# Lecture 10, February 7, 2001

EECS 105 Microelectronics Devices and Circuits, Spring 2001

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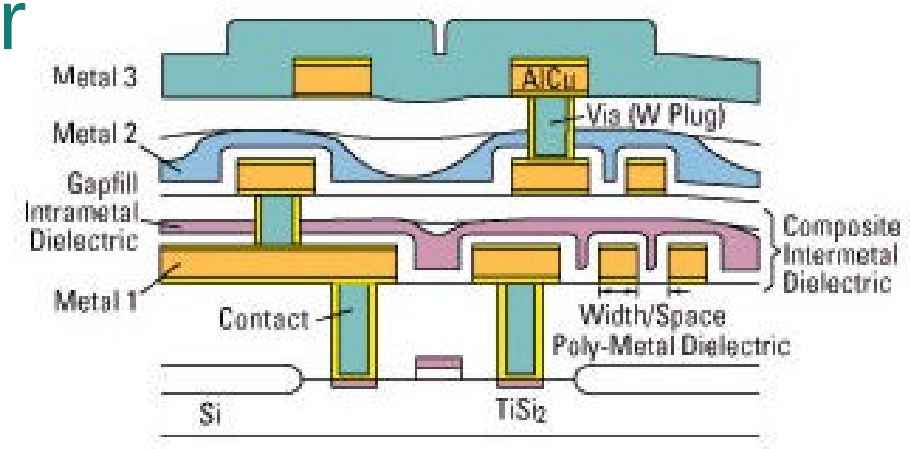



**Topics: More accurate gradual channel analysis; Physical effects including backgate, channel length modulation, mobility reduction by vertical field, and velocity saturation.**

**Reading: HS 4.4, Design problem D4.1**

Version 2/8/01

# NMOS Example

$$Q_{B,\max} = -\sqrt{2qe_s N_a \left(-2f_p\right)}$$

**Example pp. 139: $N_a = 10^{17}$; $t_{ox} = 150A$**

**$\phi_{n+} = 550$ mV $\phi_p = -420$ mV**

$$Q_{B,\max} = -\sqrt{2\left(1.6x10^{-19}\right)\left(11.7\right)\left(8.85x10^{-14}\right)\left(10^{17}\right)\left(0.84\right)} = -1.67x10^{-7} C/cm^2$$

$$C_{ox} = \frac{3.9\left(8.85x10^{-14} Fcm^{-1}\right)}{150x10^{-8} cm^1} = 2.3x10^{-7} Fcm^{-2} = 230aF/mm^2$$

$$V_{oxide} = -\frac{1}{C_{ox}}\left(-\sqrt{2qe_s N_A\left(-2f_p\right)}\right) = -\frac{-1.67x10^{-7}}{2.3x10-7} = 0.725V$$

# NMOS Example cont.

$$V_{Tn} = V_{FB} - 2f_p + \frac{1}{C_{ox}}\sqrt{2qe_s N_A\left(-2f_p\right)}$$

$$V_{Tn} = -970mV + 840mV + 725mV = 0.595V$$

**Any excess gate voltage i.e. voltage above $V_{Tn}$ creates additional mobile electrons.**

**For each volt excess gate voltage**

$$Q_{Mobile} = \left(2.3x10^{-7} Fcm^{-2}\right)\left(1V\right) = 2.3x10^{-7} C/cm^2$$

**This is $1.4x10^{12}$ electrons/$cm^2$**

# Threshold Voltage $V_{Tp}$

$$V_{Tp} = V_{FB} - 2f_n - \frac{1}{C_{ox}}\sqrt{2qe_s N_D (2f_n)}$$

**Example pp. 144: $N_d = 10^{17}$; $t_{ox} = 150A$**

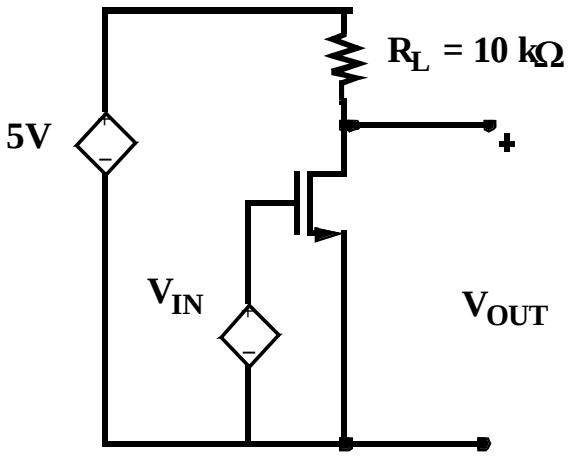
**$\phi_{n+} = 550$ mV $\phi_n = 420$ mV $C_{OX} = 2.3 \times 10^{-7}$ F/cm$^2$**

