## Unit 1: Transistor Fundamentals

# Lecture 1.6: Traditional IV Theory

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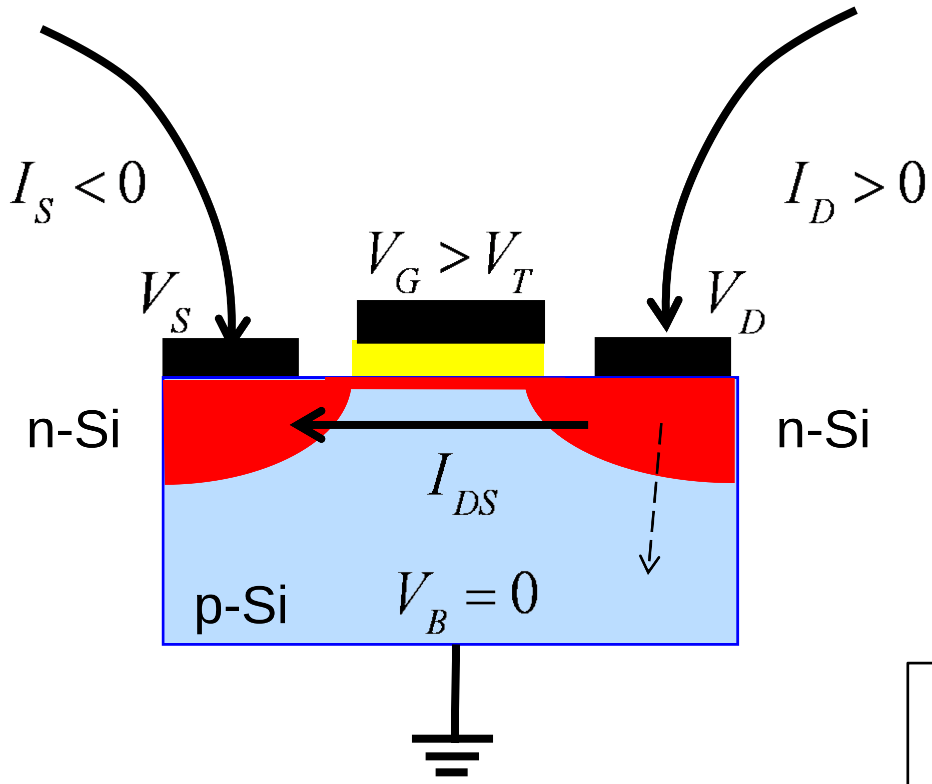
# IV characteristics of MOSFETs




