I-V characteristics of MOSFETs

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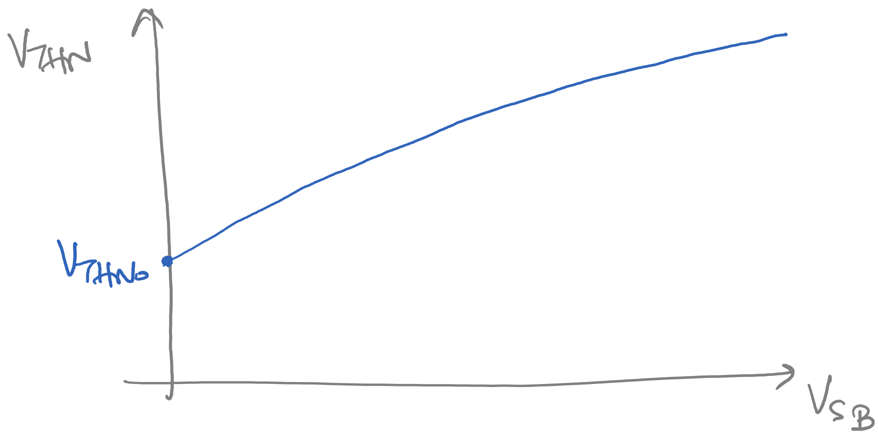
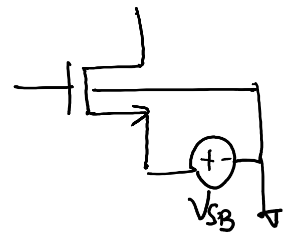
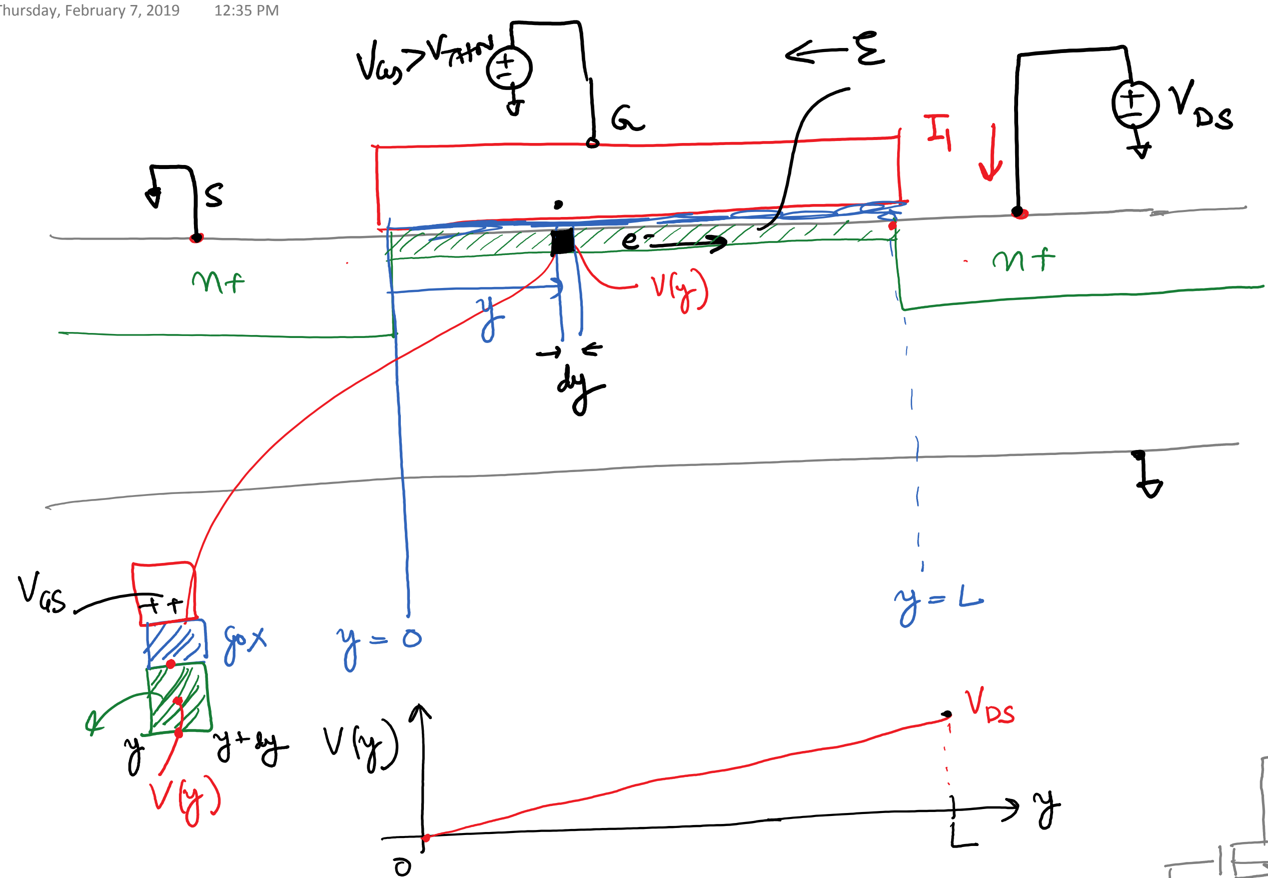
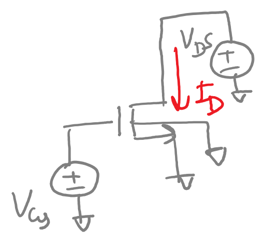
$$V_{THN} = V_{THNo} + \gamma \left(\sqrt{|2V_{fp}| + V_{SB}} - \sqrt{|2V_{fp}|} \right)$$









