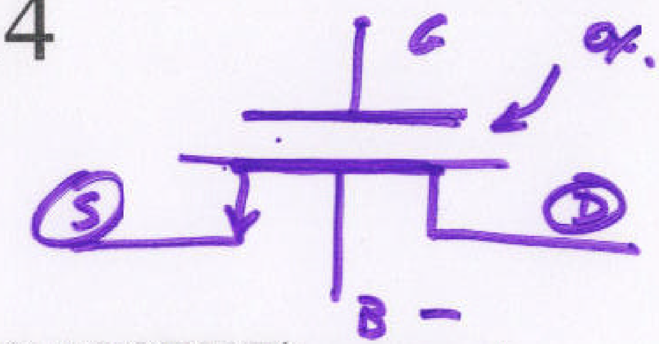
R. T. Howe

Lecture 14



- Last time:
  - MOS field effect transistor (MOSFET) ~~current-voltage characteristics~~ SYMBOL / STRUCTURE.
- Today : quantitative models for $I_D(V_{GS}, V_{DS})$ for :
  - Square-law MOSFET model ← PREFER.
  - Linear MOSFET model ("DIGITAL")

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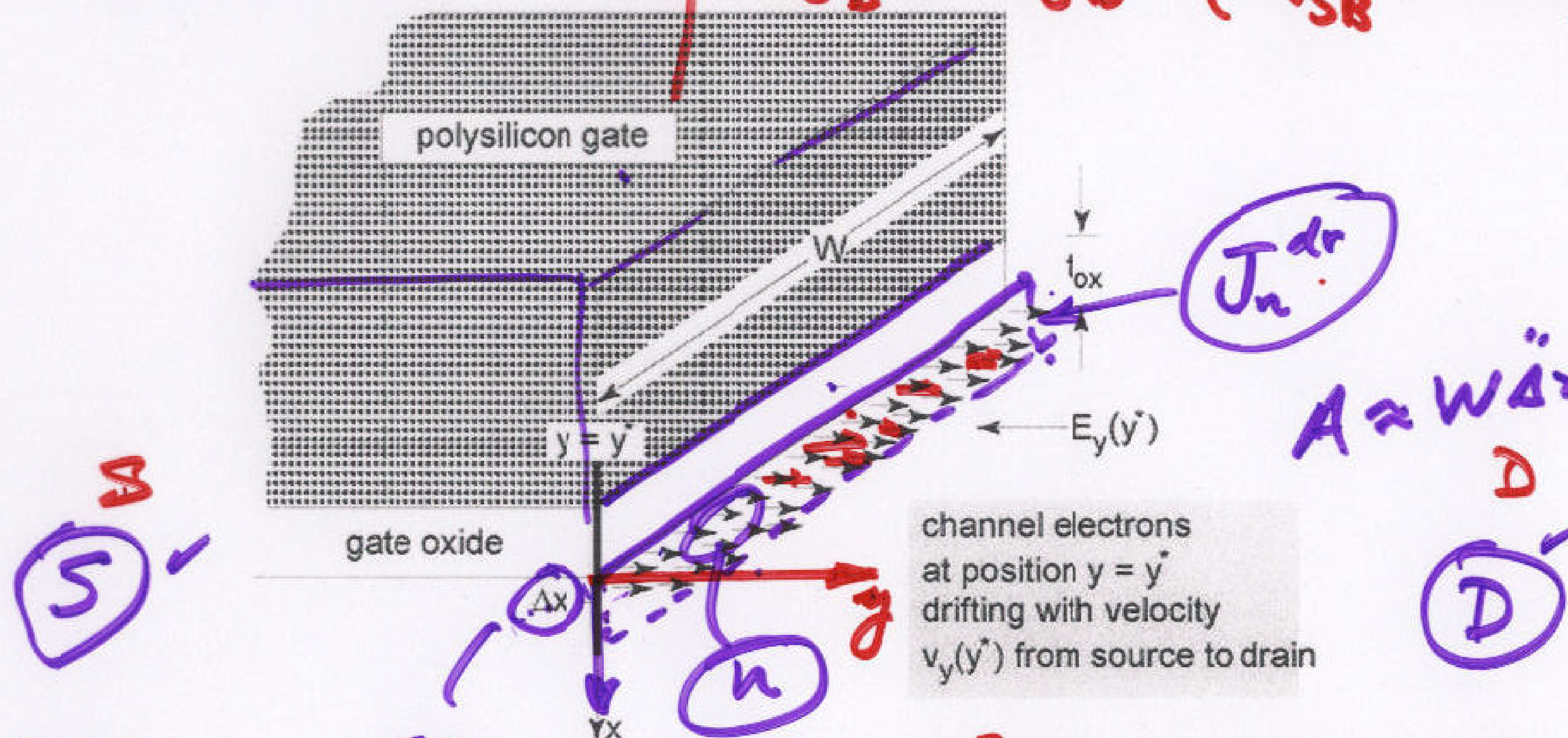
Channel Current in MOSFET

