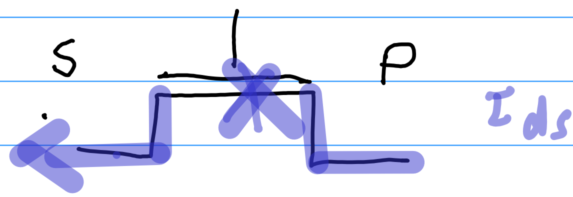
MOSFET Theory (H.2)

20160227

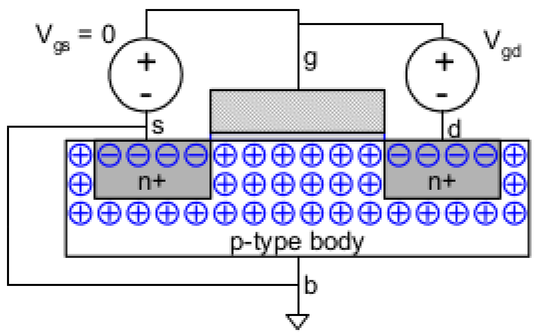
nMOS Operation Modes
Bias Method

Cut Off



- No channel
- $I_{ds} \approx 0$ — cut off

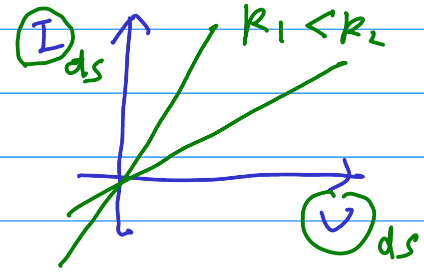
$V_{gs} < V_t$



Linear

Linear Region

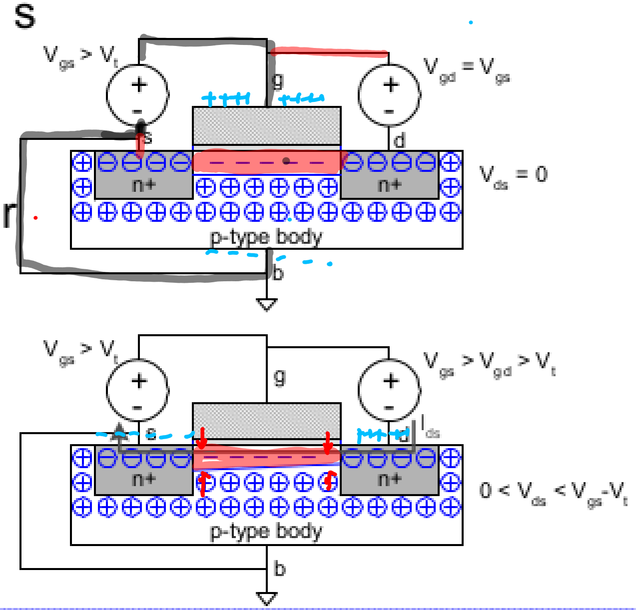
$V_g > V_t$

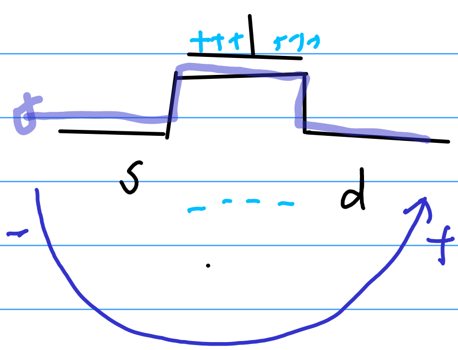


$R = \frac{V}{I}$

$\frac{1}{R} = \frac{I}{V}$

- Channel forms → current flows
- Current flows from d to s
  - e^- from s to d
- I_{ds} increases with V_{ds}
- Similar to linear resistor





$0 < V_{ds} < V_{gs} - V_t$

Channel at (D)

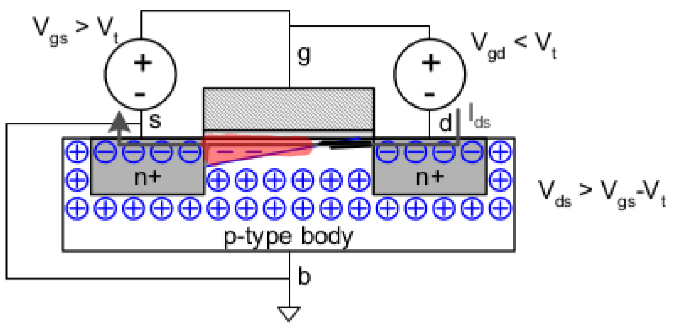
$V_g > V_t$

↓

inversion layer (channel at (S))

nMOS Saturation

- Channel pinches off
- I_{ds} independent of V_{ds}
- We say current *saturates*
- Similar to current source