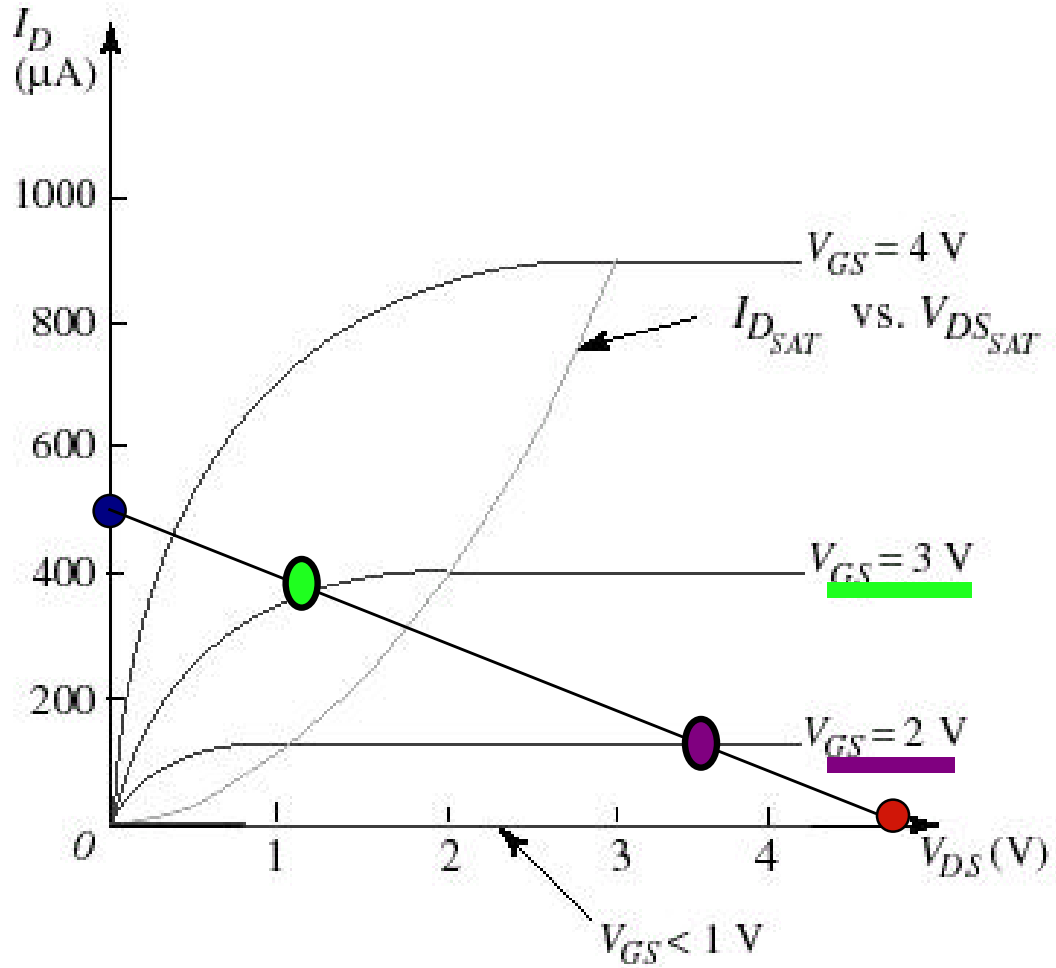
$$Q_{B,\max} = \sqrt{2qe_s N_D (2f_n)}$$

$$= \sqrt{2(1.6x10^{-19})(11.7)(8.85x10^{-14})(10^{17})(0.84)} = 1.67x10^{-7} C/cm^2$$

$$V_{Tp} = -(550-(420)) - 2(420) - \frac{1.67x10^{-7}(10^3)}{2.3x10^{-7}} mV = -1.695V$$