potential across the tiny capacitance formed by the gate and the segment of inversion layer

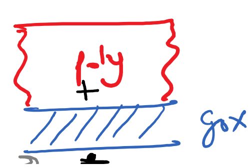
$$= V_{GS} - V(y)$$

charge per unit area in the inversion layer

$$Q'_{ch} = C'_{ox}\left[V_{GS} - V(y)\right] \longrightarrow (1)$$

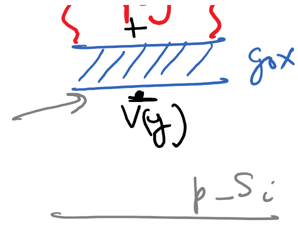
We also know that the charge Q'_b present in the inversion layer from the application of threshold voltage

$$Q'_b = C'_{ox} V_{THN} \longrightarrow (2)$$



charge

Total inversion layer charge



$$Q_I'(y) = C_{ox}'\left(V_{GS} - V(y) - V_{THN}\right) \rightarrow ③$$

charge per unit area $= Q_I'(y)$

Conductivity of the channel

1.6×10^{-19} C

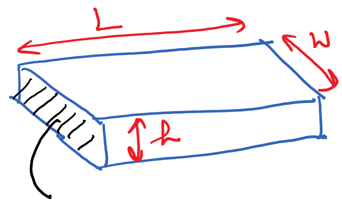
$$\sigma = n\,q\,\mu_n$$

μ_n → mobility of electron

n: electron concentration p.u. volume

Q_I': charge p.u. area

$$= \frac{Q_I'}{h}\mu_n$$



$A = W \cdot h$

$$\sigma = \frac{Q_I'(y)}{h}\mu_n$$

resistivity

$$\Rightarrow \rho = \frac{1}{\sigma} = \frac{h}{\mu_n Q_I'(y)}$$

$$R = \rho\frac{L}{A}$$

$$dR = \rho(y)\cdot\frac{dy}{A} = \rho(y)\,\frac{dy}{W\cdot h}$$

$$= \frac{\cancel{h}}{\mu_n Q_I'(y)}\cdot\frac{dy}{W\cdot\cancel{h}}$$

$$dR = \frac{1}{\mu_n Q_I'(y)}\cdot\frac{dy}{W} \longrightarrow ④$$

$\mu_n Q_I'(y) \quad W$

$$dV(y) = I_D \cdot dR = \frac{I_D}{W \mu_n Q_I'(y)} \cdot dy \qquad \because V = IR \quad (5)$$