Bias Conditions

$V_{GS} < V_t$ • Cut off

$V_{GS} > V_t$ • Linear
• Saturation

$V_{GS} > V_t$ → S-side channel

$V_{GD} > V_t$ → D-side channel

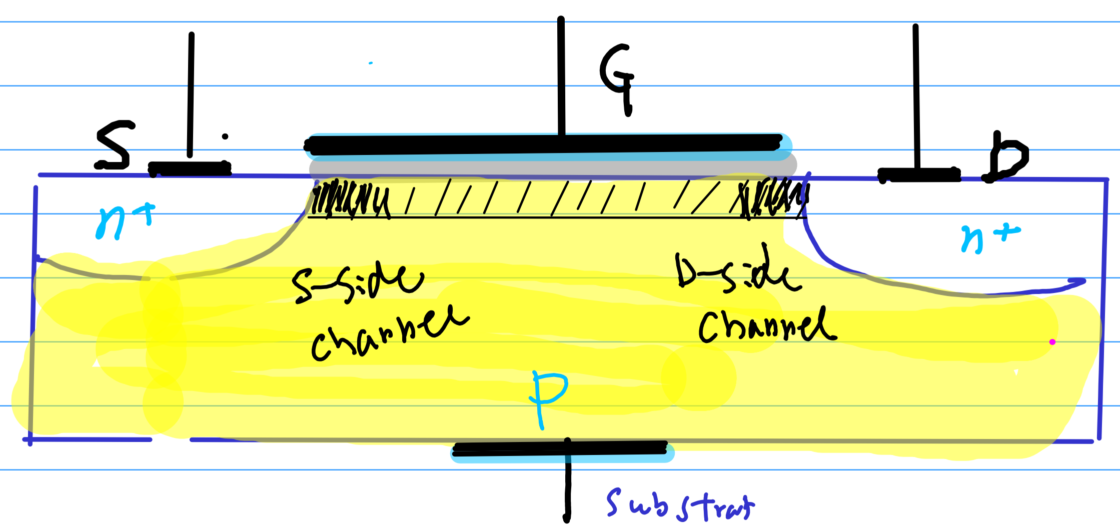
||

$V_{DS} < V_{GS} - V_t$

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

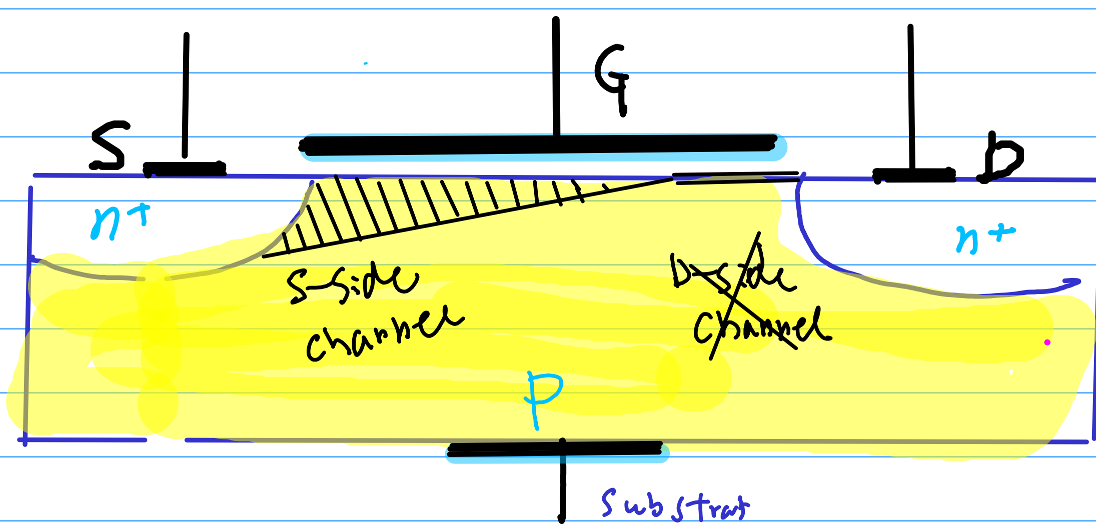
$V_{GS} - V_t > V_{DS}$

LINEAR



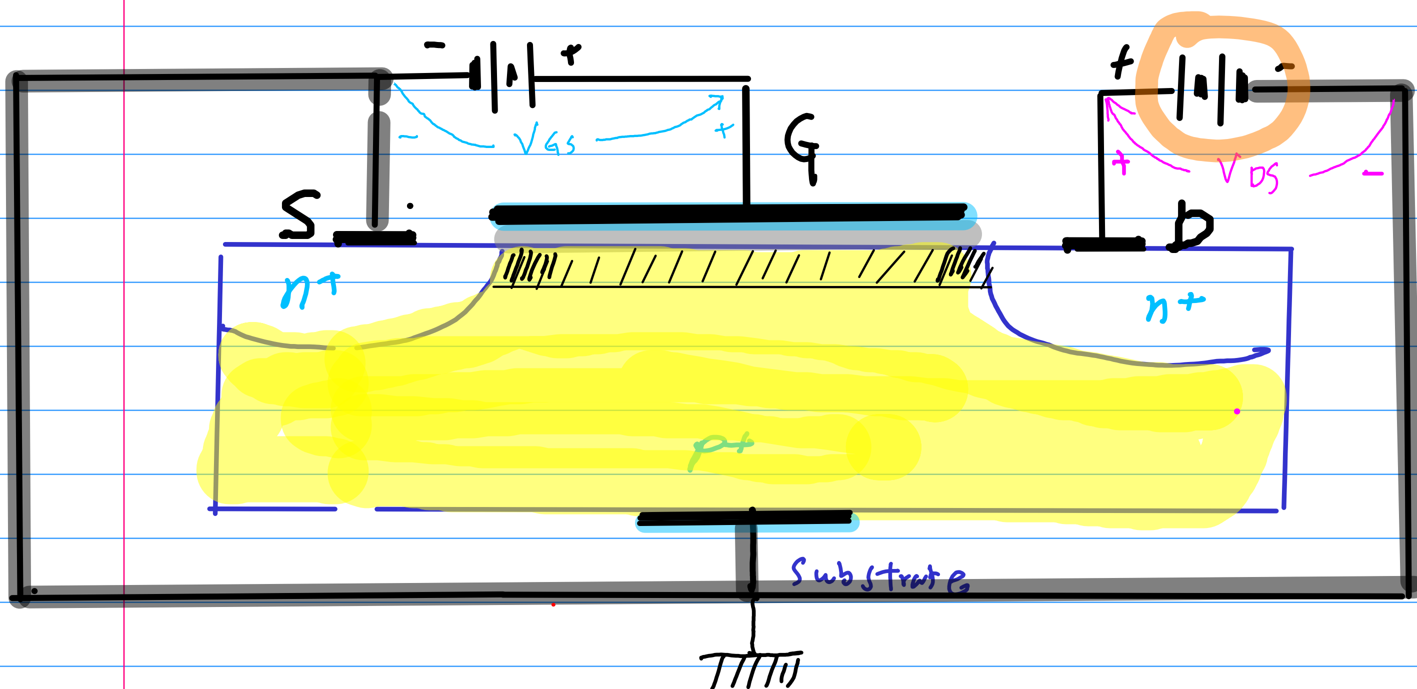
- $V_{GS} < V_t$ — • Cut off
- $V_{GS} > V_t$
  - $V_{GD} > V_t$ = $V_{DS} < V_{GS} - V_t$
    - • Linear (S-side channel, D-side channel)
  - $V_{GD} < V_t$ = $V_{DS} > V_{GS} - V_t$
    - • Saturation (S-side channel, ~~D-side channel~~)