$V_{GS} = V_{GB}$ ($V_{SB} = 0\,V$)



$A \approx W \Delta x$

KCL

30–50 Å = 3–5 nm.

[J_n positive in direction of y.]

IEEE. EE 130, 231

$$\boxed{I_D = -W v_{dr}(y)\, Q_N(y)}$$

y axis "internal convention."

Channel Current Equation

Drift current density: $J_n(y^*) = -q\, n\, v_{dr}(y^*)$ → y

$n(x, y^*)$

"$I = JA$"

Drift current (a constant, independent of y^* along the channel (why?); the reference direction is "+ in")

$I = \int J\, dA.$

$$I_D = \int_0^{\Delta x} \left[-q\, n(x,y^*)\, v_{dr}(y^*)\right] \cdot \underbrace{W dx}_{dA}$$

$$= W v_{dr}(y^*) \boxed{\int_0^{\Delta x} -q\, n(x,y^*)\, dx}$$

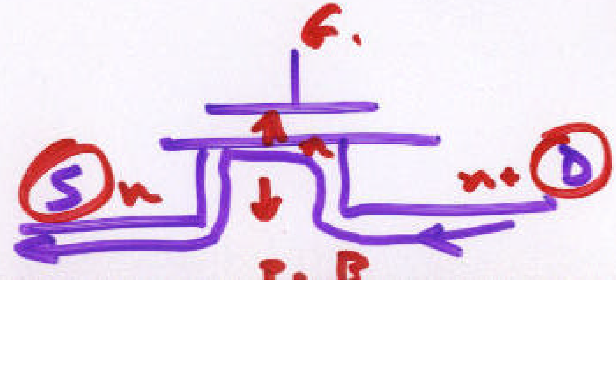
cm^{-3}

C/cm^2

INVERSION CHARGE $Q_N(y^*)$

... CONSTANT NO LEAKS!!

↑ UNDERSTAND THIS!