Substituting Eq^n (3) into (5) we get

$$dV(y) = \frac{I_D \cdot dy}{W \mu_n C_{ox}' \left(V_{GS} - V(y) - V_{THN}\right)}$$

$$\Rightarrow \quad I_D \cdot dy = W \mu_n C_{ox}' \left[V_{GS} - V(y) - V_{THN} \right] \cdot dV(y) \longrightarrow (6)$$

Let's define parameters

Transconductance parameter $\longrightarrow$ $KP_n = \mu_n C_{ox}' = \mu_n \frac{\varepsilon_{ox}}{t_{ox}} = 120 \frac{\mu A}{V^2}$

$KP_p = \mu_p C_{ox}' = \mu_p \cdot \frac{\varepsilon_{ox}}{t_{ox}} = 40 \frac{\mu A}{V^2}$

in $1 \mu m$ CMOS

$\frac{KP_n}{KP_p} = \frac{\mu_n}{\mu_p} \approx 3$ in long-channel CMOS

$$I_D \int_0^L dy = W \cdot KP_n \int_0^{V_{DS}} \left(V_{GS} - V(y) - V_{THN}\right) dV(y)$$

$$\Rightarrow \quad \boxed{I_D = KP_n \cdot \frac{W}{L} \left[\left(V_{GS} - V_{THN}\right) \cdot V_{DS} - \frac{V_{DS}^2}{2} \right]} \longrightarrow (7)$$

only true for $V_{GS} > V_{THN}$ & $V_{DS} < V_{GS} - V_{THN}$

This equation is only valid for $V_{DS} < V_{GS} - V_{THN}$ $\Rightarrow$ LINEAR OR TRIODE REGION

Beta: $\beta_n = KP_n \cdot \frac{W}{L}$

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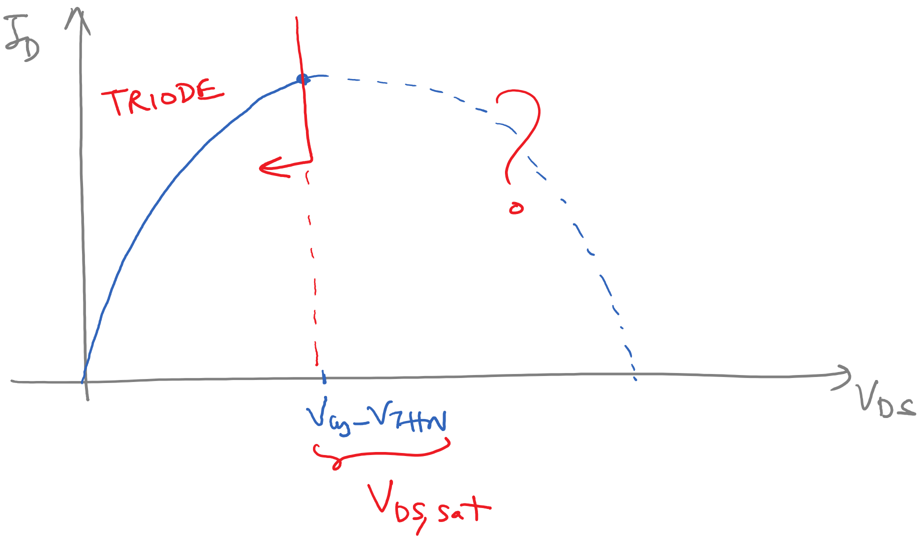

$V_{GS} > V_{THN}$

Saturation :

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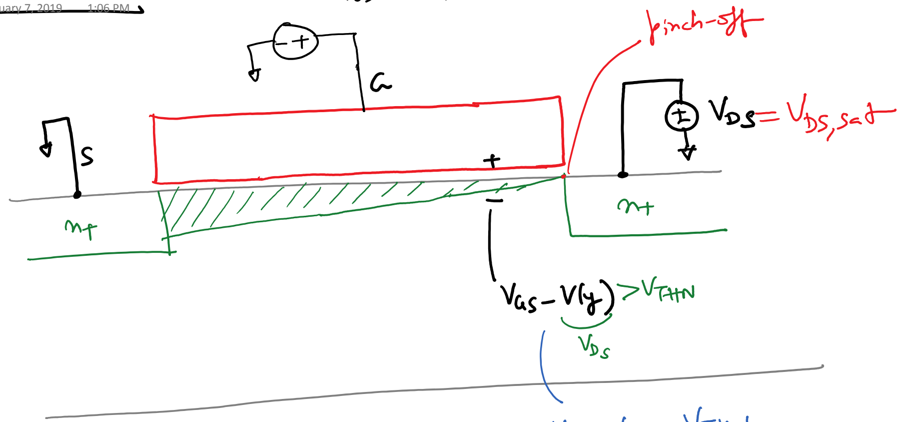
$V_{GS} > V_{THN}$