SATURATION

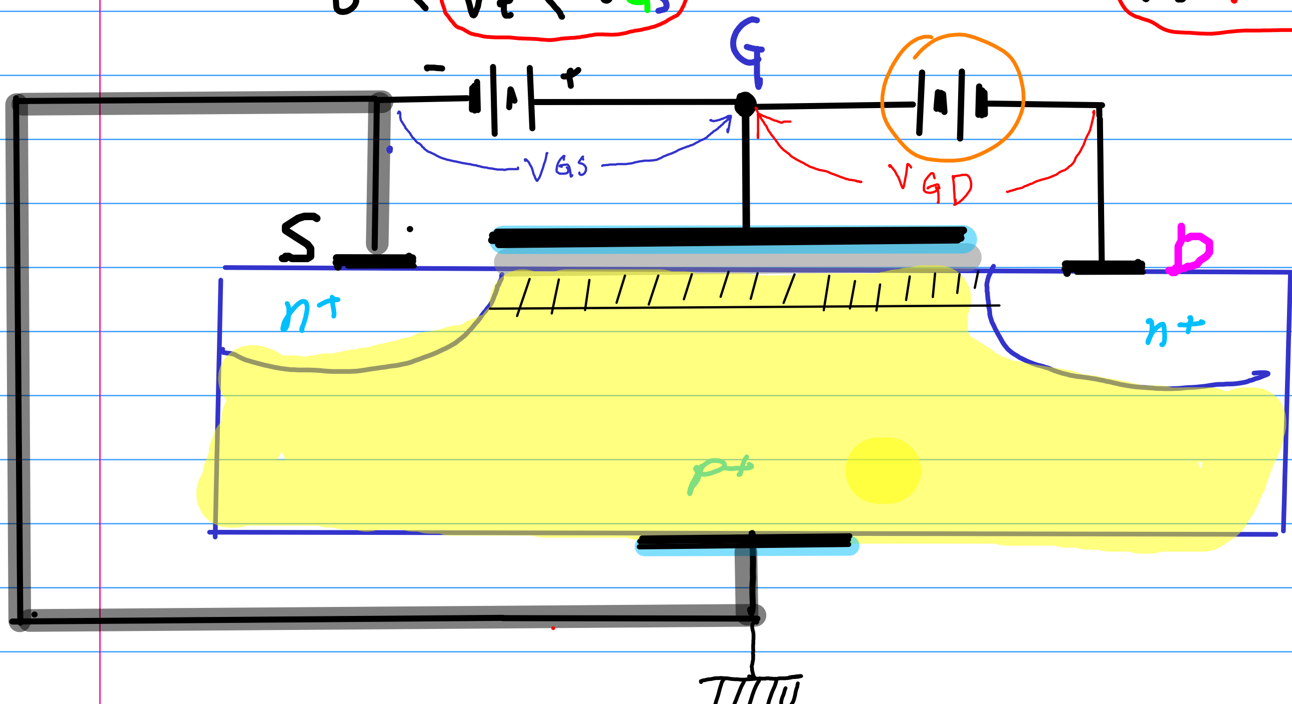


LINEAR

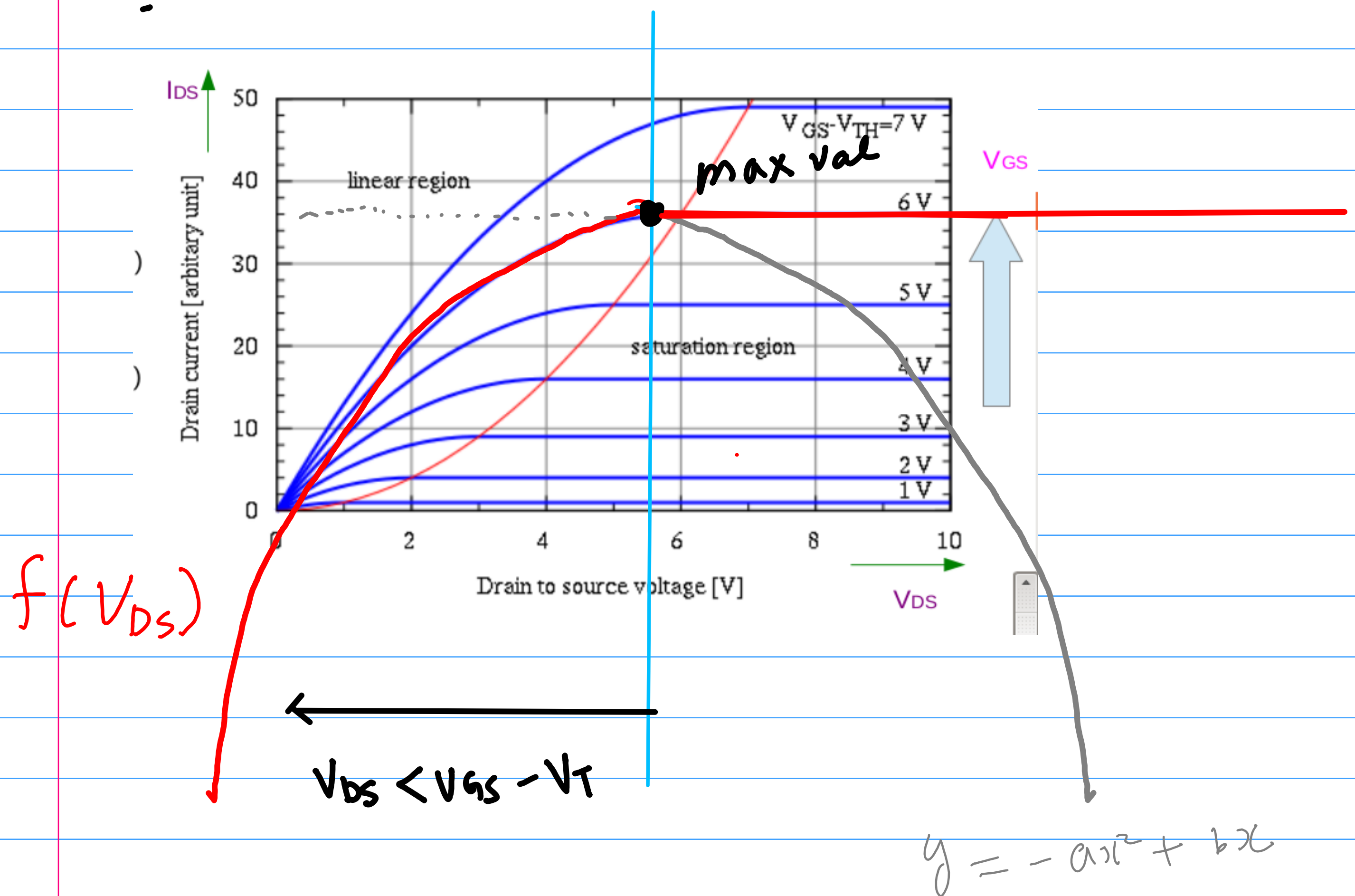
$0 < V_t < V_{GS}$ $0 < V_{DS} < V_{GS} - V_T$

