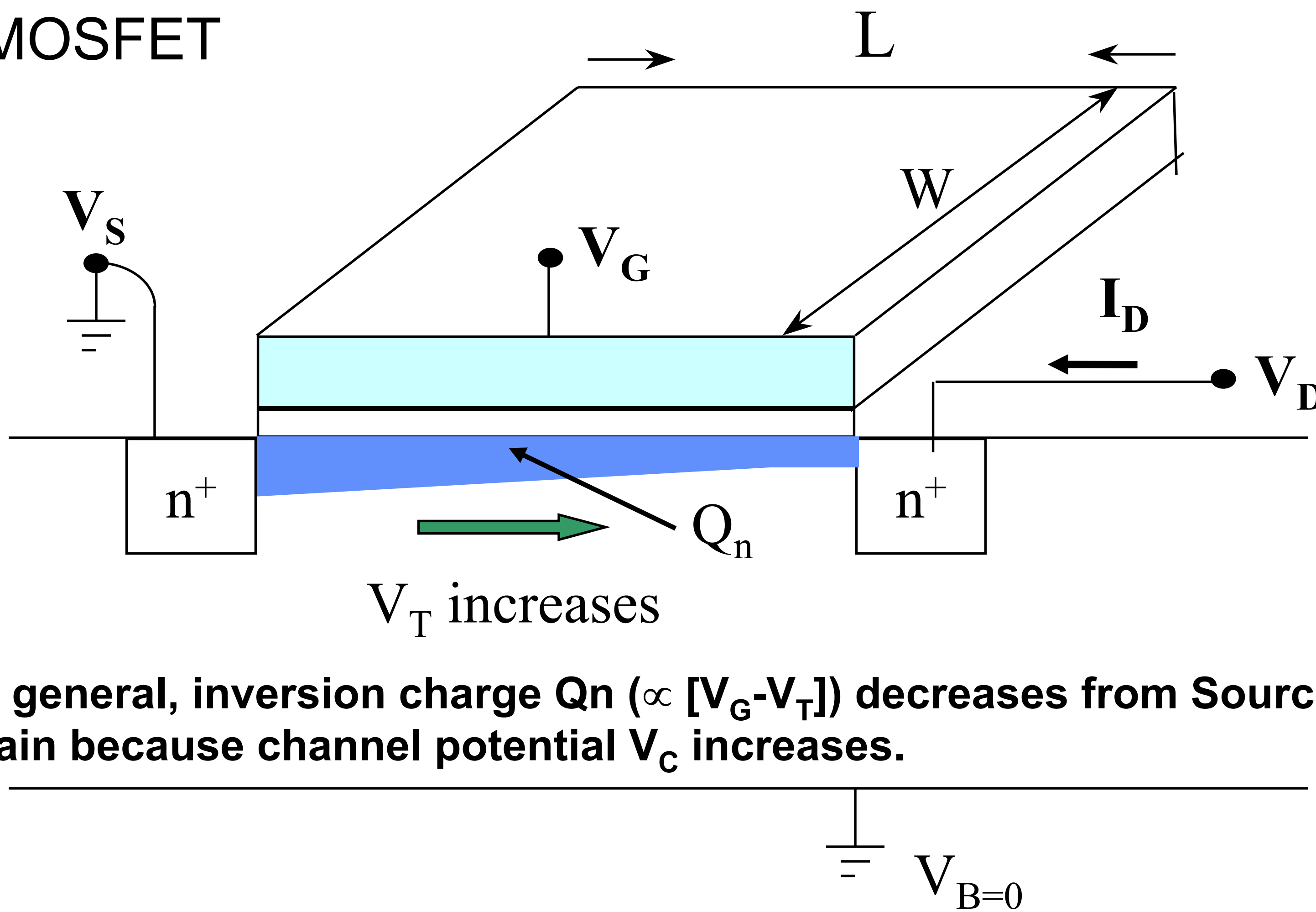
MOSFET I-V Analysis

N-MOSFET



•**In general, inversion charge Qn ($\propto$ [V_G-V_T]) decreases from Source toward Drain because channel potential V_C increases.**

Approximate Analysis

Inversion layer thickness

Inversion layer concentration

$$I_D = W\mathbf{t} \bullet (-q \;\; \mathbf{n} \; v_{drift})$$
$$= W \bullet \mathbf{Q_n} \bullet v_{drift}$$

Note: I_D is constant for all positions along channel

Let V_T **defined** to be threshold voltage at Source

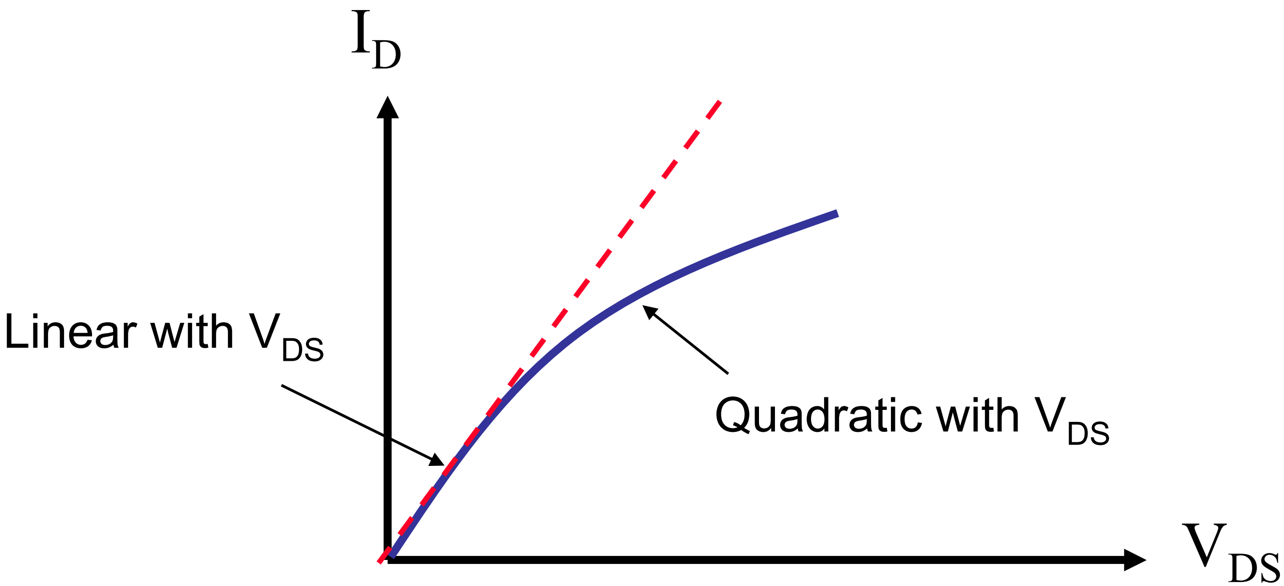
$$\mathbf{V_T(average) \sim V_T + \frac{V_{DS}}{2}}$$

[This is an approximation]