# Load Line Solution

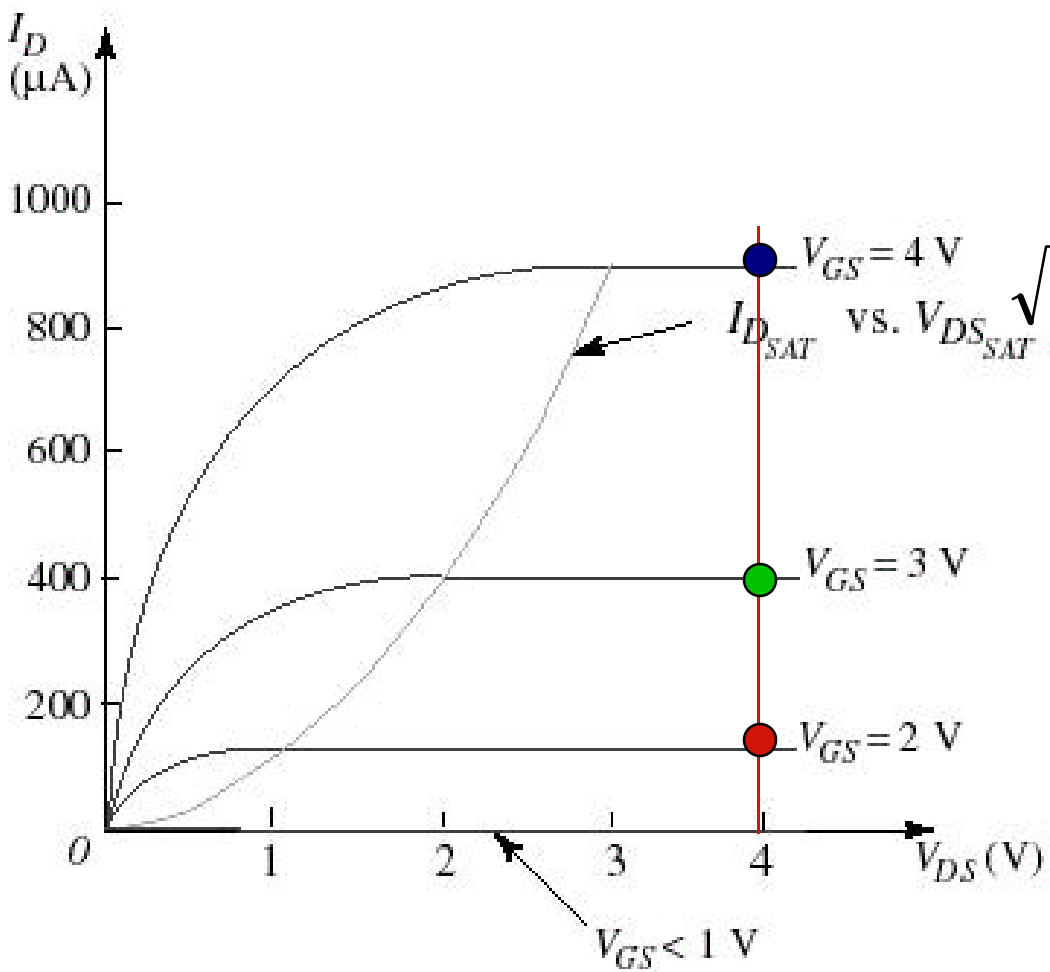



$I_{SC}$ = 500 μA

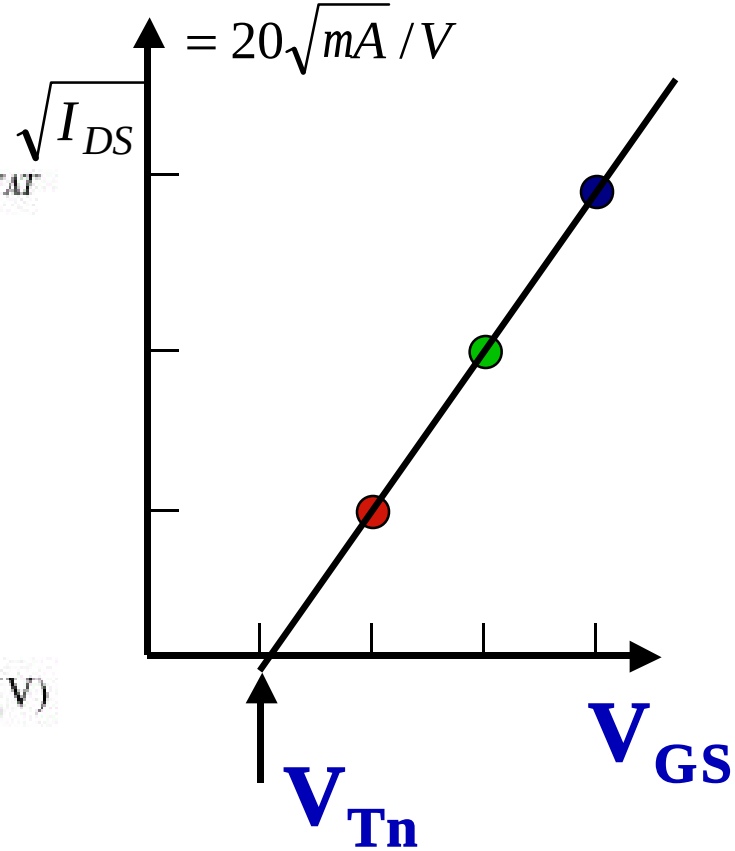
$V_{OC}$ = 5V

# Large current k and $V_T$ from I vs. V

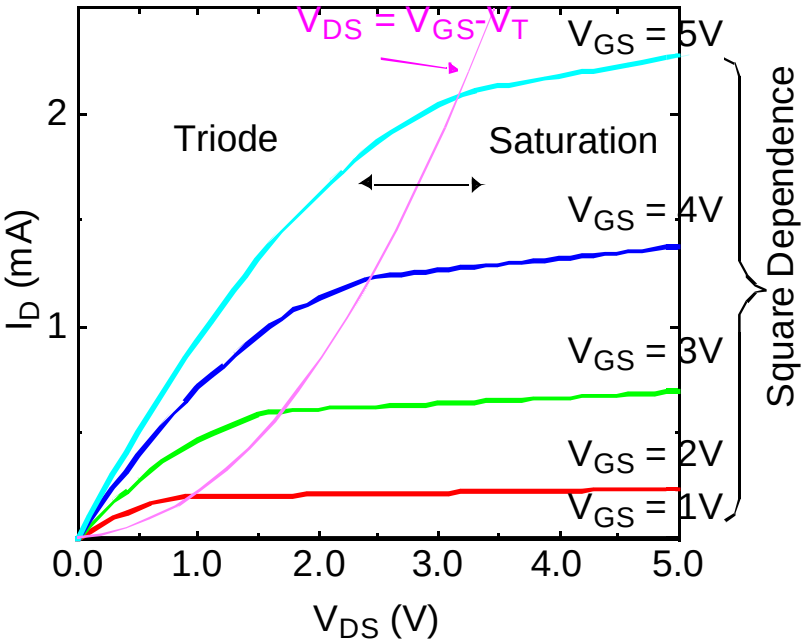



$$Slope = \sqrt{\frac{W}{2L} m_n C_{OX} (1 + l V_{DS})}$$

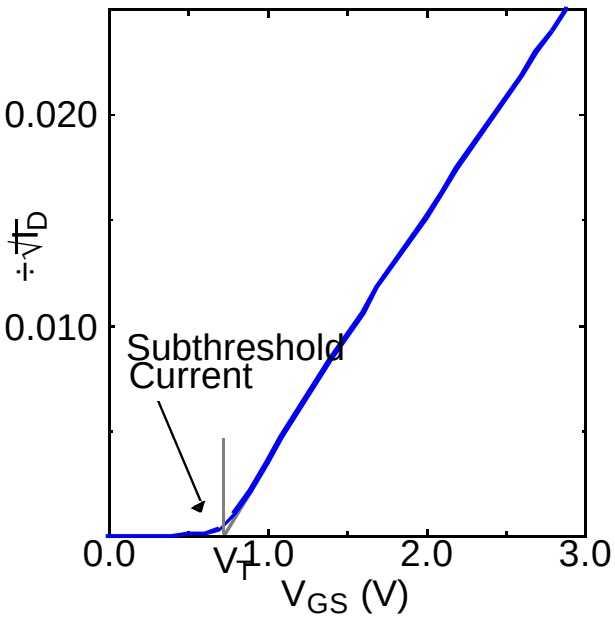
$$= 20\sqrt{mA}/V$$



# Realistic $I_{DS}$ vs. $V_{DS}$




(a) $I_D$ as a function of $V_{DS}$




(b) $\sqrt{I_D}$ as a function of $V_{GS}$ (for $V_{DS}$ = 5V).

NMOS Enhancement Transistor: W = 100 μm, L = 20 μm