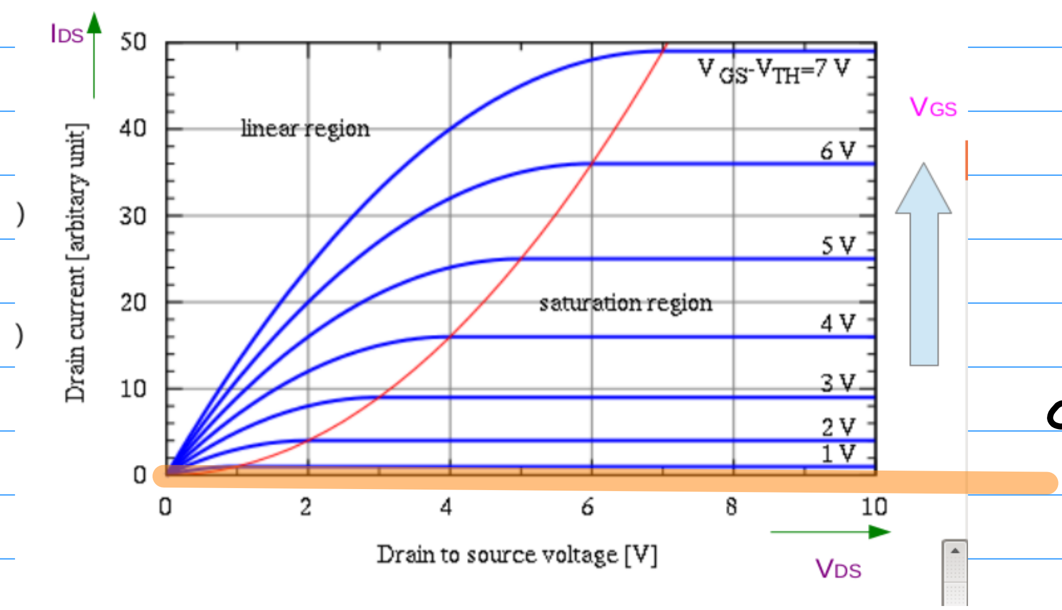


$0 < V_t < V_{GS}$ $0 < V_t < V_{GD}$



Linear → left side of a quadratic eq

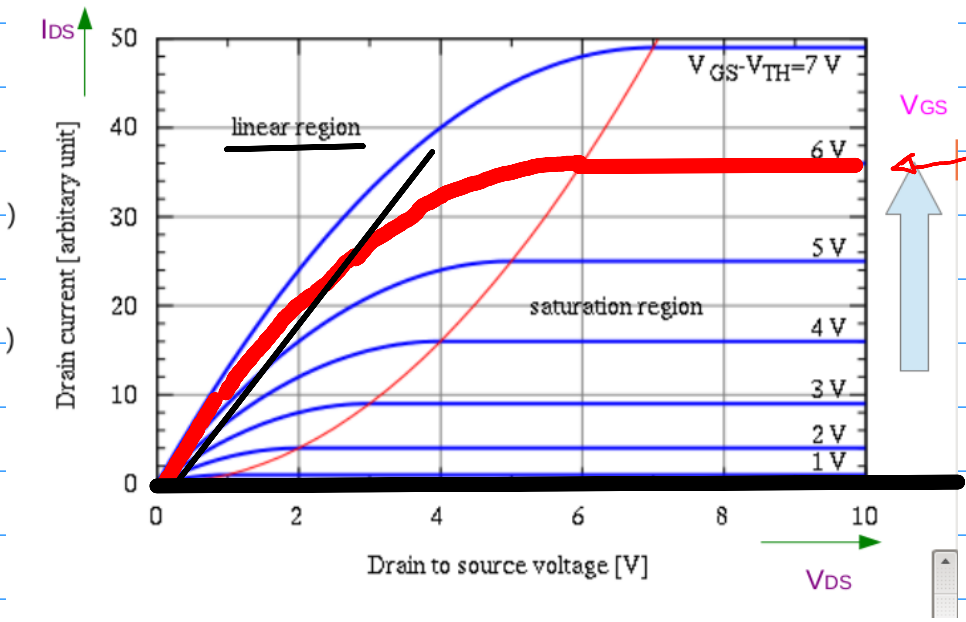




cut off

$i_{DS} = 0$

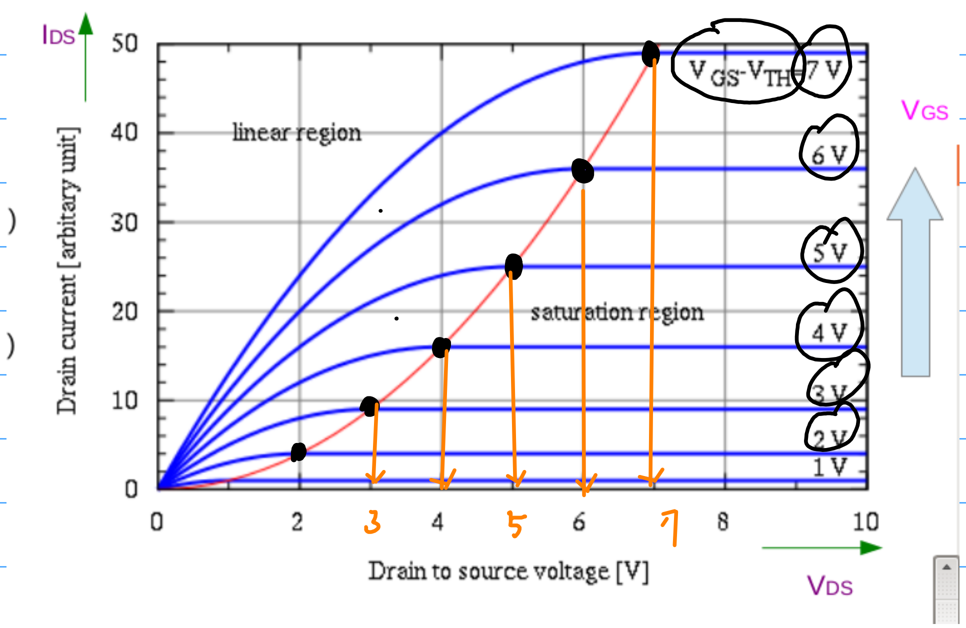
a given V_{GS}



$V_{GS} - V_T \leq 0$

$V_{GS} \leq V_T$

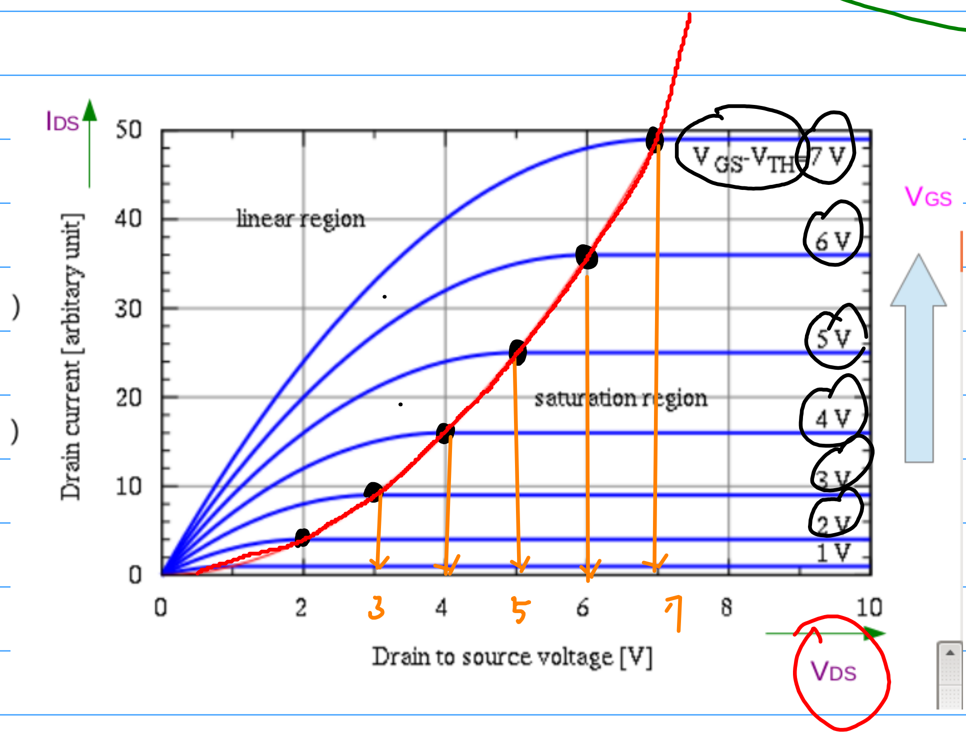
Cut off



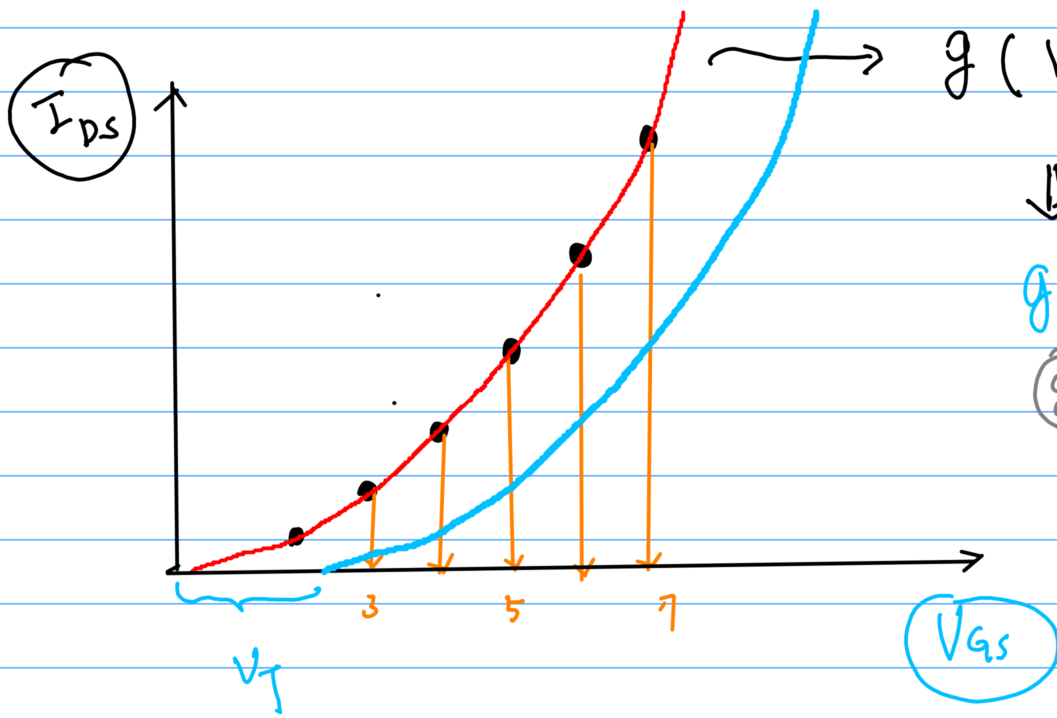
$V_{GS} - V_T = V_{DS}$

7	7
6	6
5	5
4	4
3	3
2	2
1	1

points where
$V_{DS} = V_{GS} - V_T$



$f(V_{DS})$
$= f(V_{GS} - V_T)$



$g(V_{GS} - V_T)$

⇓

$g(V_{GS})$

$g(V_T) = 0$

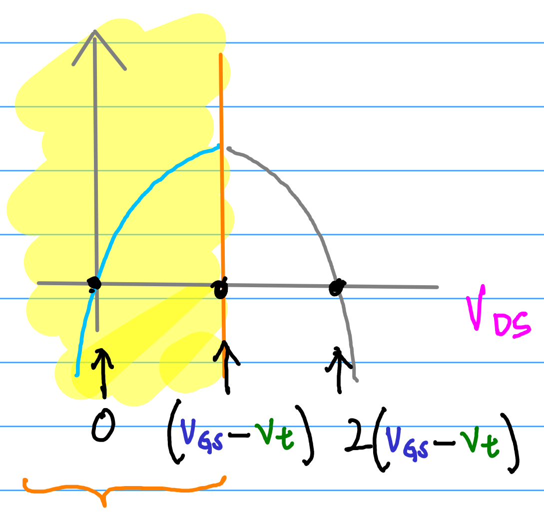
$f(V_{GS} - V_t) = \frac{\beta}{2}(V_{GS} - V_t)^2 = g(V_{GS})$