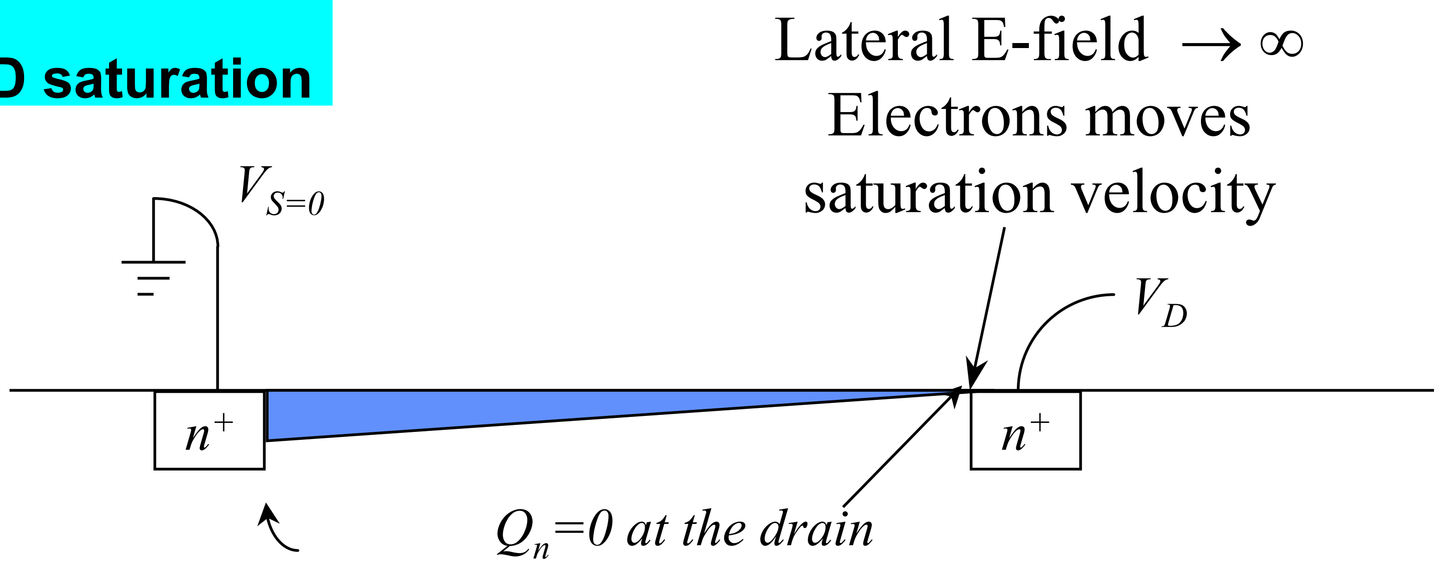
$$\mathbf{Q_n\,(average) = C_{OX}\left(V_G - V_T(average)\right)}$$
$$\mathbf{= C_{OX}\left(V_G - V_T - \frac{V_{DS}}{2}\right)}$$

$$\textbf{With } v_{drift} = -\mu_n E \approx \frac{\mu_n V_{DS}}{L}$$

$$I_D = \mu \frac{W}{L} C_{OX} \left(V_G - V_T - \frac{V_{DS}}{2} \right) V_{DS}$$



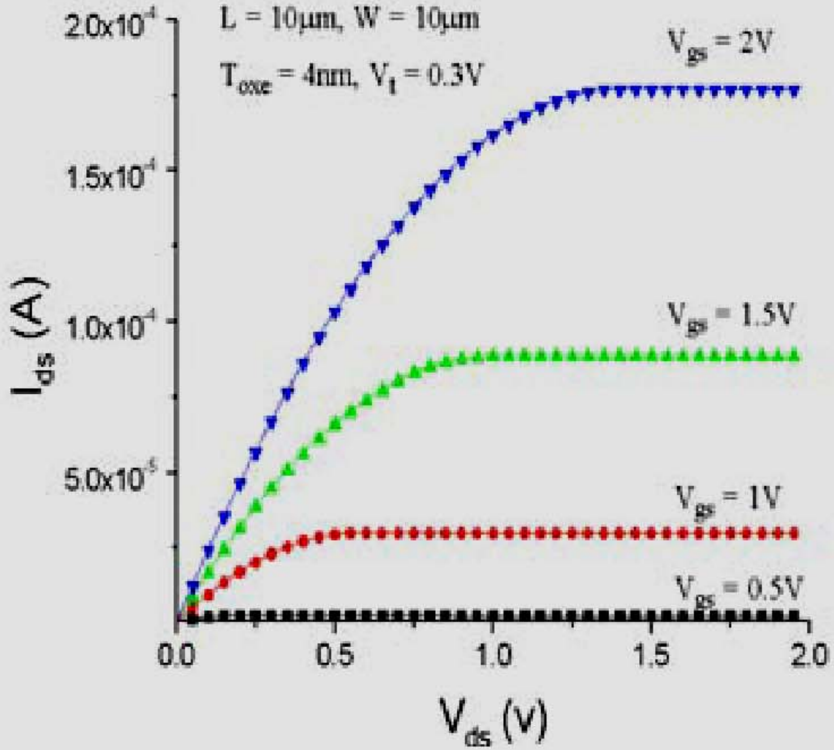
$V_{D\ saturation}$



V_{Dsat} is *defined* to be the value of V_D with Q_n=0 *at drain.*

From $Q_n = C_{ox}(V_G - V_T - V_D)$, we get $V_{Dsat} = V_G - V_T$

Saturation Current



- saturation region:

$$V_D \geq \boxed{V_{Dsat} = V_{GS} - V_T}$$

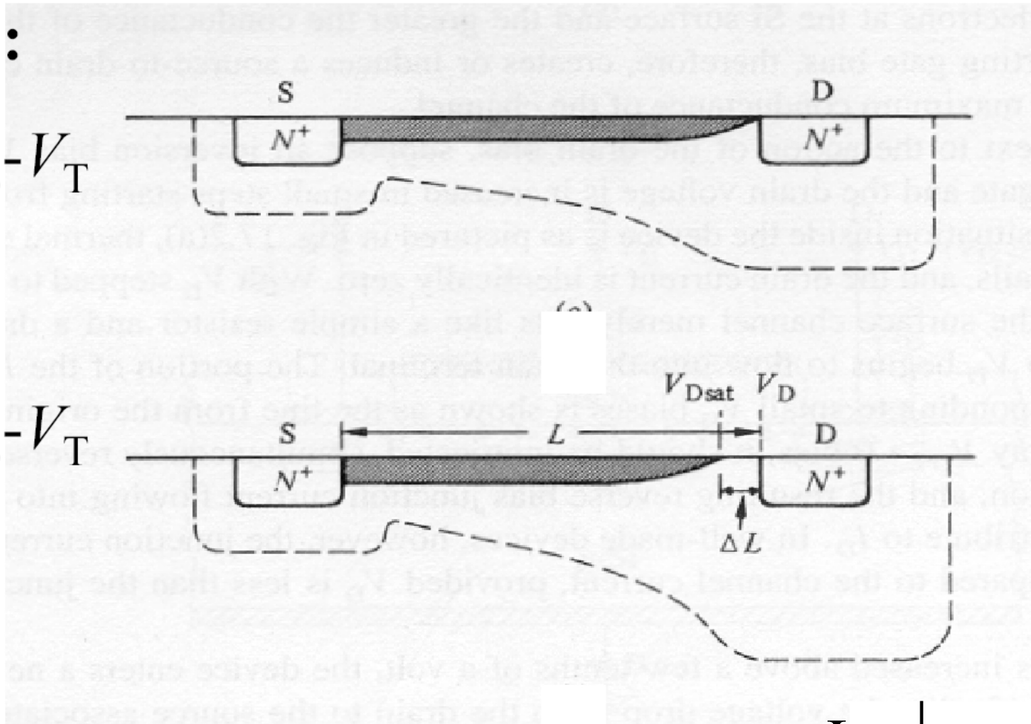
$$\boxed{I_{Dsat} = \frac{W}{2L} C_{oxe} \mu_{eff} (V_{GS} - V_T)^2}$$