# $2^{nd}$ Order Physics

- Backgate bias
- Channel-length modulation
- Mobility degredation
- Velocity saturation
- Sub-threshold leakage

**These are important topics in EE 130 and we will use a slightly patched model for EE 105.**

# Backgate bias

- When the source is not at the substrate (or well) voltage, an extra voltage source body voltage occurs that increases $x_{B,max}$ and $Q_{B,max}$ and this changes the threshold voltage.

$$V_{Tn} = V_{FB} - 2f_p + \frac{1}{C_{ox}}\sqrt{2qe_s N_A\left(-2f_p - V_{BS}\right)}$$

**Or for convenience**

$$V_{Tn} = V_{TOn} + g_n\left(\sqrt{-2f_p - V_{BS}} - \sqrt{-2f_p}\right)$$

$$g_n = \left(\sqrt{2qN_a e_s}\right)/C_{OX}$$

# Channel-length modulation

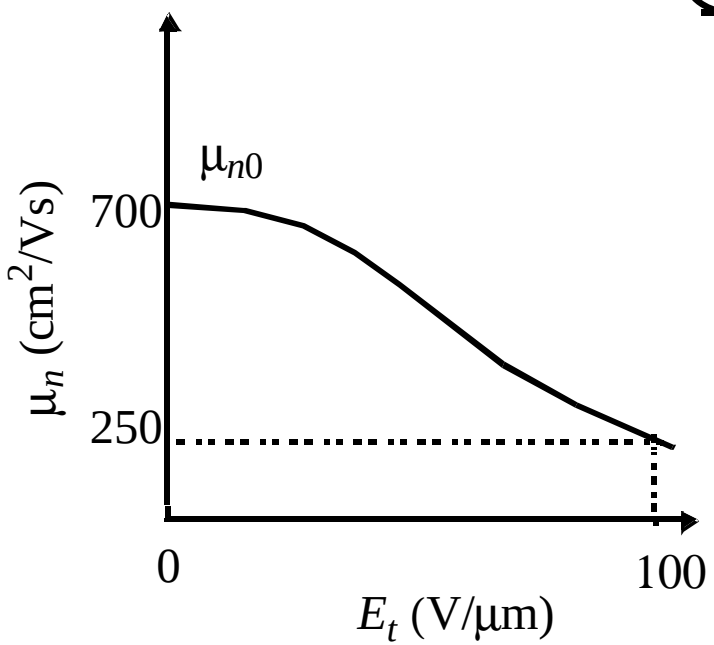
- The MOS transistor is not an ideal current source in that the current tends to increase with $V_{DS}$. This is due to the physics of the the region between pinch-off of the current and the drain. There is no simple intuitive physical model and two-dimensional simulation is needed.