$$I_{DS}\left(V_{GS}, V_{DS}\right)$$

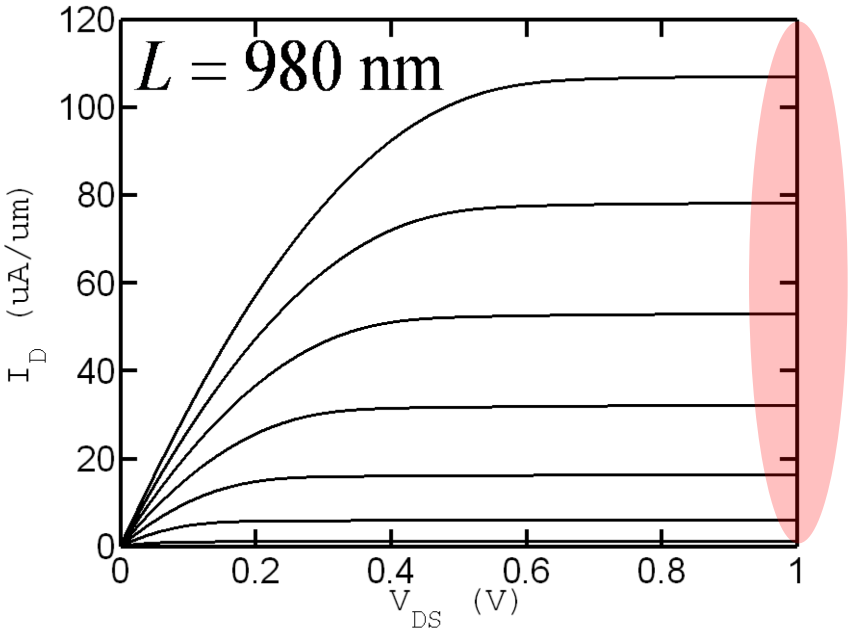
$$V_S = V_B = 0$$

Goal: To understand: $I_{DS}\left(V_S, V_G, V_D, V_B\right)$

# Long vs. short channel MOSFETs

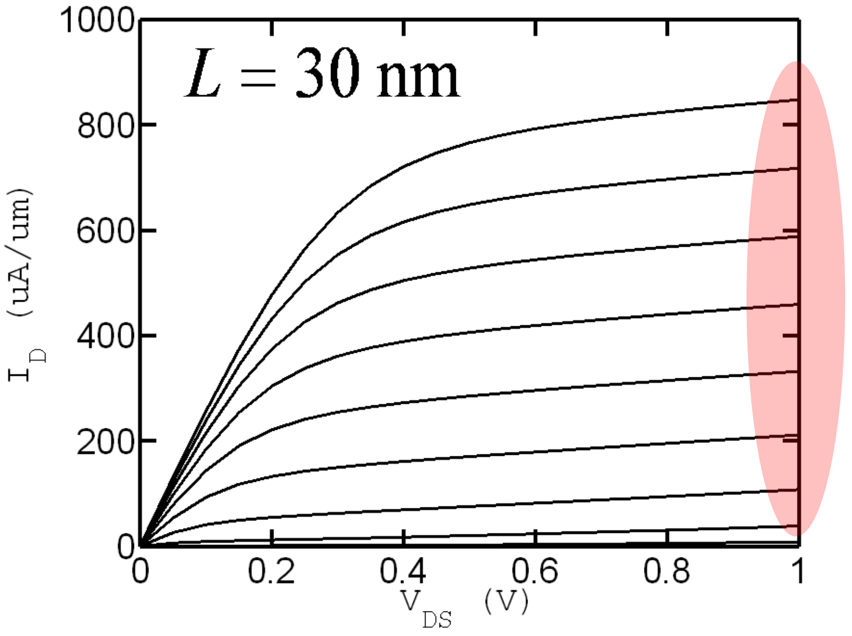
“Square Law”

$$I_{DSAT} \propto \left(V_{GS} - V_T\right)^2$$




“Velocity saturated”

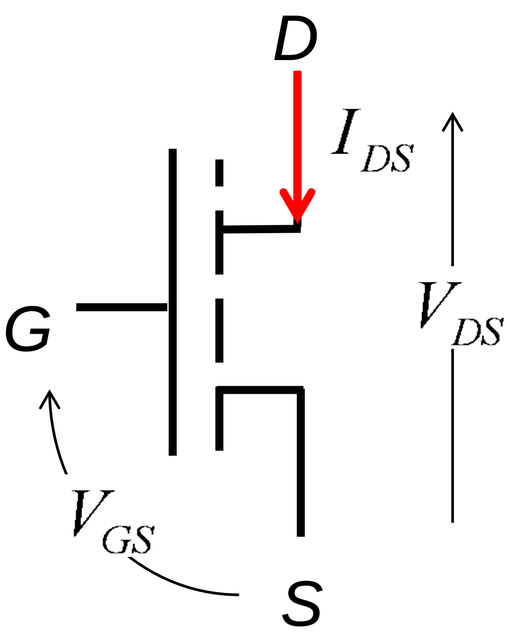
$$I_{DSAT} \propto \left(V_{GS} - V_T\right)$$



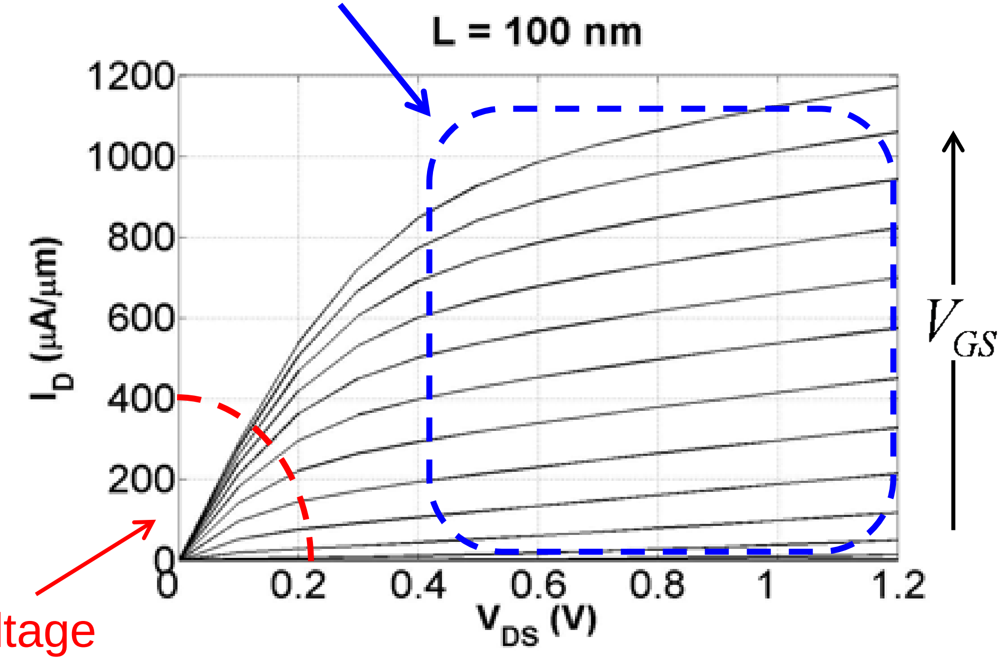

ETSOI MOSFETs provided by A. Majumdar, IBM Research, 2015.