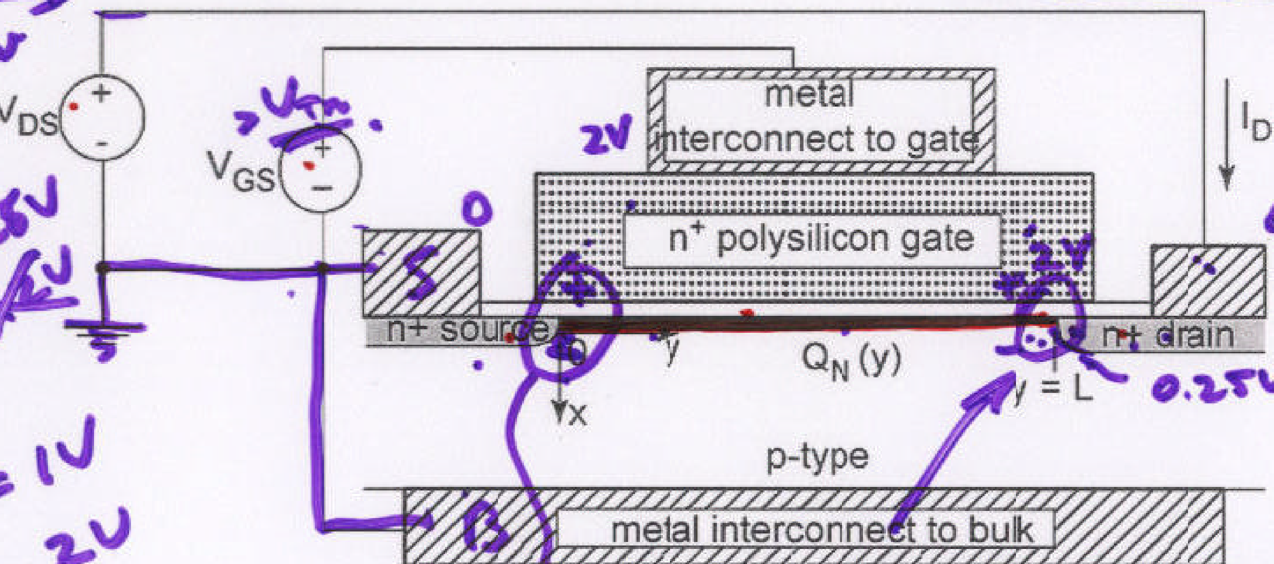


Finding $\boxed{I_D = f(V_{GS}, V_{DS})}$

$Q_N = -C_{ox}(V_{GS} - V_{Tn})$

- Approximate inversion charge $Q_N(y)$: drain is higher than the source → less charge at drain end of channel

$\boxed{I_D = -W v_{dr}^{(4)} \cdot Q_N(y)}$



$V_{DS} = \cancel{0/2V}$ 0.25V

$V_{Tn} = 1V$

$V_{GS} = 2V$

SOURCE

$2 - 0 = 2V.$

$Q_N(y=0) = -\underline{C_{ox}}(V_{GS} - V_{Tn})$

$1.75 - 1$

$Q_N(y=L) = -C_{ox}(V_{GD} - V_{Tn})$

0.25

$V_{GS} - V_{DS}$

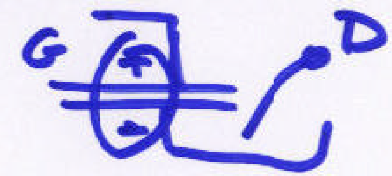
$I_D = -W \overline{v_{av}}(y)\, \overline{Q_N}(y)$ ⟹ AVERAGE

Inversion Charge

$$Q_N(y) \approx \left[Q_N(y=0) + Q_N(y=L) \right] / 2$$

$V_{DS} > 0.$

LESS CHARGE



$$Q_N(y=0) = -C_{ox}(V_{GS} - V_{Tn})$$

$$Q_N(y=L) = -C_{ox}(V_{GD} - V_{Tn})$$

$$V_{GD} = V_{GS} - V_{DS} = 1.75$$

$V_{GS} = 2$, $V_{DS} = 0.25$

Average inversion charge:

$$\overline{Q_N} = \frac{\{-C_{ox}(V_{GS} - V_{Tn}) + -C_{ox}(V_{GS} - V_{DS} - V_{Tn})\}}{2}$$

$V_{GD} = V_G - V_D$

$= V_G - V_S - [V_D - V_S]$

$$\bar{Q}_N = \frac{-C_{ox}(V_{GS} - V_{TN}) - C_{ox}(V_{GS} - V_{DS} - V_{TN})}{2}$$

$$= -C_{ox}(V_{GS} - V_{TN}) + C_{ox}\left(\frac{V_{DS}}{2}\right)$$

$$\boxed{\bar{Q}_N = -C_{ox}\left(V_{GS} - \frac{V_{DS}}{2} - V_{TN}\right)}$$

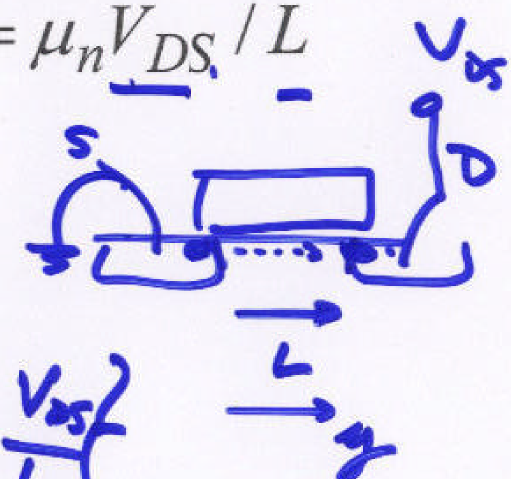
$$I_D \cong -W \, \overline{v_{dr}(y)} \, \overline{Q_N(y)}$$

Drift Velocity and Drain Current

NO SHORT CHANNEL!