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

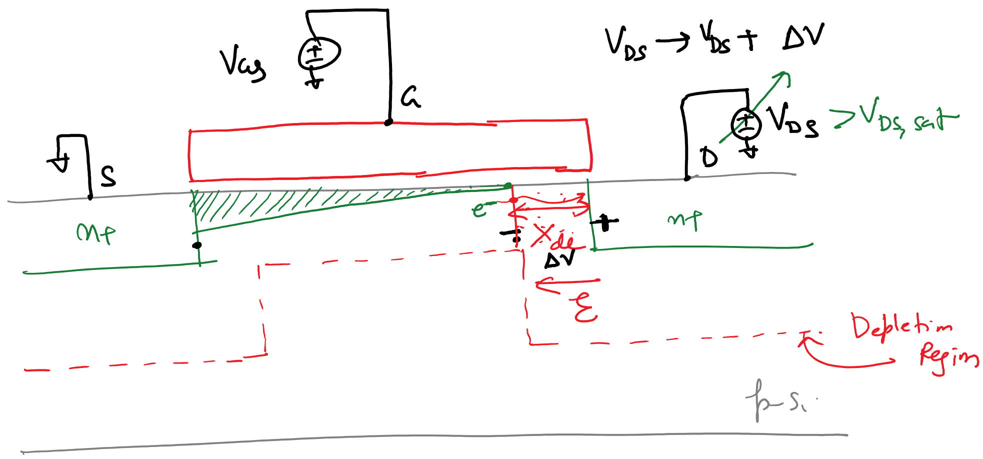
$\Rightarrow V_{DS} = V_{G} - V_{THN}$

If we have

$$V(y=L) = V_{DS} = \underbrace{V_{G} - V_{THN}}_{V_{DS,sat}}$$

$\Rightarrow Q'(y=L) = 0$

↳ channel is pinched-off at the drain edge.

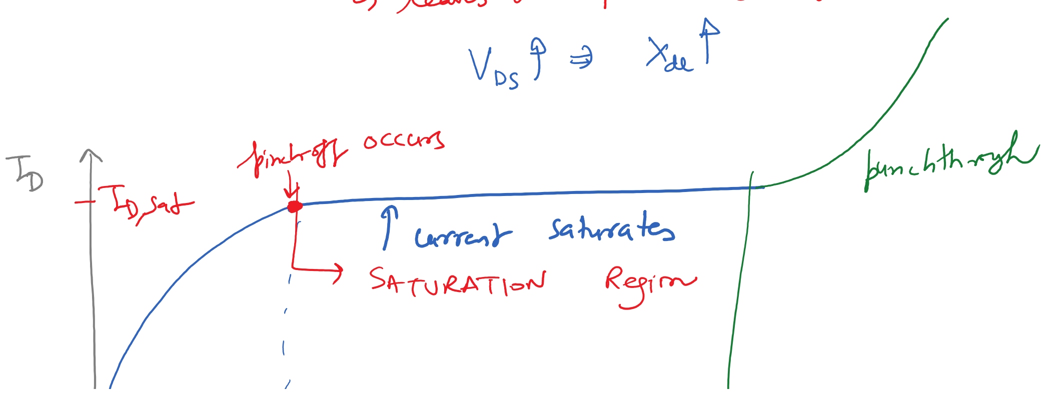


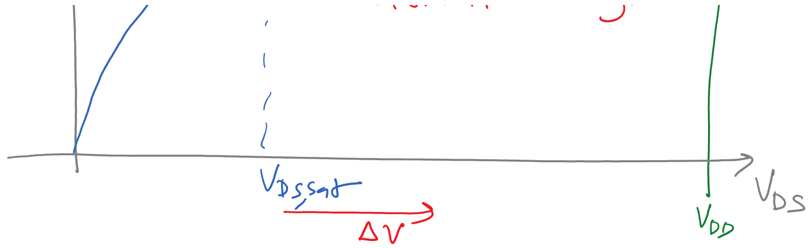
* If we increase V_{DS} beyond $V_{DS,sat}$