$$I_{ds} = \begin{cases} 0 & V_{gs} < V_t & \text{cutoff} \\ \beta\left(V_{gs} - V_t - \frac{V_{ds}}{2}\right)V_{ds} & V_{ds} < V_{dsat} & \text{linear} \\ \frac{\beta}{2}\left(V_{gs} - V_t\right)^2 & V_{ds} > V_{dsat} & \text{saturation} \end{cases}$$

for a given V_{GS}

$$f(V_{DS}) = \frac{\beta}{2}\left(2(V_{GS} - V_t) - V_{DS}\right)V_{DS}$$

$$= \frac{\beta}{2}\left(2(V_{GS} - V_t)V_{DS} - V_{DS}^2\right)$$



$y = (2a - x)x$

$= (2ax - x^2)$

$x = 0, 2a$ roots

sym axis

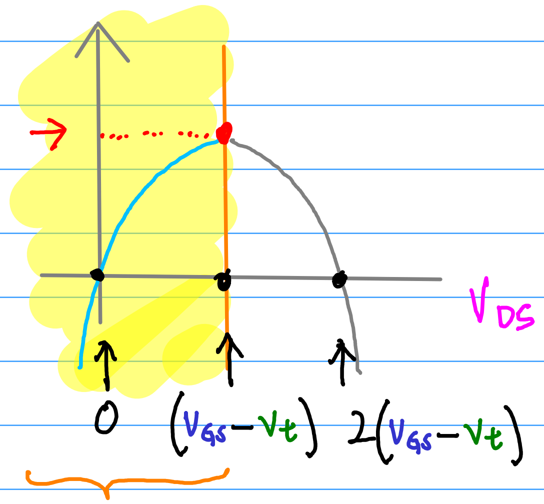
$x = a$

$V_{DS} \leq V_{GS} - V_t$

Linear Eq & Max value

for a given V_{GS} → const

$$f(V_{DS}) = \frac{\beta}{2}\left(2(V_{GS}-V_t) - V_{DS}\right)V_{DS}$$



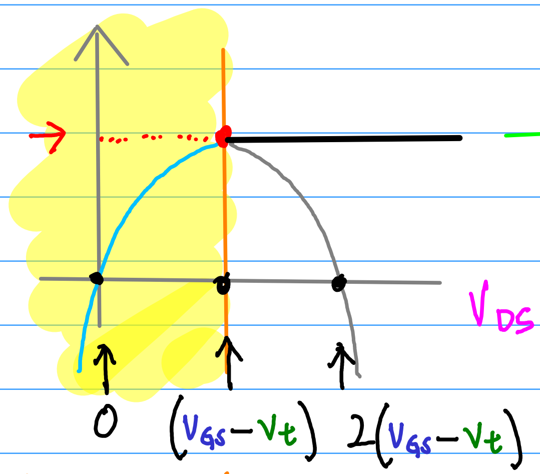
$V_{DS} \leq V_{GS}-V_t$

$$f(V_{GS}-V_t) = \frac{\beta}{2}\left(2(V_{GS}-V_t)-(V_{GS}-V_t)\right)(V_{GS}-V_t)$$

$$= \frac{\beta}{2}(V_{GS}-V_t)^2$$

$$I_{DS} = \frac{\beta}{2}(V_{GS}-V_t)^2$$: Saturated current

Saturation

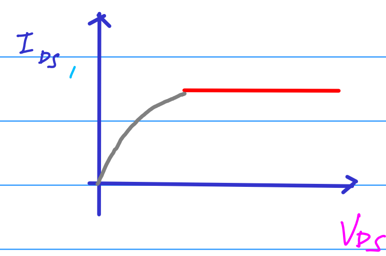


$$I_{DS} = \frac{\beta}{2}(V_{GS}-V_t)^2$$

$$V_{DS} \geq V_{GS}-V_t$$

✱ for a given V_{GS} — const with respect to V_{DS}

$$f(V_{DS}) = \frac{\beta}{2}(V_{GS}-V_t)^2 = \text{constant}$$

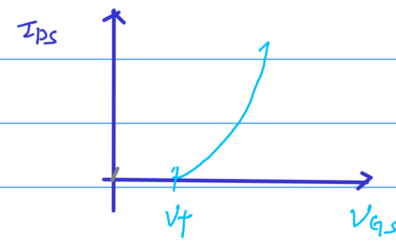


✱ But a function of V_{GS}

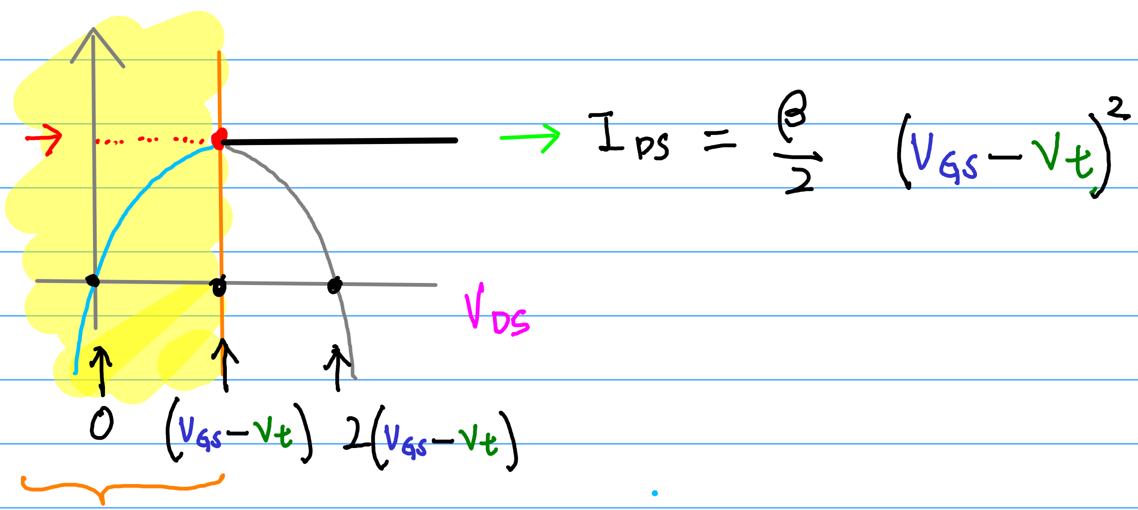
$$g(V_{GS}) = \frac{\beta}{2}(V_{GS}-V_t)^2$$

now V_{GS} is an independent variable

Quadratic equation of V_{GS}



$$I_{ds} = \begin{cases} 0 & V_{gs} < V_t & \text{cutoff} \\ \beta\left(V_{gs} - V_t - \frac{V_{ds}}{2}\right)V_{ds} & V_{ds} < V_{dsat} & \text{linear} \\ \frac{\beta}{2}\left(V_{gs} - V_t\right)^2 & V_{ds} > V_{dsat} & \text{saturation} \end{cases}$$