"Long-channel" assumption: use mobility to find v

$$v_{dr}(y) = -\mu_n E(y) \approx -\mu_n(-\Delta V / \Delta y) = \mu_n V_{DS} / L$$



Substituting:

$$I_D \cong -W \bar{v}_{dr} \bar{Q}_N \approx -W \cdot$$

$$\left\{ -C_{ox} \left(V_{GS} - \frac{V_{DS}}{2} - V_{Tn} \right) \right\} \left\{ \mu_n \frac{V_{DS}}{L} \right\}$$

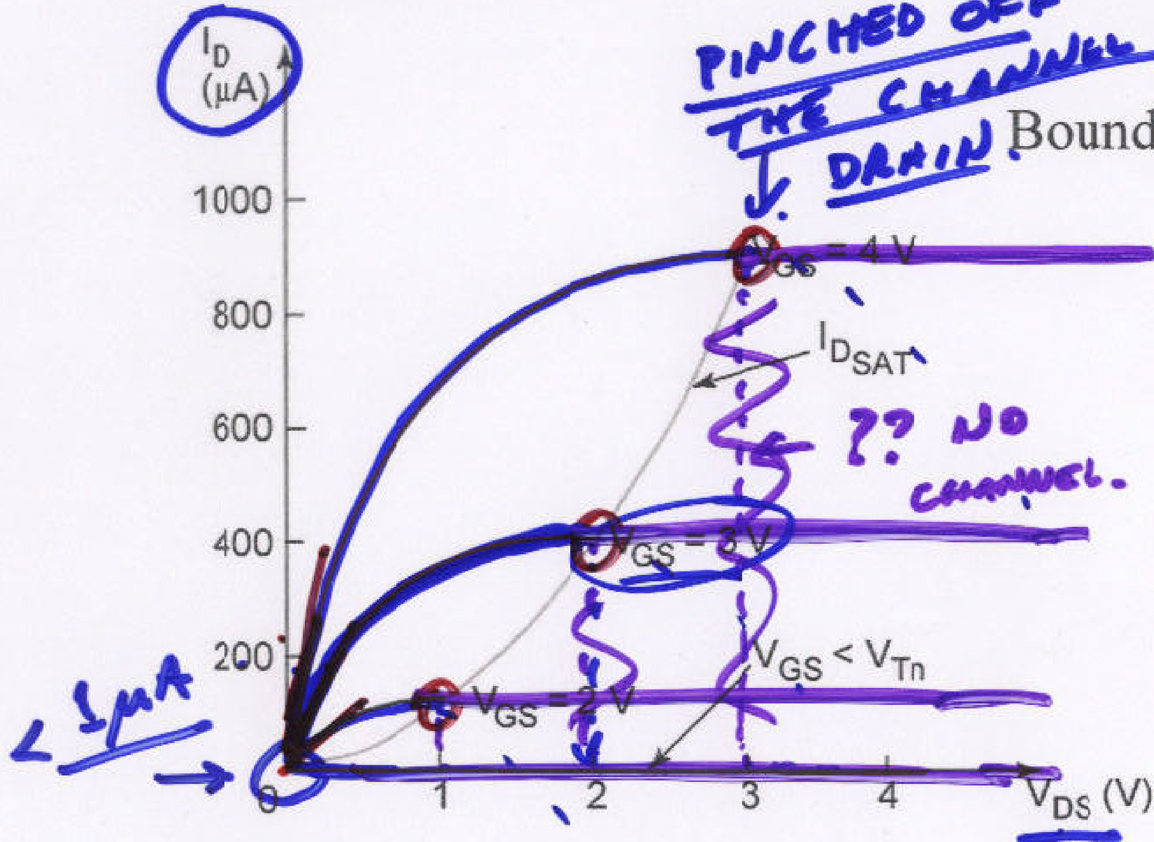
$$\boxed{I_D = \mu_n C_{ox} \left(\frac{W}{L} \right) \left(V_{GS} - V_{Tn} - \frac{V_{DS}}{2} \right) \cdot V_{DS}}$$

$V_{GS} \geq V_{Tn}$ . . . V_{DS} ?? $V_{DS} > 0$.

