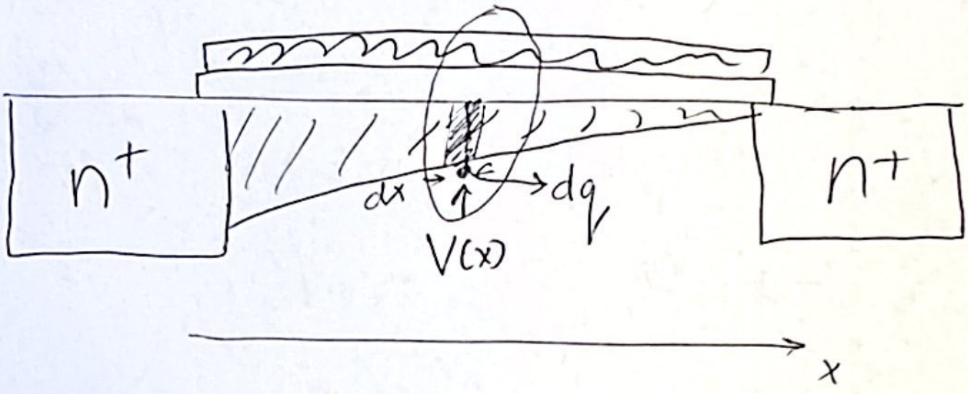
Lec15

Pinch-Off (aka Saturation region) → Same as forward active

V_{DS} is large.



$$dq = C_{ox} W dx \left(V_{GS} - V_T - V(x)\right)$$

$$\Rightarrow I_D = \frac{dq}{d\tau} = \frac{W C_{ox} dx \left(V_{GS} - V_T - V(x)\right)}{\frac{dx^2}{\mu_n dV}}$$

$$= \mu_n C_{ox} W \left[V_{GS} - V_T - V(x)\right] \frac{dV}{dx}$$

I_D of each section = I_D of entire transistor since they are in series.

$$\Rightarrow I_D \underbrace{\int_0^L dx}_{L} = \mu_n C_{ox} W \int_0^{V_{DS}} \left(V_{GS} - V_T - V(x)\right) dV$$

$$\Rightarrow I_D = \mu_n C_{ox} \frac{W}{L}\left[(V_{GS} - V_T)V_{DS} - \frac{V_{DS}^2}{2}\right]$$ → More accurate Triode equation

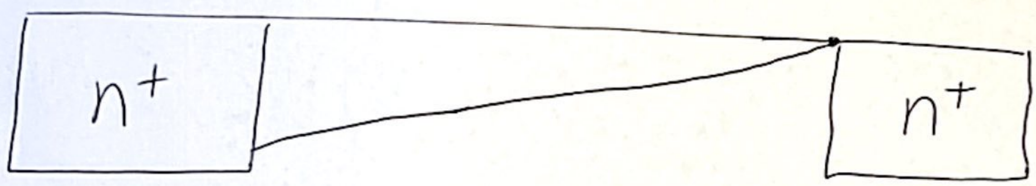
> <u>Assumption:</u> $V_T(x) = V_T$ ⇒ V_T does not change over the channel (Not true but ok for our purposes).

> This is not a good (VC) current source!

<u>Pinch off</u>

$q_{ch}(\text{at drain}) = WL\, C_{ox}\,(V_{GS} - V_T - V_{DS})$

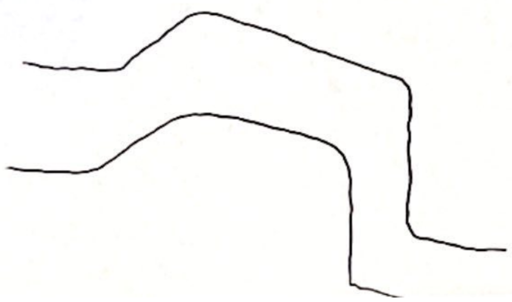
At $V_{DS} = V_{GS} - V_T$ $q_{ch} = 0$ ⇒ Channel is ~~pi~~ "pinched off"

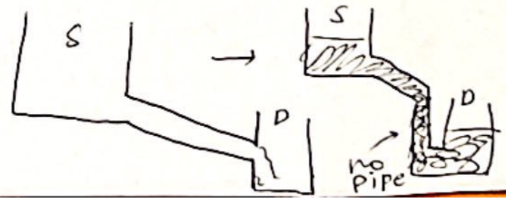


> Does this mean no current flows? No!

There is a strong electric field in the depletion region.

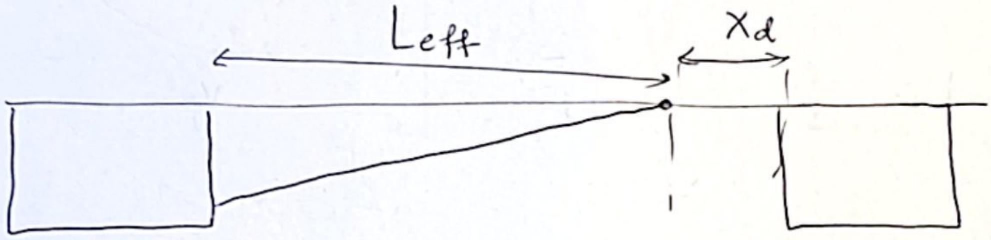
(Something like a "waterfall")





Pinch-Off (aka Saturation) ($\Rightarrow$ FA in BJT)

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



If $L \gg x_d \Rightarrow$ Charge in channel becomes independant of $V_{DS} \Rightarrow$ Good! (for current source).