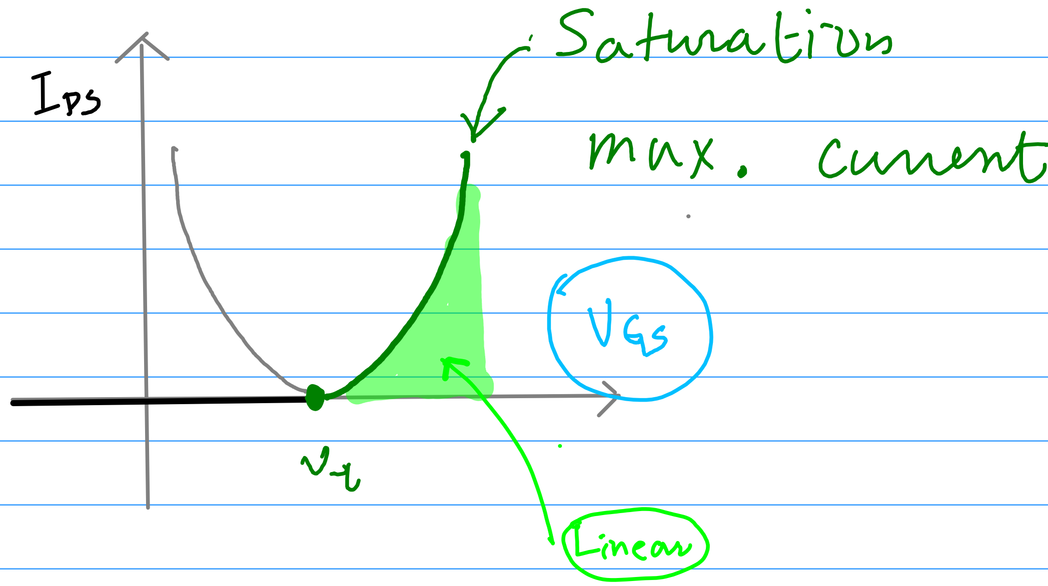


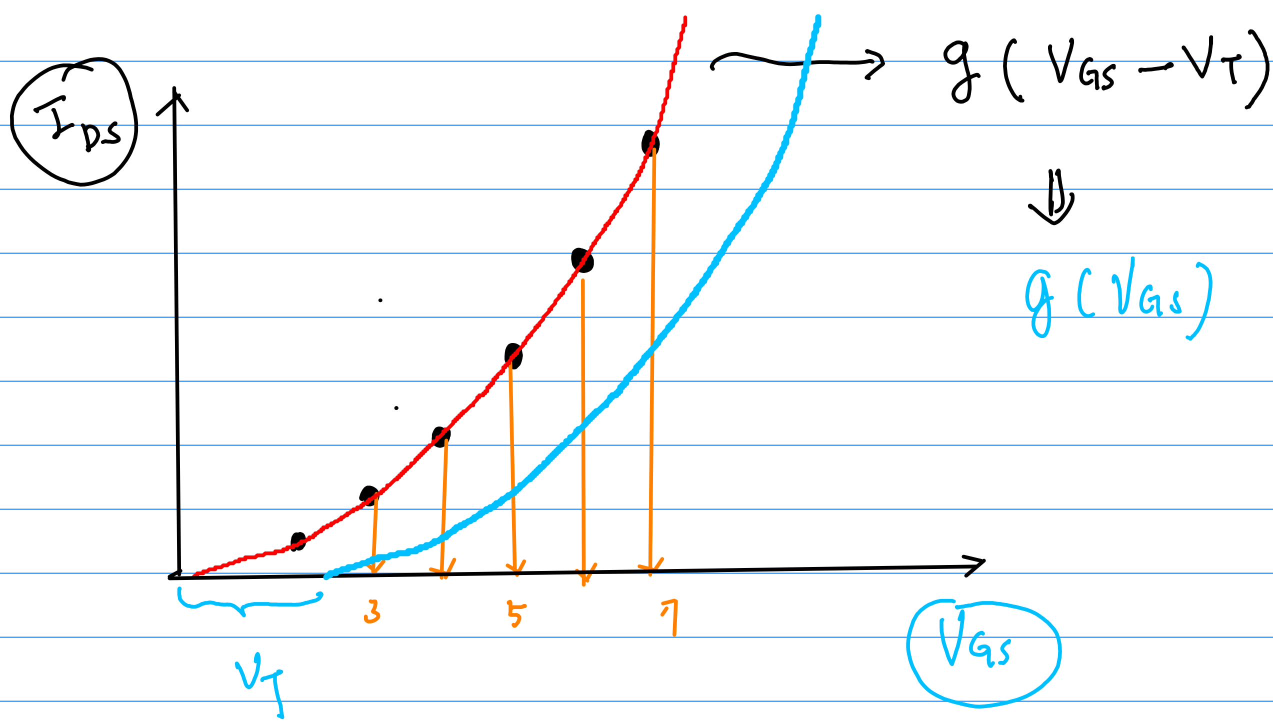
$V_{DS} \leq V_{GS} - V_t$

$V_{GS} < V_t$

Cutoff

$I_{ds} = 0$

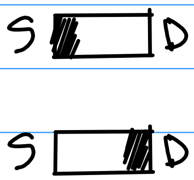




① Cut off

$$V_{GS} < V_t$$

② Linear



$$0 < V_t < V_{GS}$$
$$0 < V_t < V_{GD}$$

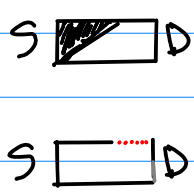
$\equiv$

$$0 < V_t < V_{GS}$$
$$V_{DS} < V_{GS} - V_t$$

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

$V_{GS} - V_t > V_{DS}$

③ Saturation



$$0 < V_t < V_{GS}$$
$$V_{GD} < V_t$$

$\equiv$

$$0 < V_t < V_{GS}$$
$$V_{GS} - V_t < V_{DS}$$

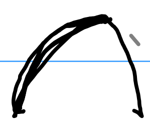
① Cut off $V_{GS} < V_t$

$I_{DS} = 0$

② Linear $0 < V_t < V_{GS}$ $\quad V_{DS} < V_{GS} - V_t$

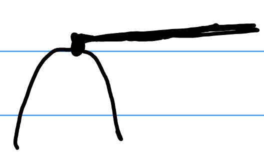
$$I_{DS} = f(V_{DS}) = \frac{\beta}{2}\left(2(V_{GS}-V_t) - V_{DS}\right)V_{DS}$$

$$= \frac{\beta}{2}\left(2(V_{GS}-V_t)V_{DS} - V_{DS}^2\right)$$



③ Saturation $0 < V_t < V_{GS}$ $\quad V_{GS} - V_t < V_{DS}$

$$I_{DS} = f(V_{DS}) = \frac{\beta}{2}(V_{GS}-V_t)^2 = \text{constant !}$$



* for a given V_{GS}

$$V_{DS} = V_{GS} - V_{GD} = \cancel{V_G} - V_S - (\cancel{V_G} - V_D)$$
$$= V_D - V_S$$

