Recitation Class 8

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Outline

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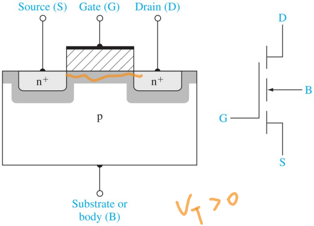
MOSFET

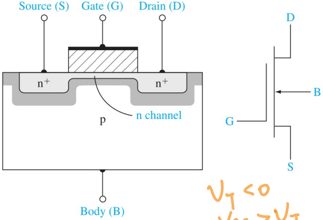
$V_{GS} = 0$



$V_T > 0$

(a) n-channel enhancement MOSFET

$V_{GS} < V_T$



$V_T < 0$

$V_{GS} > V_T$

(b) n-channel depletion MOSFET

Enhancement mode: the semiconductor substrate is not inverted directly under the oxide with zero gate voltage.

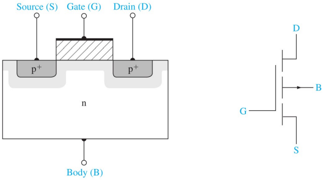
Depletion mode: a p-channel region exists under the oxide with $0\,V$ applied to the gate.

MOSFET

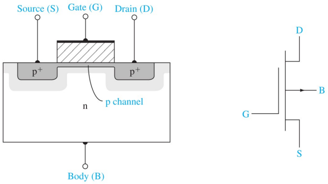
$V_{SG}+V_T > 0.$

$V_T < 0$

$V_{SG}+V_T < 0$



(a) p-channel enhancement MOSFET



(b) p-channel depletion MOSFET

V_{GS} - V_T

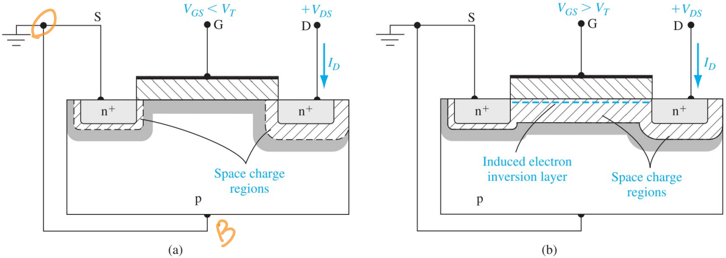


Figure: (a) $V_{GS} < V_T$, (b) $V_{GS} > V_T$

For NMOS

- $V_{GS} < V_T$: no inversion layer, no current.
- $V_{GS} > V_T$: inversion layer created, current flow from drain to source.

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

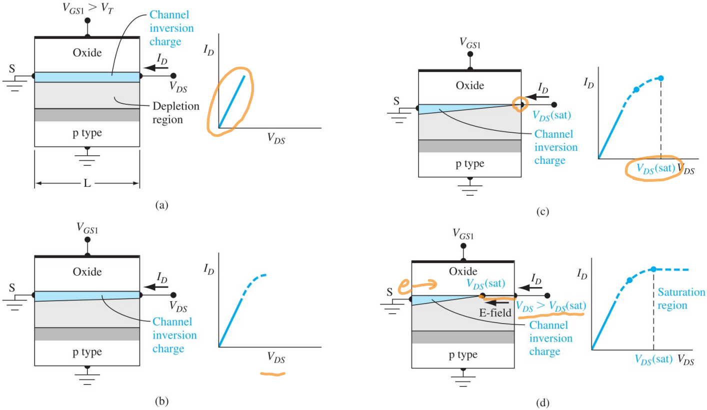
- V_{DS} low ($V_{GS} < V_{GS} - V_T$): act as a controllable resistor.

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

- G_{DS} high ($V_{DS} \geq V_{GS} - V_T$): saturation

$$\boxed{I_D = \mu_n C_{ox} \frac{W}{2L} (V_{GS} - V_T)^2 \quad \text{(saturation)}}$$

V_{GS} - V_T



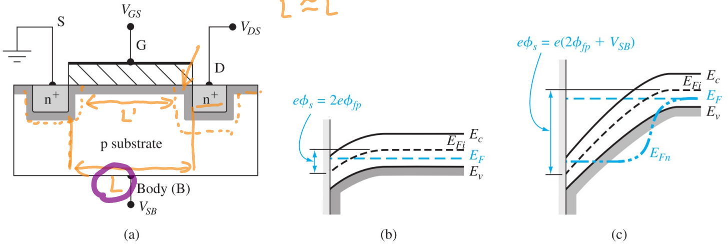
After pinch off: the electrons are injected into the space charge region where they are swept by the E-field to the drain contact.