↳ inversion layer is pushed away from the drain

↳ leaves a depletion region of length X_{de}

$V_{DS} \uparrow \Rightarrow X_{de} \uparrow$





* Beyond pinchoff, any increase in V_{DS} is dropped across the depletion region
  - ↳ voltage across the inversion layer doesn't increase
    - ↳ current doesn't increase beyond the pinchoff current, $I_{D,sat}$

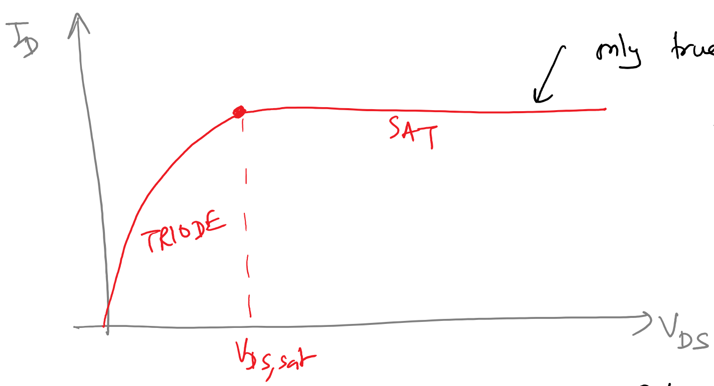
$$I_D = k\ell_n \frac{W}{L}\left[(V_{GS}-V_{THN})V_{DS} - \frac{V_{DS}^2}{2}\right].$$

In saturation, V_{DS} across the channel $= V_{GS}-V_{THN}$

$$* \; I_{D,sat} = k\ell_n \frac{W}{L}\left[(V_{GS}-V_{THN})^2 - \frac{(V_{GS}-V_{THN})^2}{2}\right]$$

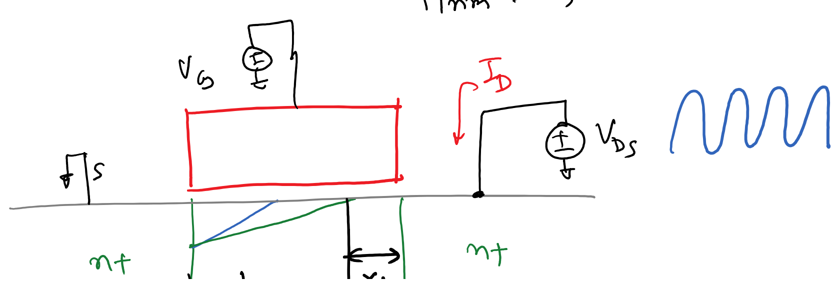
$$\boxed{I_D = \frac{1}{2} k\ell_n \frac{W}{L}(V_{GS}-V_{THN})^2}$$

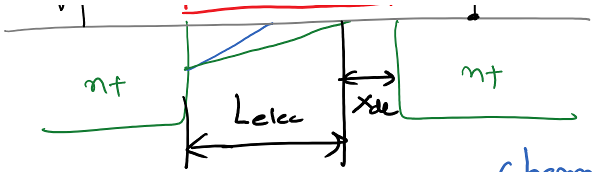
Saturation
$V_{DS} > V_{GS}-V_{THN}$



only true if $X_{de} << L$

for small length $L < 1\,\mu m \Rightarrow$ Submicron CMOS
14nm → nanoscale CMOS





Channel Length Modulation (CLM)

$$\underbrace{L_{elec}} = L - x_{de}$$

Current in saturation

$$I_D = \frac{1}{2} k P_n \frac{W}{L_{elec}} (V_{GS} - V_{THN})^2$$

$V_{DS} \uparrow \Rightarrow x_{de} \uparrow \Rightarrow L_{elec} \downarrow \Rightarrow I_D \uparrow$