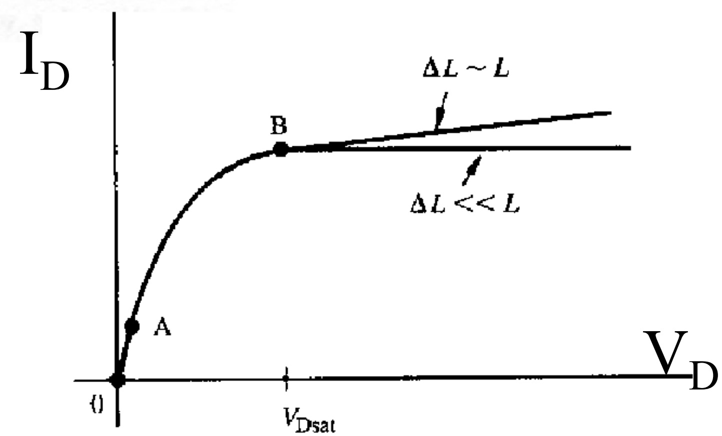
Pinch-Off & Channel-Length Modulation

$V_{GS} > V_T$:

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

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





MOSFET I-V Characteristics Summary

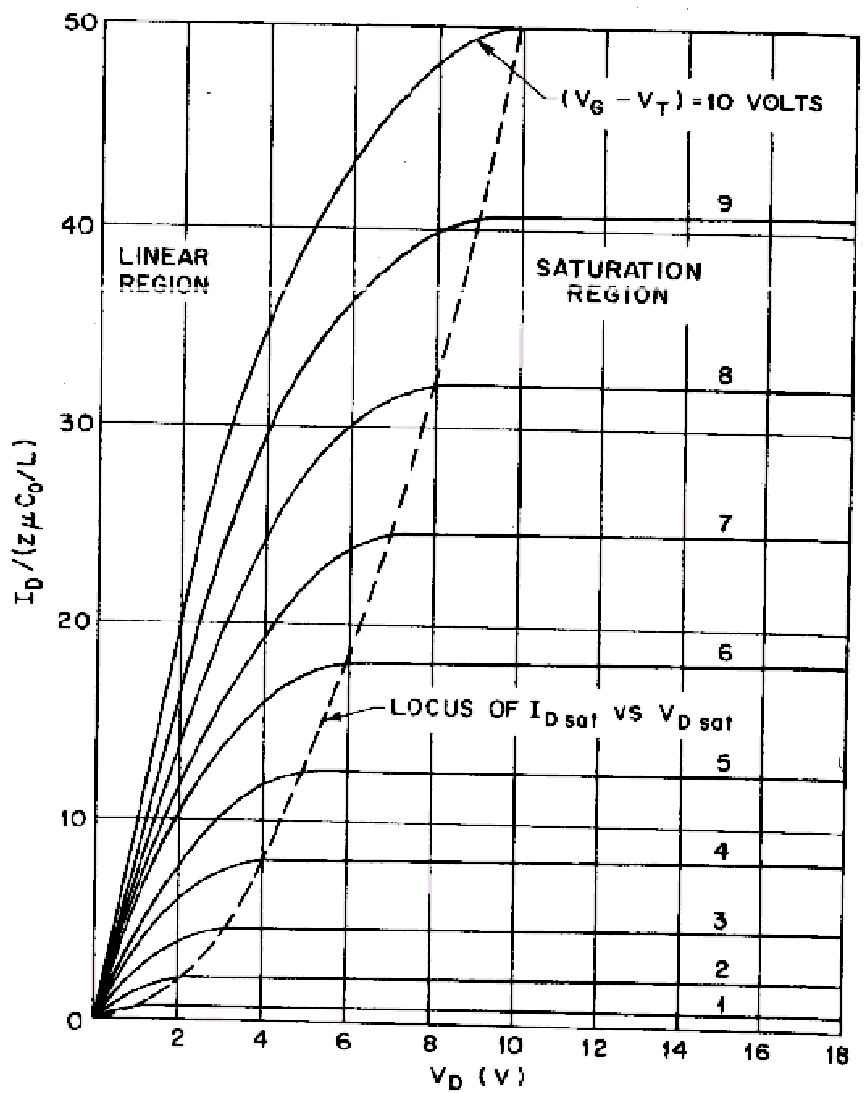
For $V_D < V_{Dsat}$

$$I_D = \frac{\mu_n W}{L} C_{OX}\left(V_G - V_T - \frac{V_{DS}}{2}\right)V_{DS}$$

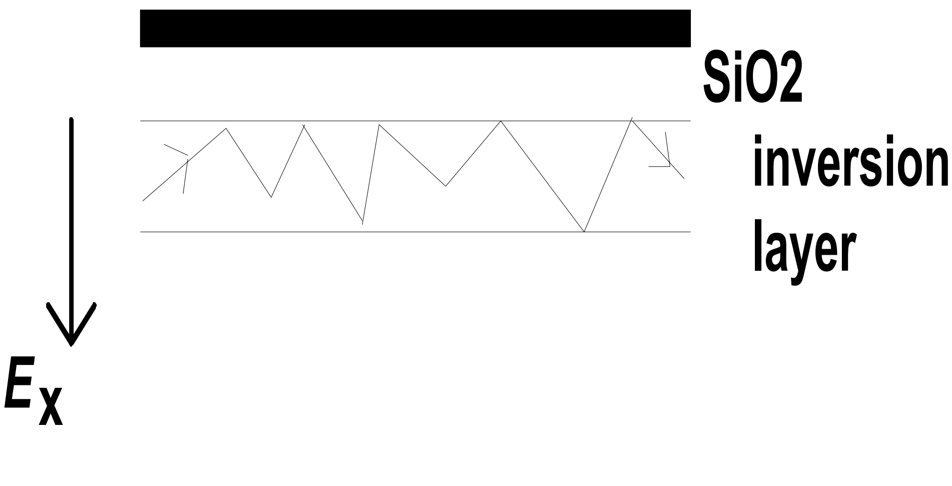
For $V_D > V_{Dsat}$

$$I_D = I_{Dsat} = \frac{\mu_n W}{2L} C_{OX}(V_G - V_T)^2$$

Note: $V_{Dsat} = V_G - V_T$



Mobility of inversion charge carriers



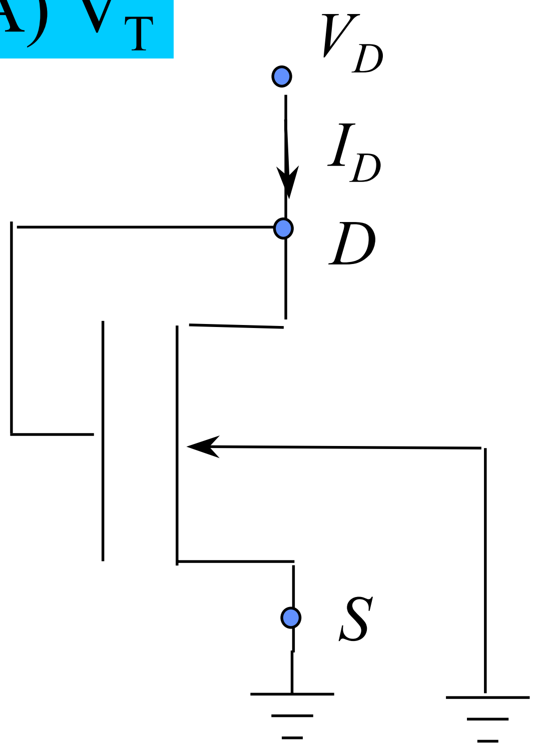
*Carrier will experience additional scattering at the Si/SiO2 interface