$I_D = \mu_n C_{ox} (W/L)(V_{GS} - V_{Tn} - \frac{V_{DS}}{2})(V_{DS})$

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

Square-Law Characteristics



PINCHED OFF THE CHANNEL @ DRAIN

Boundary: what is $I_{D,SAT}$?

$V_{GS} = 3$ V

$V_{DS} = 2$ V.

$V_{GD} = V_{GS} - V_{DS} = 1$ V $= V_{Tn}$.

$V_{GS} = 3$ V. $\Rightarrow$ $V_{DS} = 2$ V.

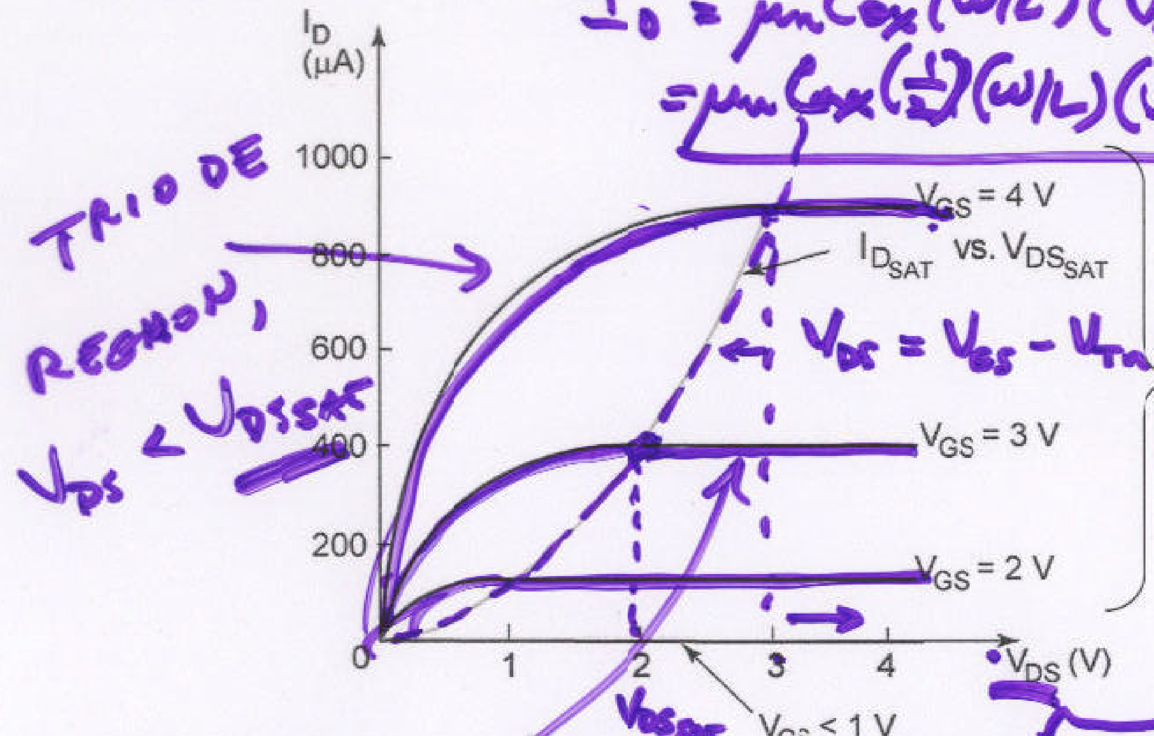
$I_D = -W v_{dr}(y)\, Q_N(y)$

The Saturation Region

When $V_{DS} > V_{GS} - V_{Tn}$, there isn't any inversion charge at the drain … according to our ~~simplistic~~ HYPER. simplistic model

$I_D = \mu_n C_{ox}(W/L)\left(V_{GS} - V_{Tn} - \left[\frac{V_{GS}-V_{Tn}}{2}\right]\right)\left(\frac{V_{GS}-V_{Tn}}{2}\right)$ ← $V_{DS_{SAT}}$

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



Why do curves flatten out?