Taylor's Series approximation of $f(x)$ around $x = x_0$

$$f(x) = f(x_0) + \left.\frac{df}{dx}\right|_{x_0} (x - x_0) + \frac{1}{2!} \left.\frac{d^2 f}{dx^2}\right|_{x_0} (x - x_0)^2 + \cdots$$

$$I_D(V_{DS}) = I_D(V_{DS,sat}) + \frac{\partial I_D}{\partial V_{DS}} (V_{DS} - V_{DS,sat}) + \cdots$$

$$\frac{\partial I_D}{\partial V_{DS}} = -\frac{kP_n}{2} \frac{W}{L_{elec}^2} (V_{GS} - V_{THN})^2 \cdot \frac{\partial L_{elec}}{\partial V_{DS}}$$

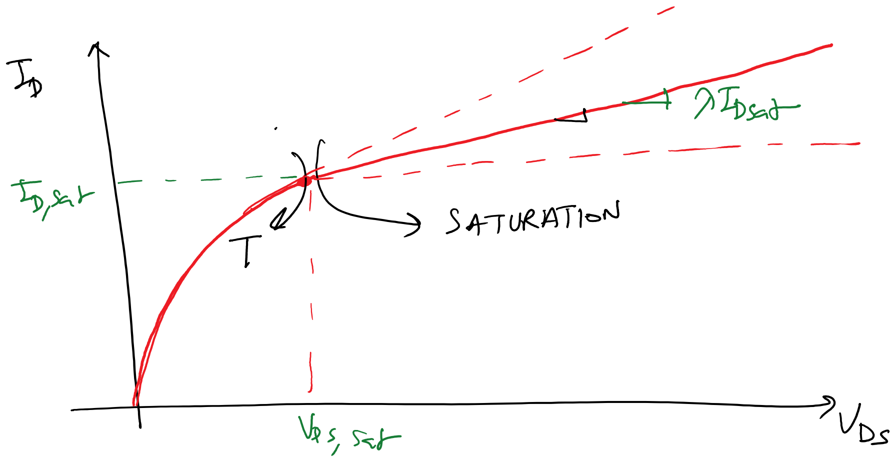
$$= I_D \cdot \left[\frac{1}{L_{elec}(V_{DS,sat})} \cdot \frac{\partial x_{de}}{\partial V_{DS}} \right] \rightarrow \lambda$$

$\lambda \Rightarrow$ Channel length modulation parameter

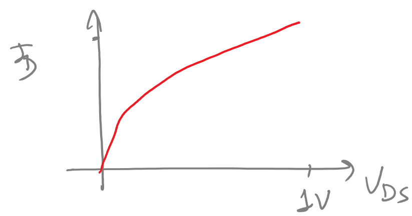
$$I_D = \frac{kP_n}{2} \frac{W}{L} (V_{GS} - V_{THN})^2 \cdot \left[\underbrace{1 + \lambda (V_{DS} - V_{DS,sat})} \right]$$

Some books

$$I_D = \frac{kP_n}{2} \cdot \frac{W}{L} (V_{GS} - V_{THN})^2 \cdot (1 + \lambda V_{DS}).$$



$$r_o = \left[\frac{\partial I_D}{\partial V_{DS}}\right]^{-1} = \frac{1}{\lambda I_{D,sat}}$$



$$
I_D = \begin{cases} 0, & V_{GS} < V_{THN} \quad \text{CUTOFF} \\ KP_n \cdot \frac{W}{L}\left[(V_{GS} - V_{THN})V_{DS} - \frac{V_{DS}^2}{2}\right], & V_{DS} < V_{GS} - V_{THN},\ V_{GS} > V_{THN} \quad \text{TRIODE} \\ \frac{1}{2} KP_n \frac{W}{L}(V_{GS} - V_{THN})^2 \cdot \left[1 + \lambda(V_{DS} - V_{DS,sat})\right], & V_{DS} > V_{DS,sat}\ \&\ V_{GS} > V_{THN} \quad \text{SATURATION} \end{cases}
$$