*Channel mobility is lower than bulk mobility

* μ(effective) is extracted from MOSFET I-V characteristics
* Typically ~0.5 of μ(bulk)

Parameter Extraction from MOSFET I-V

(A) V_T



$$For\ V_D = V_G > V_T$$

$$V_T'\ at\ drain$$

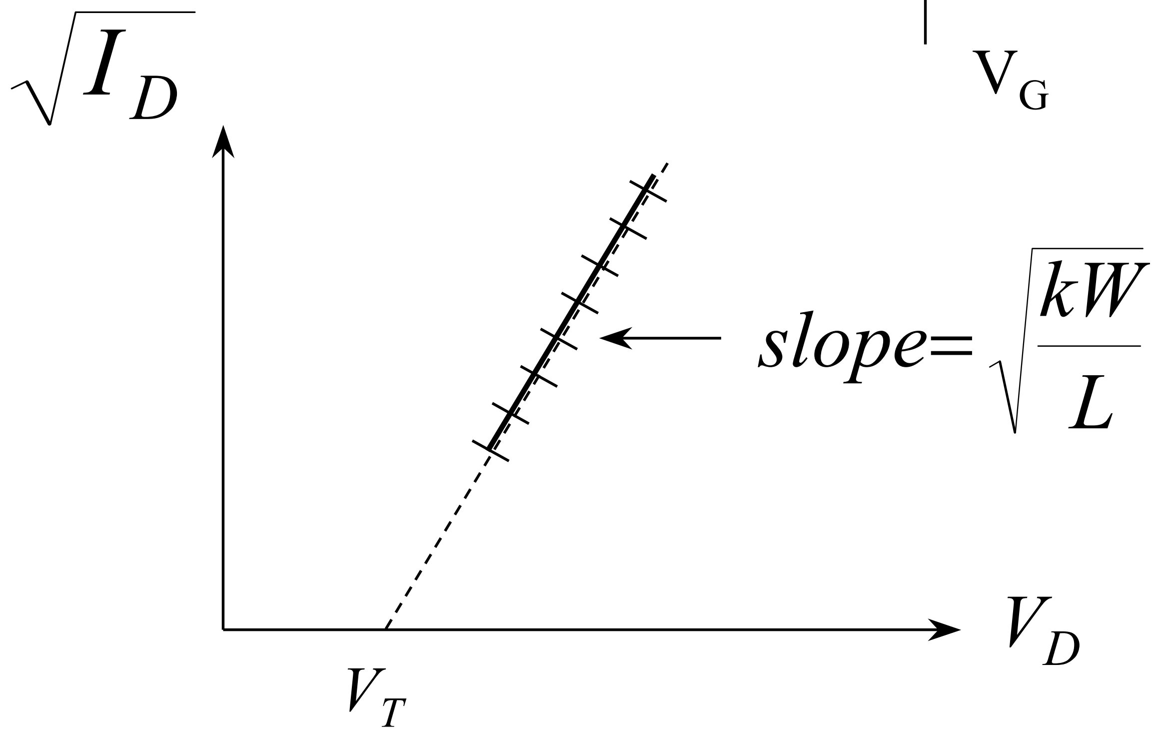
$$= V_{FB} + V_D + 2\left|\phi_p\right| + \frac{1}{C_{OX}}\sqrt{2\varepsilon_s q N_a\left(2\left|\phi_p\right| + V_D\right)}$$

$$\Rightarrow V_G - V'_T < 0$$

$$\Rightarrow Drain\ is\ at\ pinch-off$$

$$\Rightarrow MOSFET\ is\ in\ saturation\ mode.$$

$$\therefore I_D = I_{Dsat} = \underbrace{k}_{\mu_n C_{OX}} \frac{W}{L}\left(\underbrace{V_D}_{V_G} - V_T\right)^2$$

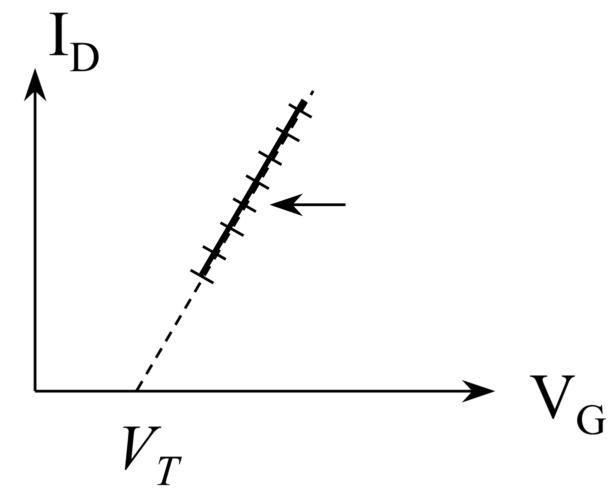


Alternative way to extract V_T

•Measure I_D versus V_G for a **fixed** ***small*** V_{DS} (say <100mV)

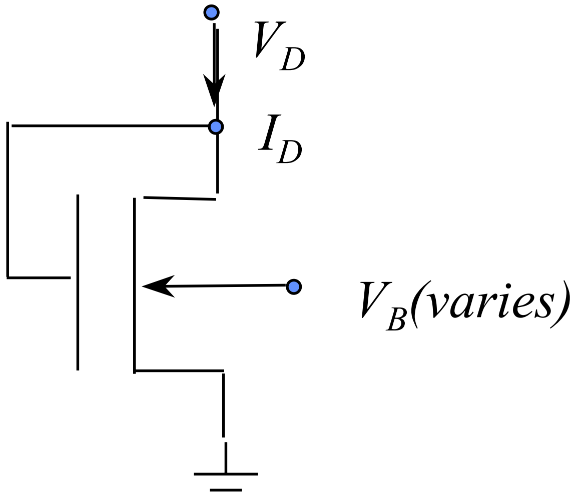
$$\mathbf{I_D = \frac{\mu_n W}{L} C_{OX}\left(V_G - V_T - \cancel{\frac{V_{DS}}{2}}\right) V_{DS}}$$