Transconductance

$$
\begin{aligned}
g_m &= \frac{\partial I_D}{\partial V_{GS}} \\
&= \begin{cases} \mu_n C_{ox} \dfrac{W}{L} V_{DS}, & 0 < V_{DS} < V_{GS} - V_T \\ \mu_n C_{ox} \dfrac{W}{L} \left(V_{GS} - V_T \right), & V_{DS} > V_{GS} - V_T \end{cases}
\end{aligned}
$$

Substrate Bias Effects

L' ≈ L



$$V_{SB} = 0 : \quad Q'_{SD}(\max) = -\sqrt{2e\varepsilon_s N_a (2\phi_{fp})}$$

$$V_{SB} > 0 : \quad Q'_{SD} = -\sqrt{2e\varepsilon_s N_a (2\phi_{fp} + V_{SB})}$$

$$\boxed{\Delta V_T = -\frac{\Delta Q'_{SD}}{C_{ox}} = \frac{\sqrt{2e\varepsilon_s N_a}}{C_{ox}}\left[\sqrt{2\phi_{fp} + V_{SB}} - \sqrt{2\phi_{fp}}\right]}$$

where $\underbrace{\Delta V_T}_{>0} = V_T(V_{SB} > 0) - V_T(V_{SB} = 0)$ for NMOS.

Substrate Bias Effects

$$\boxed{\begin{aligned} \Delta V_T &= -\frac{\Delta Q'_{SD}}{C_{ox}} = \frac{\sqrt{2e\varepsilon_s N_a}}{C_{ox}}\left[\sqrt{2\phi_{fp} + V_{SB}} - \sqrt{2\phi_{fp}}\right] \\ &= \gamma\left[\sqrt{2\phi_{fp} + V_{SB}} - \sqrt{2\phi_{fp}}\right], \qquad \gamma = \frac{\sqrt{2e\varepsilon_s N_a}}{C_{ox}} \end{aligned}}$$

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I - Subthreshold Conduction (Leakage Current)

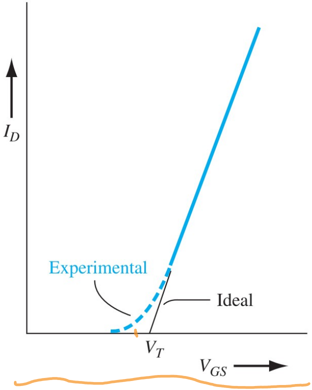
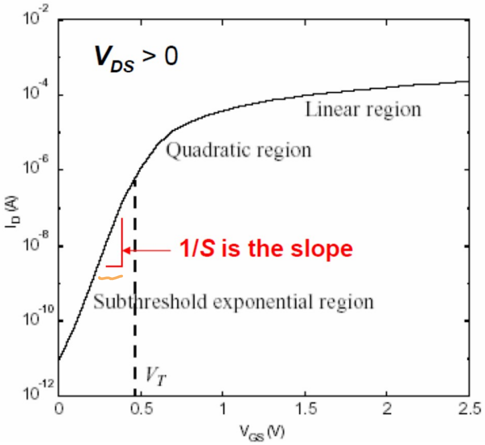


Figure: Comparison of ideal and experimental plots of $\sqrt{I_D}$ versus V_{GS}.

When $V_{GS} < V_T$, $I_D \propto \exp\left(\frac{qV_{GS}}{nkT}\right)$

I - Subthreshold Conduction (Leakage Current)

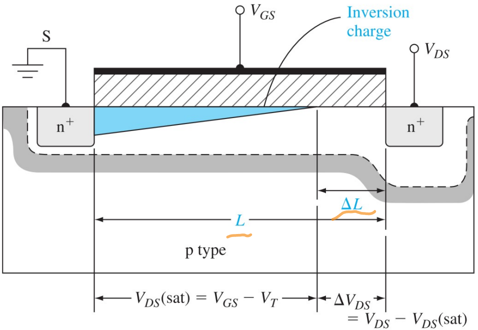
Slope Factor: defined to be the inverse slope of the $\log(I_D)$ vs. V_{GS} characteristic in the subthreshold region.



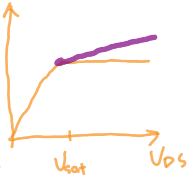
$$S = n\left(\frac{kT}{q}\ln(10)\right) \text{(Volts per decade)}$$

$S \geq 60mV/dec$ at room temperature.

II - Channel Length Modulation



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



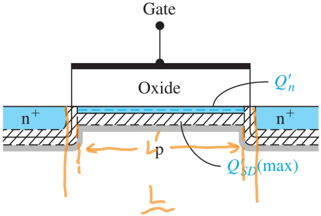
III - Velocity Saturation

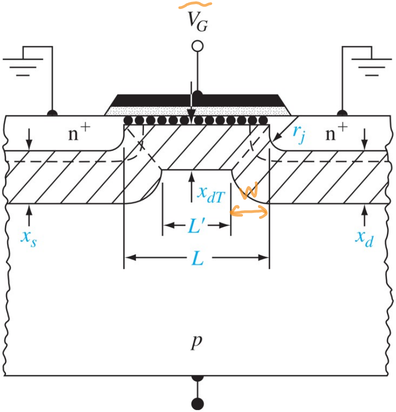
$E = \frac{V}{d}$

$$I_{DSAT} = WC_{ox}\left[V_{GS} - V_T - \frac{V_{DSAT}}{2}\right] v_{sat}$$

where $V_{DSAT} = \frac{L}{\mu_n} v_{sat}$.

IV - Short Channel Effect





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