$$\boxed{V_{GD} = V_{GS} - V_{DS}}$$

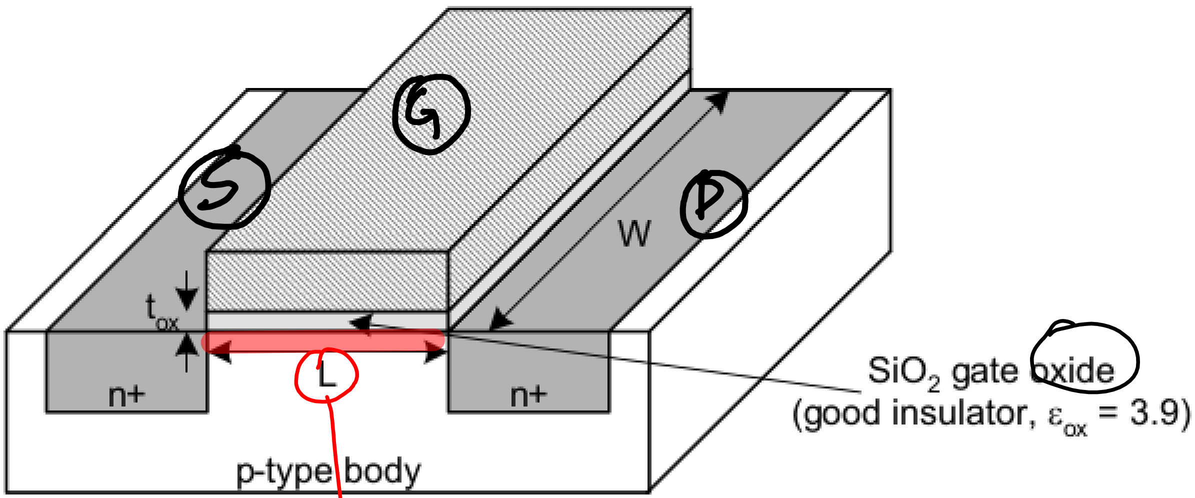
$V_{GD} \geq V_t$ **<u>Linear</u>**

$$\boxed{V_{GS} - V_{DS} \geq V_t}$$

$V_{GD} < V_t$ **<u>Saturation</u>**

$$\boxed{V_{GS} - V_{DS} < V_t}$$

Transconductance $(\beta) = \frac{1}{R}$

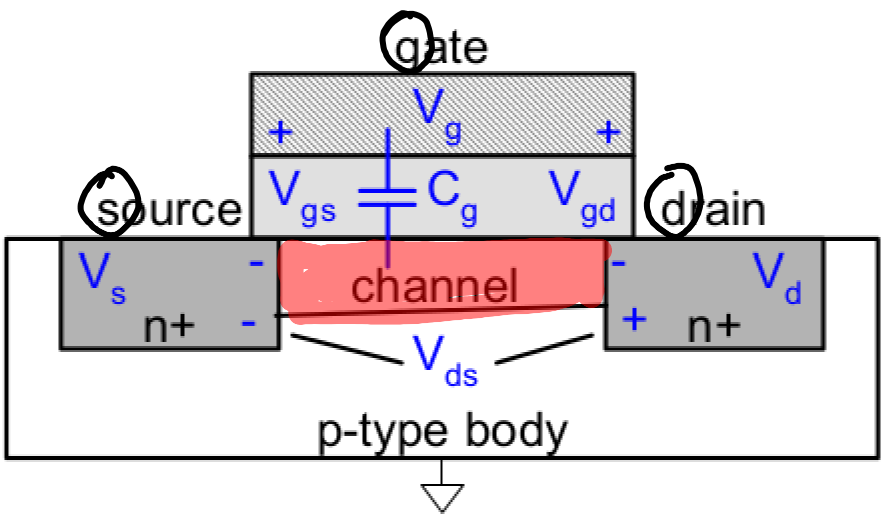


channel Length

$L \uparrow \quad I_{ds} \downarrow$

$W \uparrow \quad I_{ds} \uparrow$

$\frac{W}{L} \uparrow \quad I_{ds} \uparrow$



$$\beta = \mu_n C_{ox} \left(\frac{W}{L} \right)$$

① Cut off

$$V_{GS} < V_t$$

$$I_{DS} = 0$$

② Linear

$$0 < V_t < V_{GS} \qquad V_{DS} < V_{GS} - V_t$$

$$I_{DS} = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)\left(2(V_{GS}-V_t) - V_{DS}\right)V_{DS}$$

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

β

③ Saturation

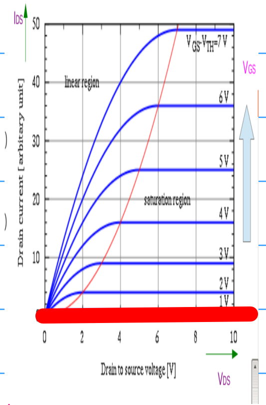
$$0 < V_t < V_{GS} \qquad V_{GS} - V_t < V_{DS}$$

β

$$I_{DS} = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)(V_{GS}-V_t)^2 = \text{constant !}$$

* <u>for a given V_{GS}</u>

① Cut off

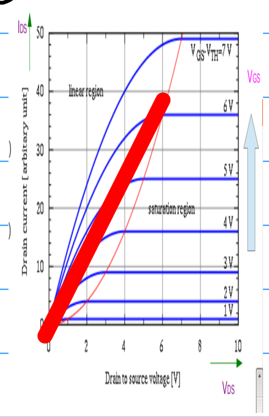


OFF

$$\text{slope} = \frac{1}{R} = 0$$

$$R = \infty$$

② Linear



ON

$$\text{slope} = \frac{1}{R}$$

$$0 < R \ll \infty$$

Digital

↕

Analog

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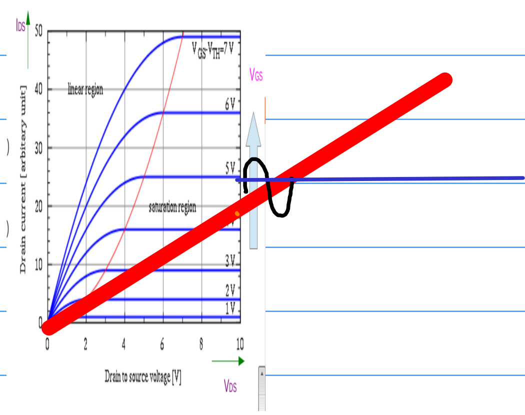
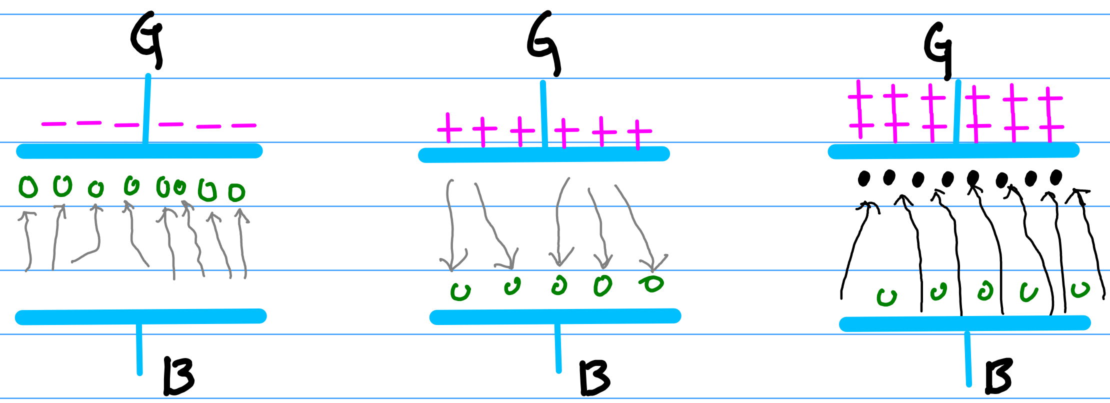
③ Saturation



AMP

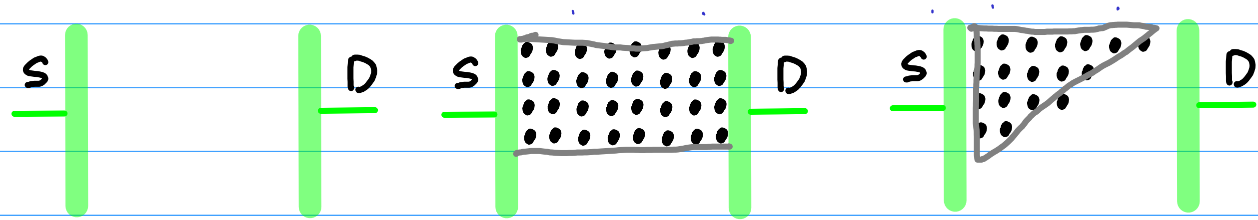
MOS Structure : V_{GB} Bias

Accumulation	Depletion	Inversion
majority carriers	majority carrier	minority carrier



attracts holes	repels holes	repels holes attracts electrons
$V_{GB} < 0$	$0 < V_{GB} < V_t$	$V_t < V_{GB}$