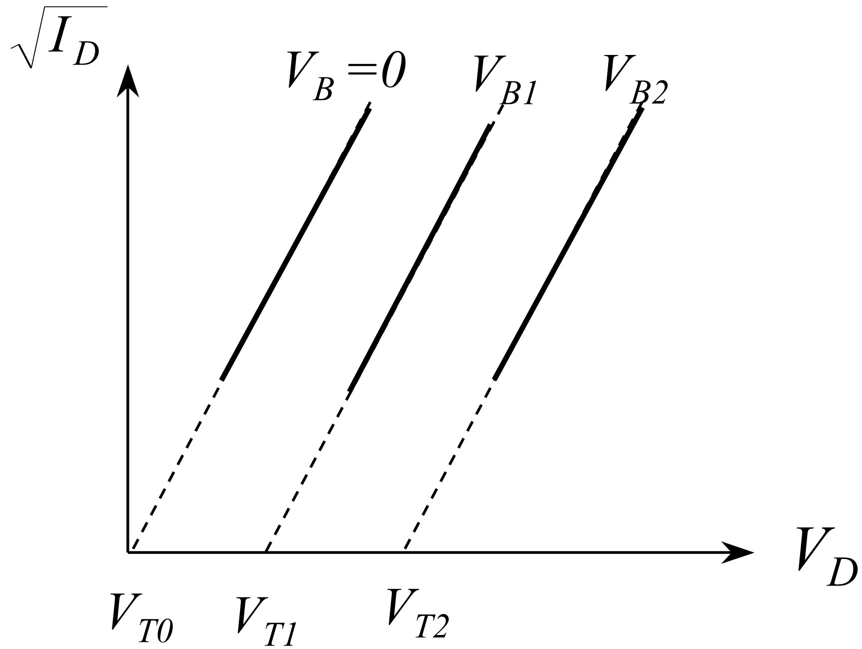
$$\mathbf{\approx \frac{\mu_n W}{L} C_{OX}\left(V_G - V_T\right) V_{DS}}$$



The intercept of I_D versus V_G plot on V_G-axis is V_T.

(B) Body Coefficient γ

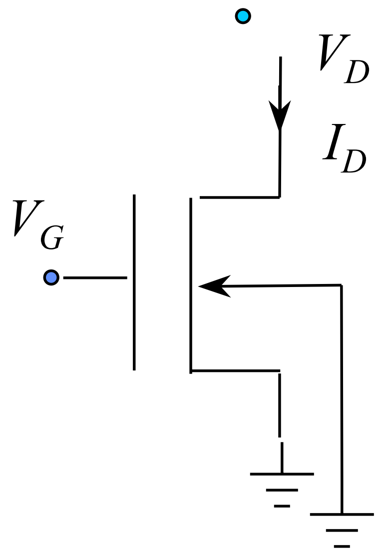


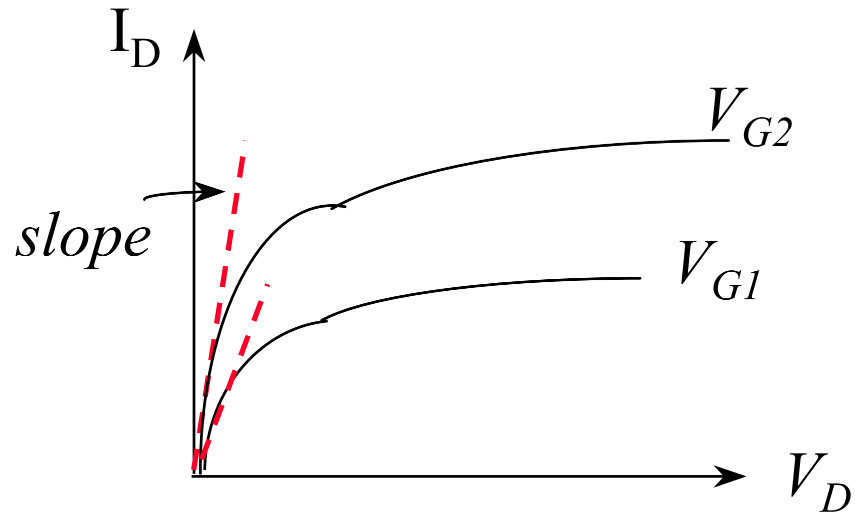


$$\gamma \equiv \left[\frac{V_T\left(with\,V_{SB} \neq 0\right) - V_T\left(with\,V_{SB} = 0\right)}{\sqrt{2\left|\phi_p\right| + \left|V_{SB}\right|} - \sqrt{2\left|\phi_p\right|}} \right]$$

$$= \frac{\sqrt{2\varepsilon_s q N_a}}{C_{OX}}$$

(C) $\mu_n C_{OX} \dfrac{W}{L}$



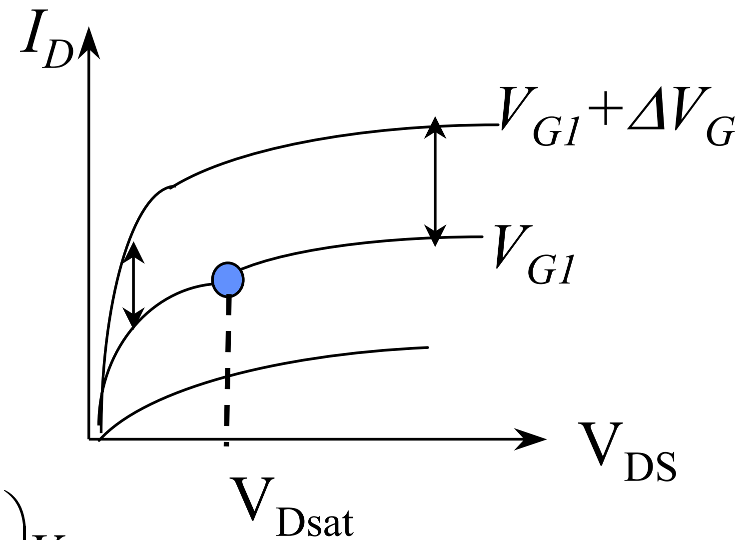


$$I_D = \mu_n \frac{W}{L} C_{OX} \left(V_G - V_T - \frac{V_D}{2} \right) V_D$$

$$\frac{\partial I_D}{\partial V_D} = \mu_n C_{OX} \frac{W}{L} (V_G - V_T) \text{ for small } V_D$$

(D) Transconductance g_m

$$g_m \equiv \left.\frac{\partial I_D}{\partial V_G}\right|_{fixed\ V_D}$$



(a) For $V_{DS}<V_{Dsat}$

$$I_D = \frac{\mu_n W}{L} C_{OX}\left(V_G - V_T - \frac{V_{DS}}{2}\right)V_{DS}$$

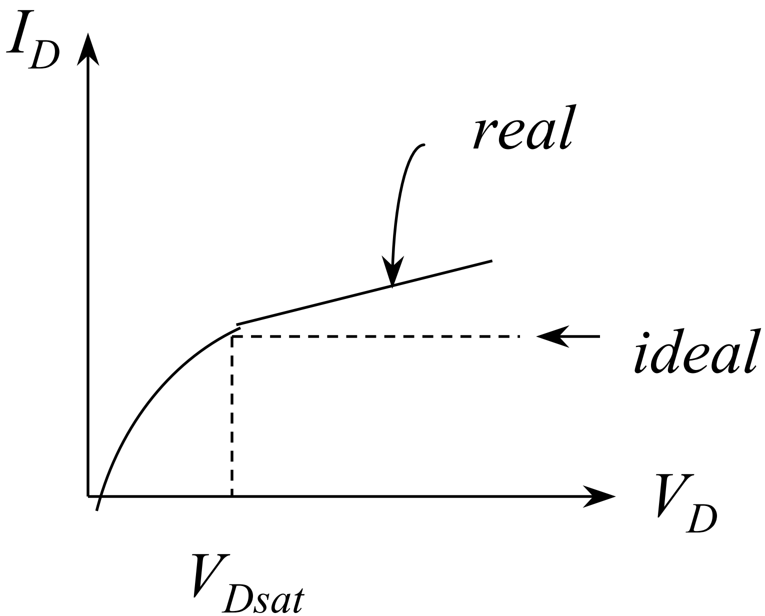
$$\therefore \frac{\partial I_D}{\partial V_G} = \mu_n C_{OX}\frac{W}{L}\cdot V_{DS}$$ [g_m varies with V_{DS}]