$I_{D_{SAT}} = I_{D_{MAX}} = I_D(V_{GS}, V_{DS_{SAT}} = V_{GS} - V_{Tn})$

Square-Law Current in Saturation

Current stays at maximum (where $V_{DS} = V_{GS} - V_{Tn} = V_{DS,SAT}$)

$$\boxed{I_D = \widetilde{\mu_n C_{ox}} (W/2L)(V_{GS} - V_{Tn})^2;}$$

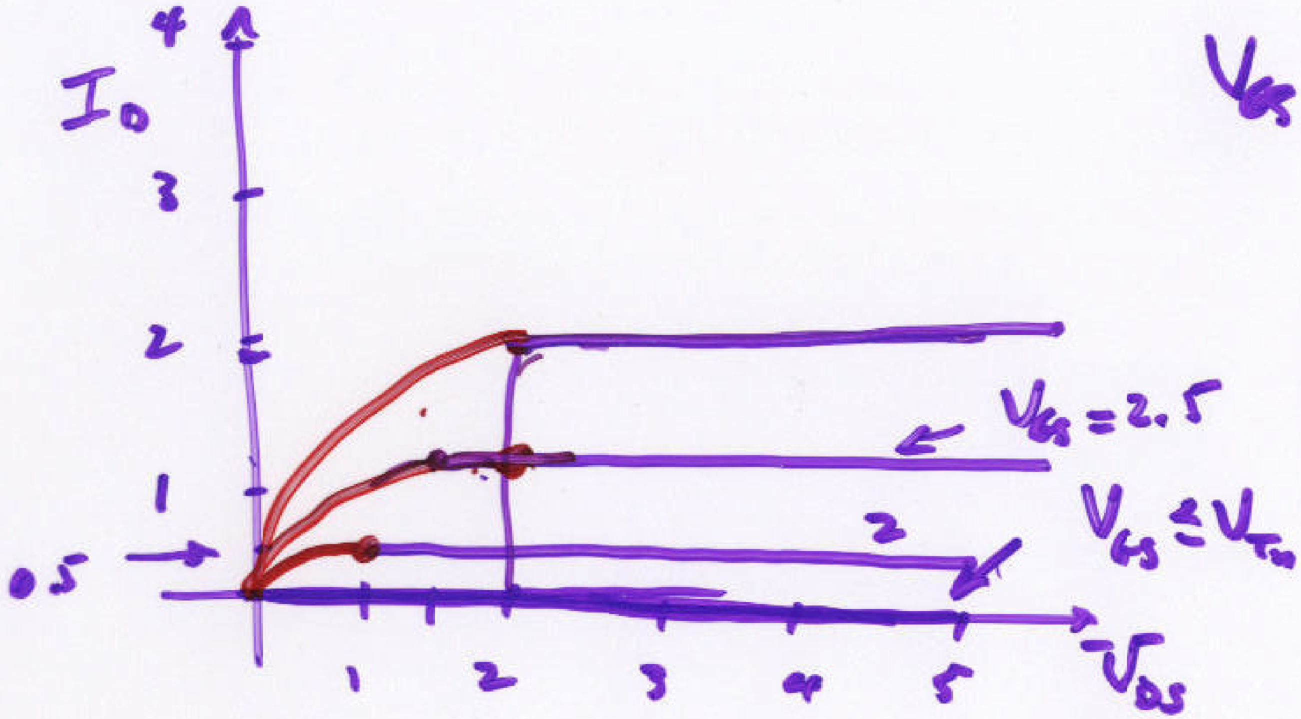
$V_{GS} > V_{Tn}$

$V_{DS} \geq V_{DS,SAT} = V_{GS} - V_{Tn}$

Measurement: I_D increases slightly with increasing V_{DS}
model with linear "fudge factor"

$$I_{D,SAT} = \mu_n C_{ox} (W/2L)(V_{GS} - V_{Tn})^2 \underline{(1 + \lambda_n V_{DS})}$$

λ_n small.



V_{GS}	I_D
$V_{GS} = 0$	0
1	0
2.	0.5 mA.
2.5	
3.	

$$\left.\begin{aligned} \mu_n C_{ox} &= 100\,\mu A/V^2 \\ W/2L &= \left(20/2(2)\right) = 5 \end{aligned}\right] \quad 500\,\mu A/V^2$$

1 V

$$I_{DSAT} = \underbrace{(500\,\mu A/V^2)}_{0.5\ \frac{mA}{V^2}}\left(V_{GS} - \cancel{V_{TN}}\right)^2 \ldots \quad \frac{2.5 - 1.}{2 - 1} = .$$

$$V_{DS} \geq V_{DSSAT} = V_{GS} - V_{TN}$$