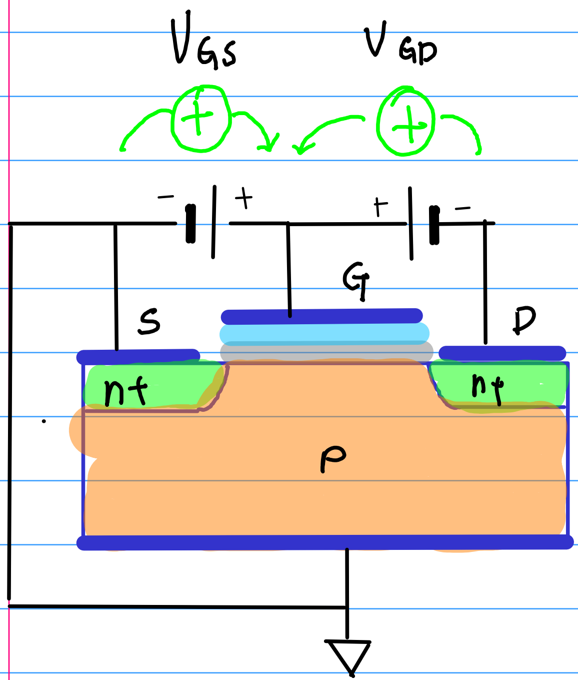
OFF	LIN	SAT

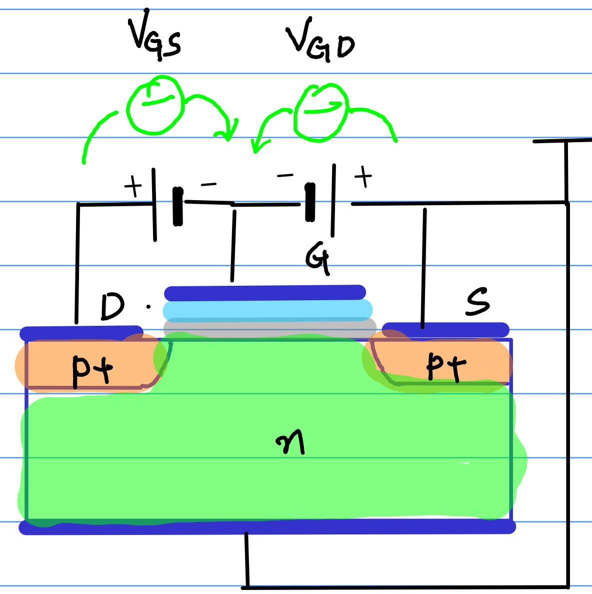


OFF	LIN	SAT
$V_{GB} < V_t$	$V_t < V_{GB}$	$V_t < V_{GB}$
	$V_{DS} < V_{GS} - V_t$	$V_{DS} > V_{GS} - V_t$

Accumulation	Depletion	Inversion	
$V_{GB} < 0$	$0 < V_{GB} < V_t$	$V_t < V_{GB}$	
		$V_{DS} < V_{GS} - V_t$	$V_{DS} > V_{GS} - V_t$
OFF		LIN	SAT

Linear Mode Bias Condition ①





$V_{GS} > V_{Tn}$, $V_{GD} > V_{Tn}$

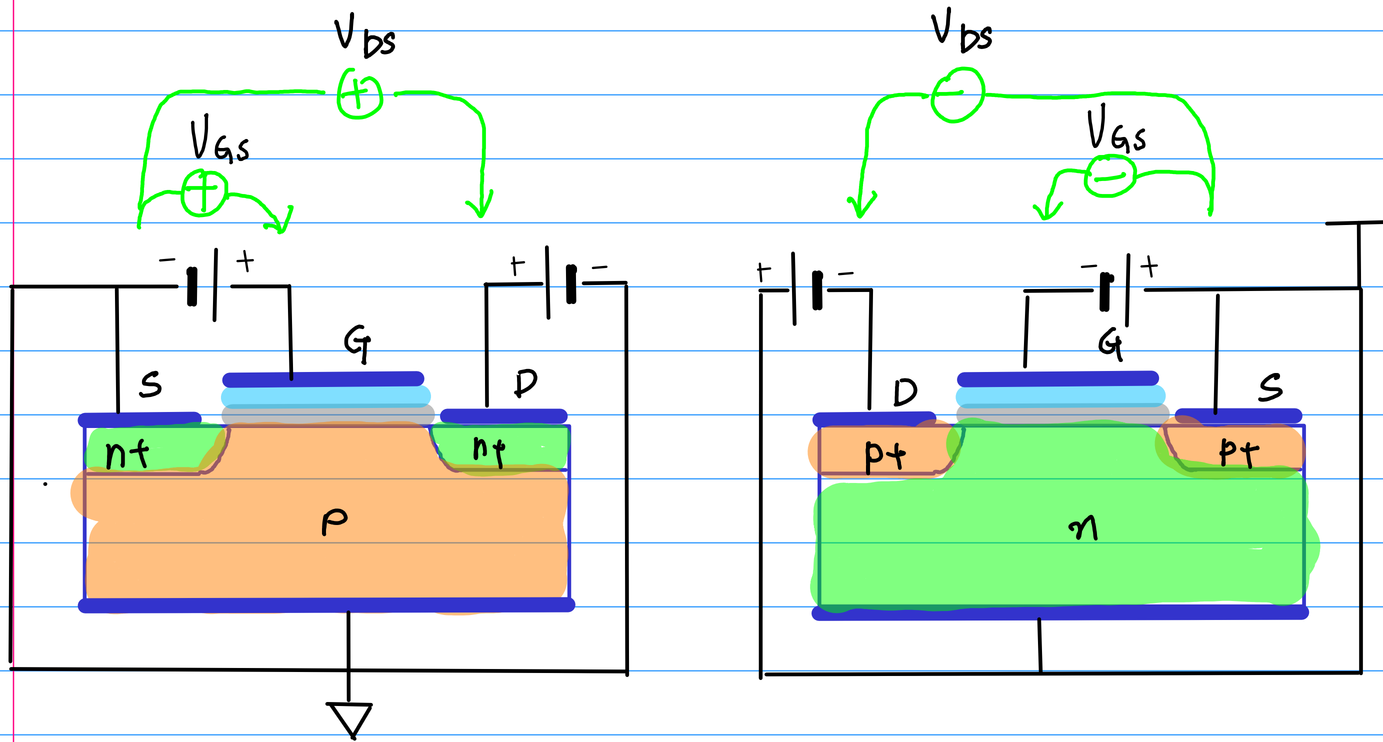
$V_{GS} < V_{Tp}$, $V_{GD} < V_{Tp}$

$-V_{SG} < V_{Tp}$ $\quad -V_{DG} < V_{Tp}$

$V_{SG} > -V_{Tp}$ $\quad V_{DG} > -V_{Tp}$

$V_{SG} > |V_{Tp}|$, $V_{DG} > |V_{Tp}|$

Linear Mode Bias Condition ②



$V_{GD} = V_{GS} - V_{DS} > V_{Tn}$

$V_{GS} - V_{Tn} > V_{DS}$

$V_{GS} > V_{Tn}$,

$V_{DS} < V_{GS} - V_{Tn}$

$V_{GD} = V_{GS} - V_{DS} < V_{Tp}$

$V_{GS} - V_{Tp} < V_{DS}$

$V_{GS} < V_{Tp}$,

$V_{DS} > V_{GS} - V_{Tp}$

$-V_{SD} > -V_{SG} - V_{Tp}$

$V_{SD} < V_{SG} + V_{Tp}$

$V_{GS} < V_{Tp}$,

$V_{SD} < V_{SG} + V_{Tp}$

$V_{SG} > |V_{Tp}|$

$V_{SD} < V_{SG} - |V_{Tp}|$

- Wafer Growth
- Photo-lithography
- Doping
  - Diffusion
  - Implantation
- Oxidation
- Deposition
  - Dielectric
  - Polysilicon
  - Metals
- Etching
  - Chemical
  - Chemical-Mechanical
  - Mechanical
- Expitaxial Growth

References

Some Figures from the following sites

[1] http://pages.hmc.edu/harris/cmosvlsi/4e/index.html
Weste & Harris Book Site

[2] en.wikipedia.org