{cases} 0 & V_{gs} < V_t & \text{Cutoff} \\ \beta\left(V_{GT} - V_{ds}/2\right)V_{ds} & V_{ds} < V_{\text{dsat}} & \text{Linear} \\ \dfrac{\beta}{2}V_{GT}^2\left(1+\dfrac{V_{DS}}{V_A}\right) & V_{ds} > V_{\text{dsat}} & \text{Saturation} \end{cases}$$