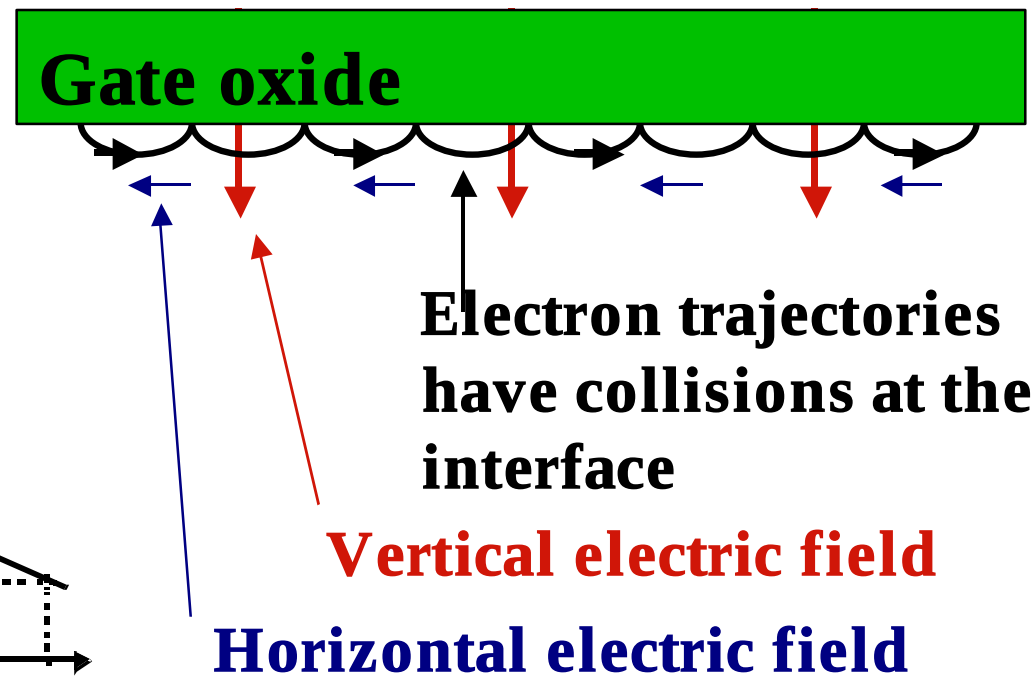
**Length reduction model**

$$\frac{\Delta L}{L} = l_n V_{DS} \qquad l_n = \frac{0.1 mmV^{-1}}{L}$$

$$I_{DS} = \left(\frac{W}{2L}\right) m_n C_{OX} \left(V_{GS} - V_{Tn}\right)^2 \left(1 + l_n V_{DS}\right)$$