(b) For $V_{DS} > V_{Dsat}$

$$I_D = I_{Dsat} = \frac{\mu_n W}{2L} C_{OX}(V_G - V_T)^2$$

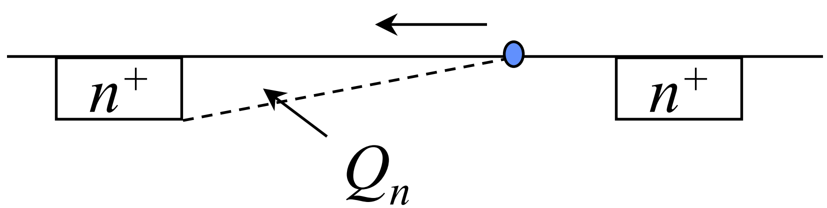
$$\frac{\partial I_D}{\partial V_G} = \frac{\mu_n W}{L} C_{OX}\cdot(V_G - V_T)$$ [g_{msat} varies with V_G]

(E) Channel Modulation Parameter λ

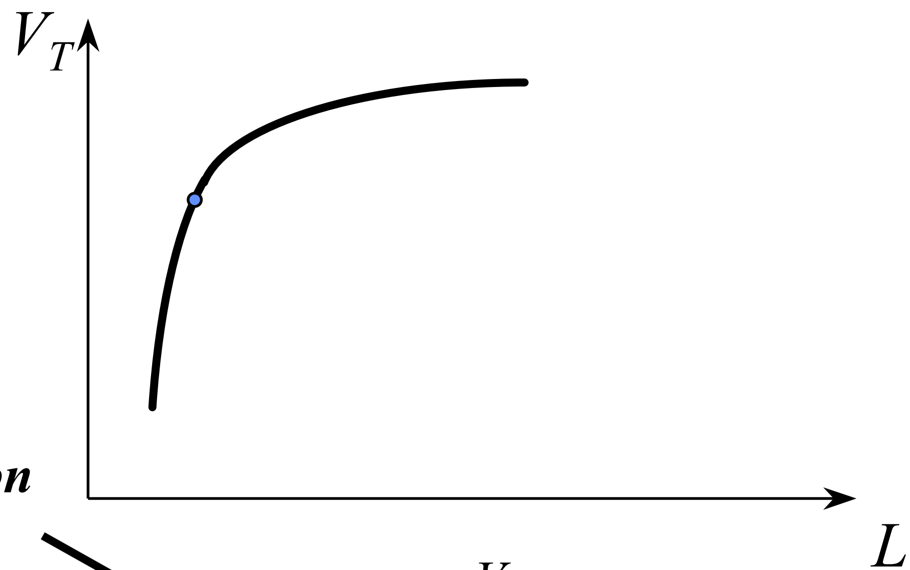


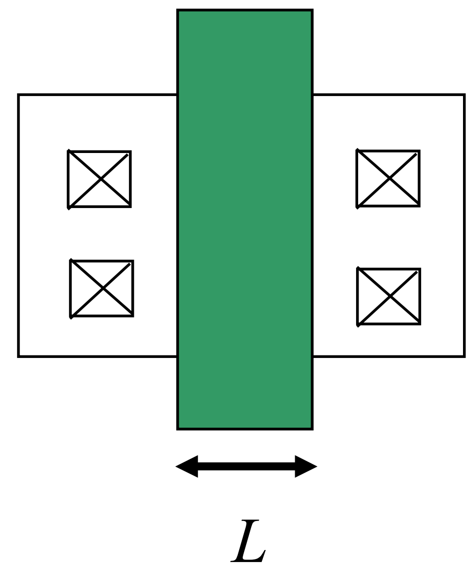
$$I_{Dsat} = \frac{k}{2}\left(V_G - V_T\right)^2\left(1 + \lambda V_{DS}\right)$$

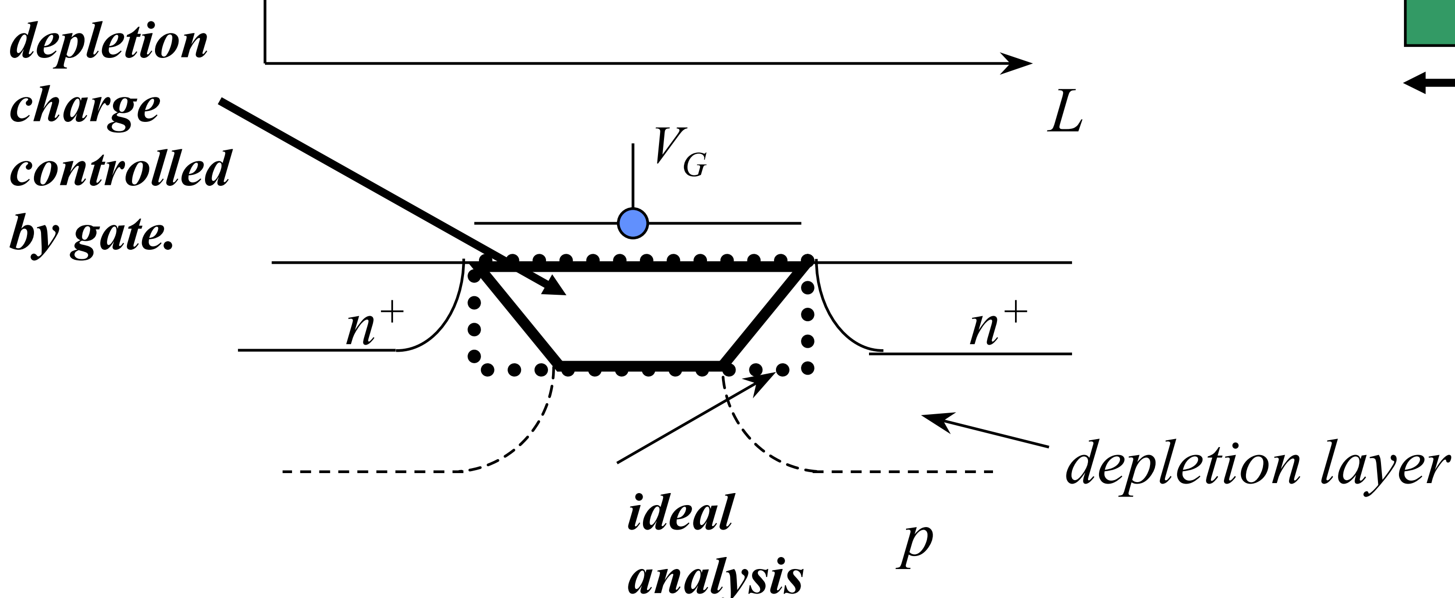
$$Typically \;\; \lambda \sim 0.1\, to\, 0.01\, (volt)^{-1}$$