> At pinch off point $V(x) = V_{GS} - V_T$ so it appears like a transistor always at pinch off with $L \longrightarrow L_{eff}$.

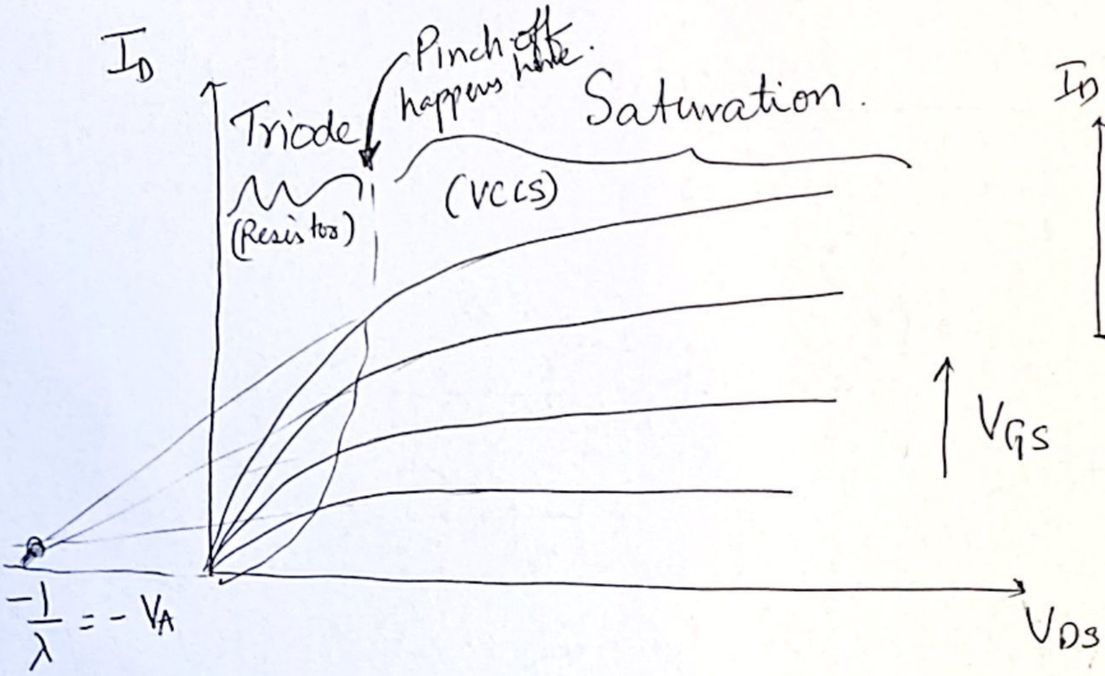
$$\Rightarrow I_D = \mu_n C_{ox} \frac{W}{L_{eff}} \left[(V_{GS} - V_T)(V_{GS} - V_T) - \frac{(V_{GS} - V_T)^2}{2} \right]$$

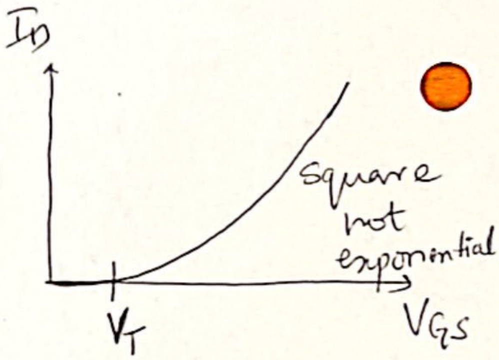
$$\boxed{I_D = \frac{1}{2} \mu_n C_{ox} \frac{W}{L_{eff}} (V_{GS} - V_T)^2}$$

Pinch-Off (current Source)

> Impact of V_{DS} is absorbed in L_{eff} $\rightarrow$ Channel Length Modulation! (BWM in BJT).