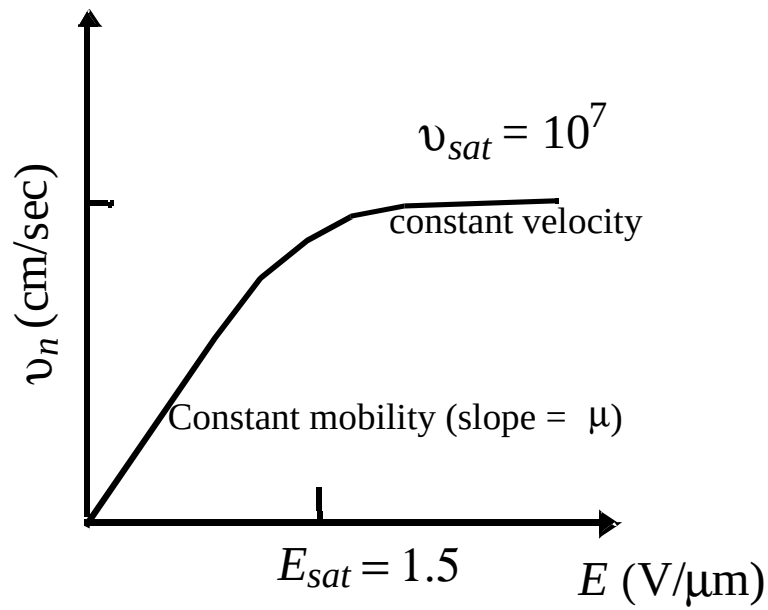
# Mobility Degradation



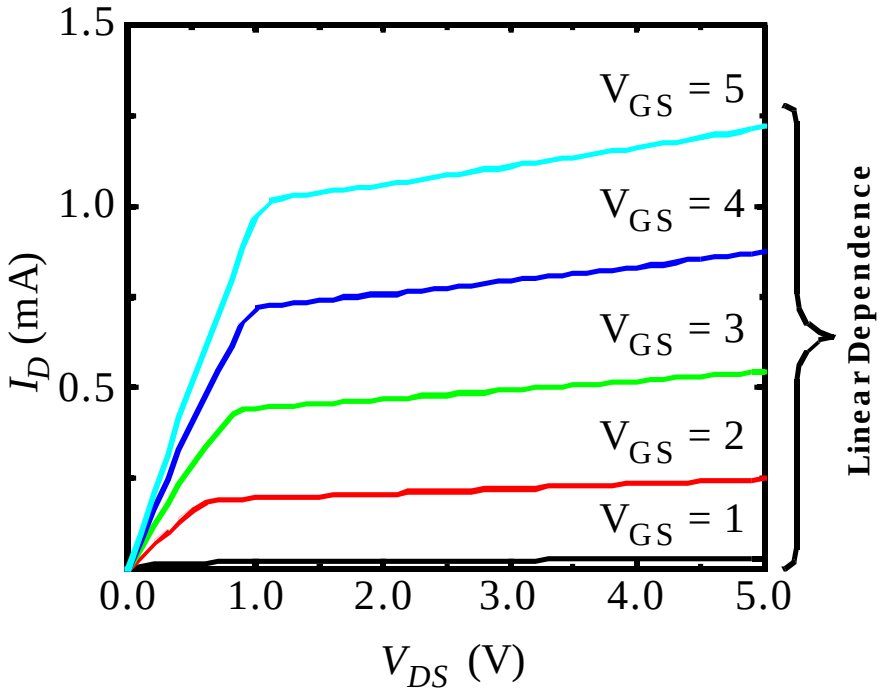



# Velocity saturation

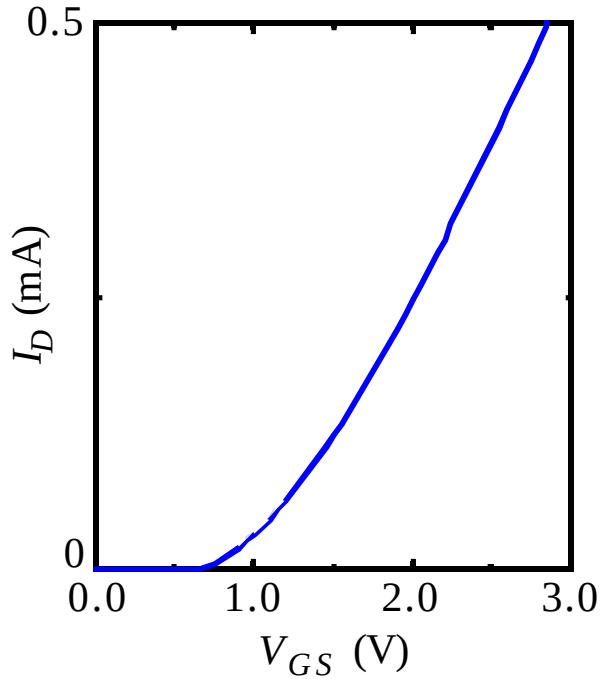
- The electron velocity no longer increases once the horizontal field reaches 1.5V/μm.
- This effect becomes noticeable for a 1 μm device at 2 volts $V_{DS}$.



# $I_{DS}$ vs. $V_{DS}$ with Velocity Saturation




(a) $I_D$ as a function of $V_{DS}$




(b) $I_D$ as a function of $V_{GS}$ (for $V_{DS}$ = 5 V).

**Linear Dependence on $V_{GS}$**

# Improved $I_{DS}$ vs. $V_{DS}$ Model

$$V_{Tn} = V_{TOn} + g_n\left(\sqrt{-2f_p - V_{BS}} - \sqrt{-2f_p}\right)$$

**Typical values:**

**$V_{Tn}$ = 1V**

**$\mu_n C_{OX}$ = 50 $\mu$A/V$^2$**

**W/L = 4**

**$\gamma_n$ = 0.8V$^{-1/2}$**

**$\lambda$n = 0.05V$^{-1}$**

**cutoff**

$$V_{GS} \le V_{Tn}$$

$$I_{DS} = 0$$

**triode**

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

$$I_{DS} = \left(\frac{W}{L}\right) m_n C_{OX}\left[V_{GS} - V_{Tn} - (V_{DS}/2)\right](1 + l_n V_{DS})V_{DS}$$

**saturation**

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

$$I_{DS} = \left(\frac{W}{2L}\right) m_n C_{OX}\left(V_{GS} - V_{Tn}\right)^2 (1 + l_n V_{DS})$$