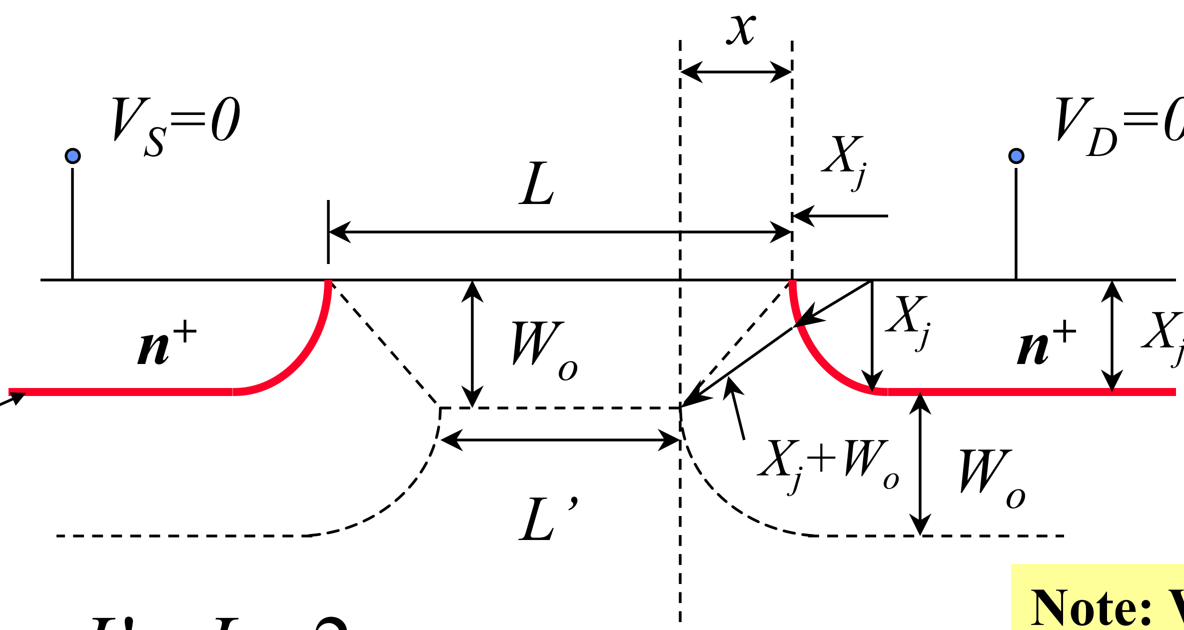


Short Channel Effect on V_T









Same electric potential because of heavily doped n+

Note: W_o is x_{dmax}

$$L' = L - 2x$$

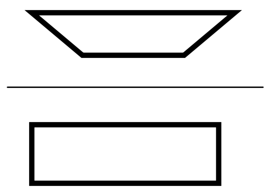
$$= L - 2\left[\sqrt{\left(X_j + W_o\right)^2 - W_o^2} - X_j\right]$$

$$= L - 2X_j\left[\sqrt{1 + \frac{2W_o}{X_j}} - 1\right]$$

Area of gate charge distribution

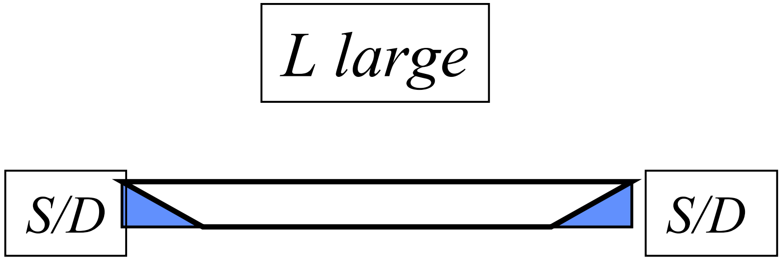
$$= q \cdot N_a \cdot \frac{L + L_1}{2} \cdot W_o \cdot W$$

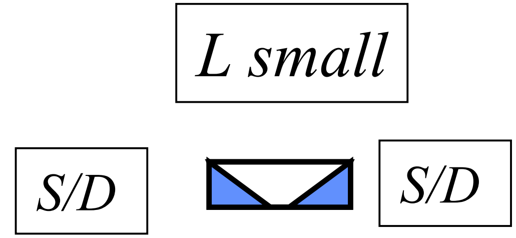
$$\therefore \frac{Q_{actual}}{Q_{ideal}} =$$



$$= 1 - \frac{X_j}{L}\left[\sqrt{1 + \frac{2W_o}{X_j}} - 1\right] \equiv f$$

"Yau Model" for short-channel effect.





To make f → 1

$X_j \downarrow$

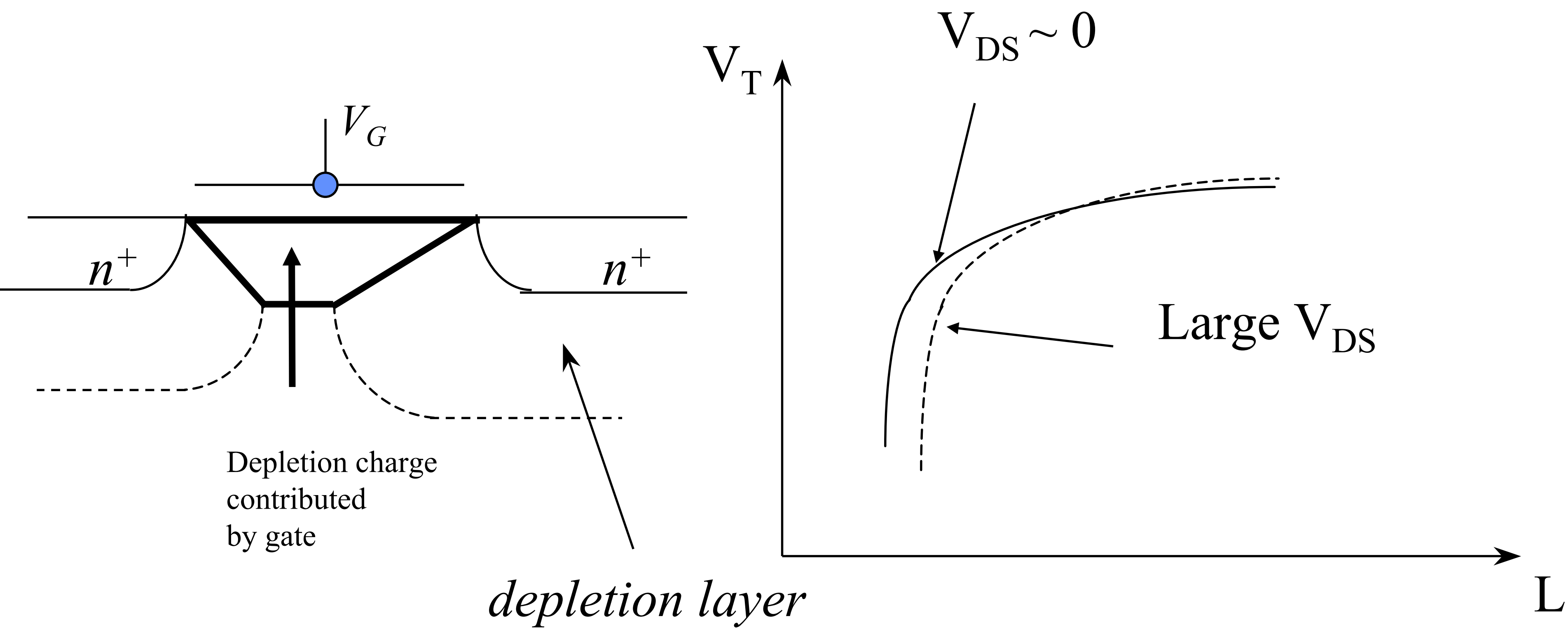
- Implantation at low energy
- Small Dt.
- Minimize channeling and transient enhance diffusion