> We incorporate this CLM into a constant λ.





$$\rightarrow \quad I_D = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_T)^2 (1 + \lambda V_{DS})$$

Pinch off. (Saturation) $V_{GS} - V_T < V_{DS}$

For continuity

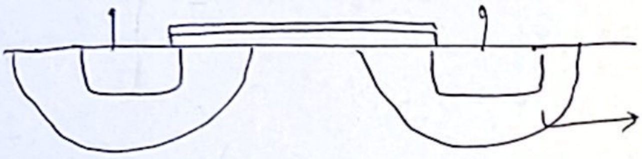
$$I_D = \mu_n C_{ox} \frac{W}{L} \left[(V_{GS} - V_T) V_{DS} - \frac{V_{DS}^2}{2} \right] (1 + \lambda V_{DS})$$

Triode (Linear) $V_{GS} - V_T > V_{DS}$

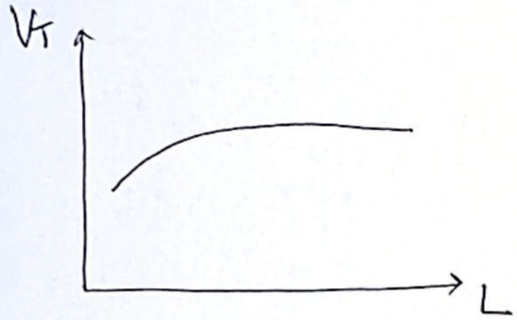
Short Channel Effects

2003	2007	2012	2018	2025
90nm	45nm	22nm	7nm	2nm
Lg = 50nm	25nm	20nm	10nm	6nm

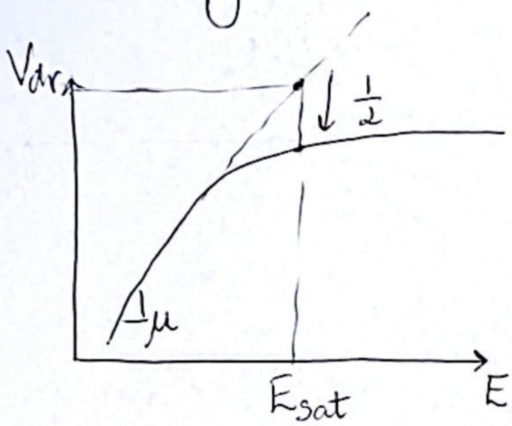
1) Threshold voltage variation (roll-off)



These depletion regions become a significant fraction of the depletion region that forms the channel.



2) Velocity Saturation

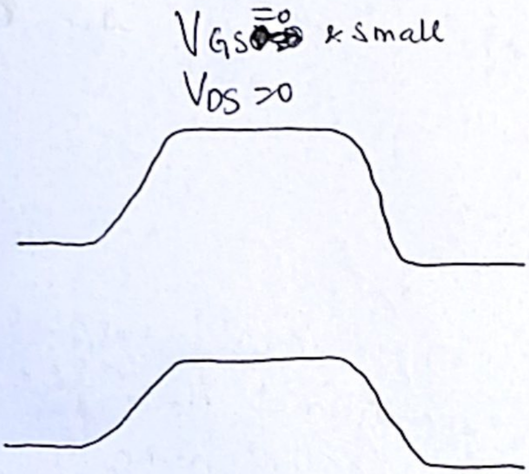


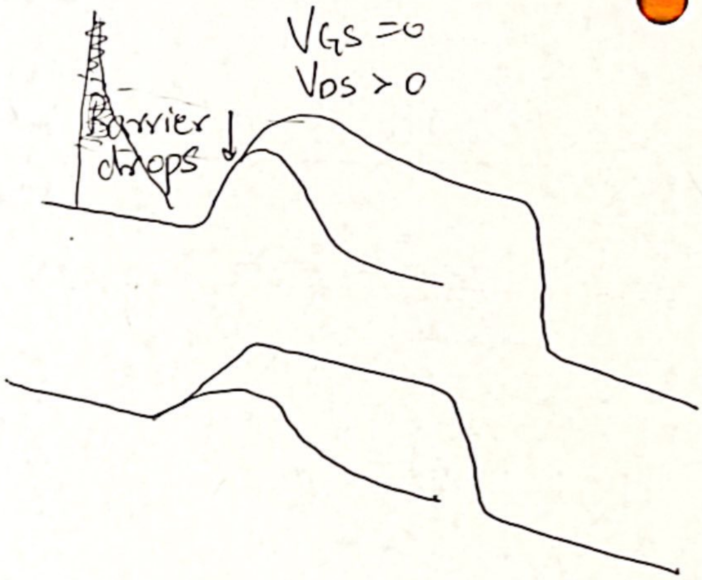
$$v(E) = \frac{\mu E}{1 + \frac{E}{E_{sat}}}$$

Saturation (Pinch-off)

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

3) Drain Induced Barrier Lowering



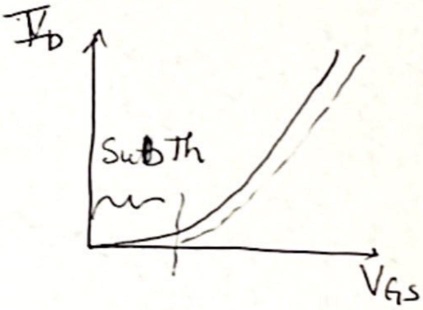


=> > V_T drops with V_{DS}.

> OFF leakage current.

4) Sub threshold Conduction

> Due to weak inversion electrons in the channel.



5) Hot electron effects

> High energy electrons close to drain can create e-h pair generation => Substrate leakage current.

> Embed into oxide => V_T degradation