$W_o \downarrow$

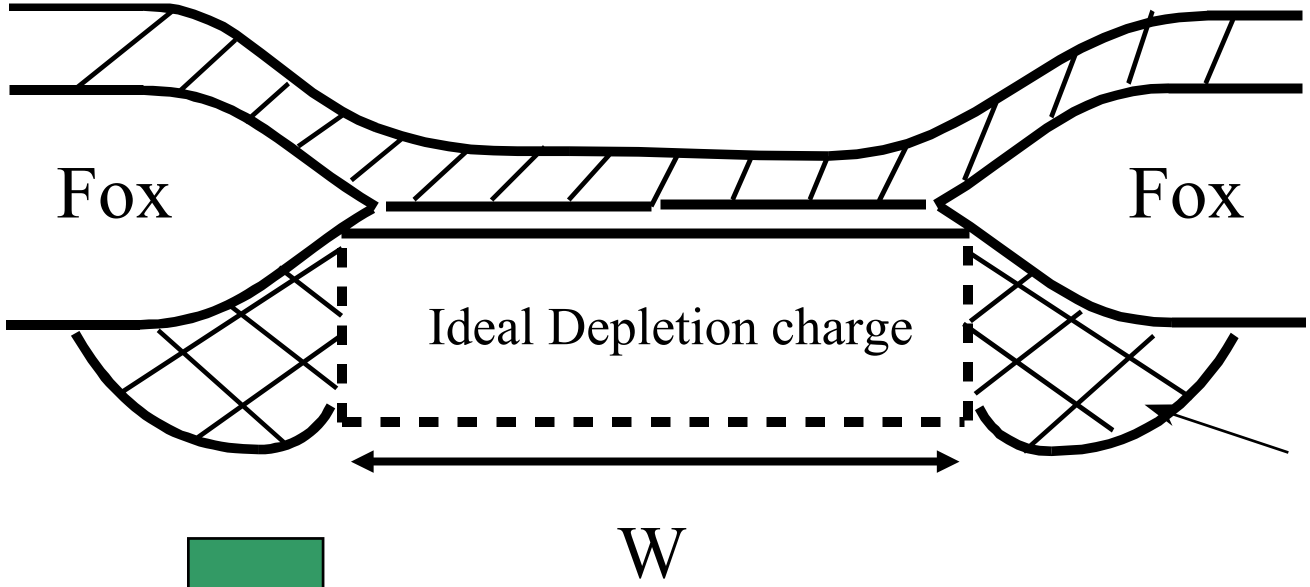
- Increase N_a

Effect of V_{DS} on V_T Lowering

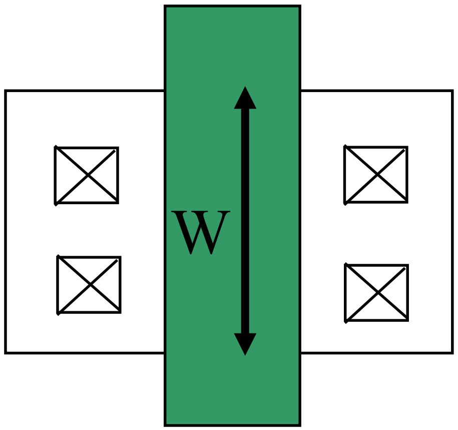
Large $V_{DS} \Rightarrow$ Larger S/D depletion charge at the drain side
$\Rightarrow$ Smaller depletion region charge contributed by gate
$\Rightarrow$ V_T starts to decrease at larger L



Narrow Width Effect (related to W)

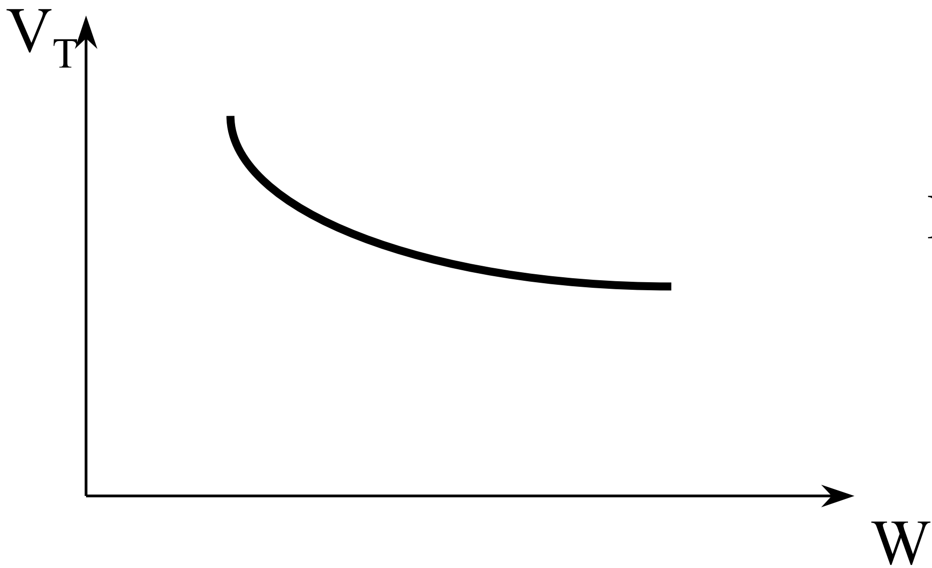


parasitic charge which has to be created by gate bias

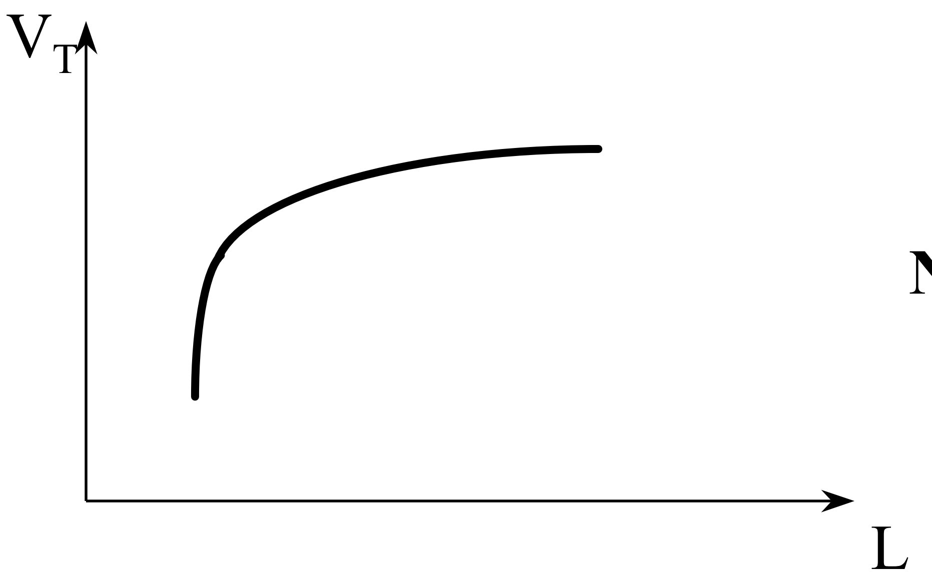


$\therefore V_T$ is larger than ideal analysis.

Professor Nathan Cheung, U.C. Berkeley



Narrow Width Effect



Narrow Channel Effect

Small Geometry Effects Summary