# MOSFET IV characteristic

circuit symbol



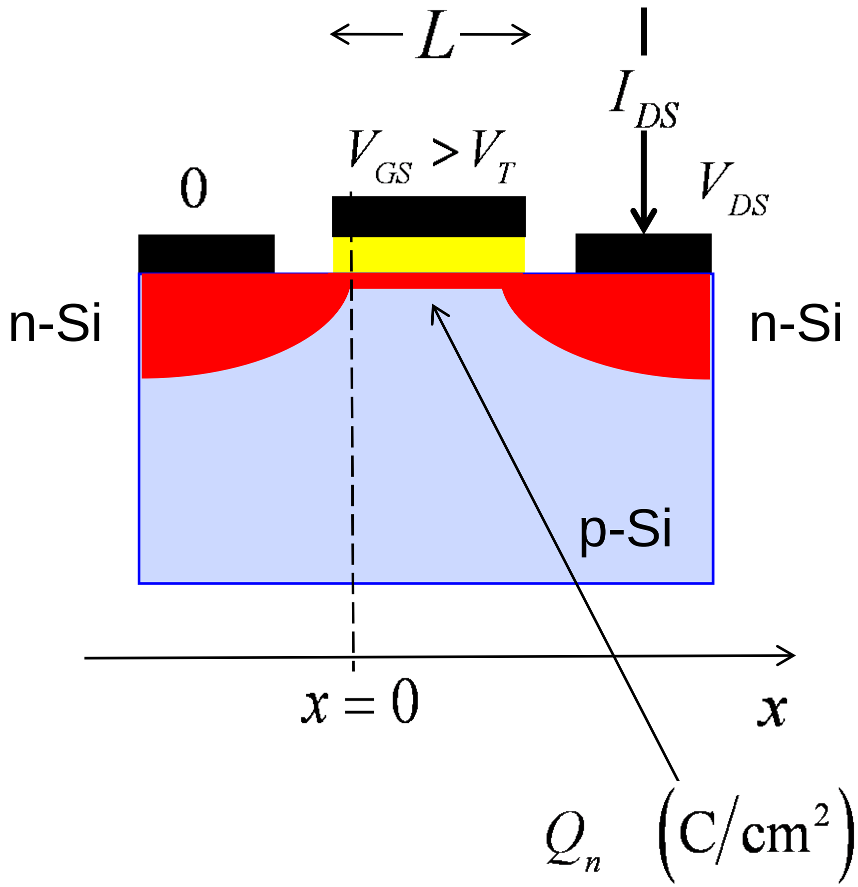

gate-voltage controlled current source

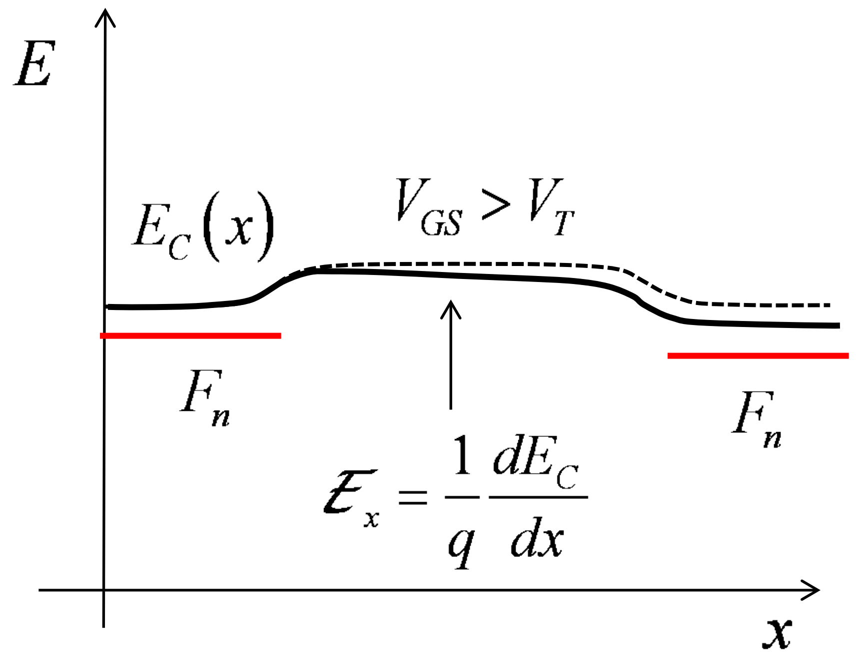



gate-voltage controlled resistor

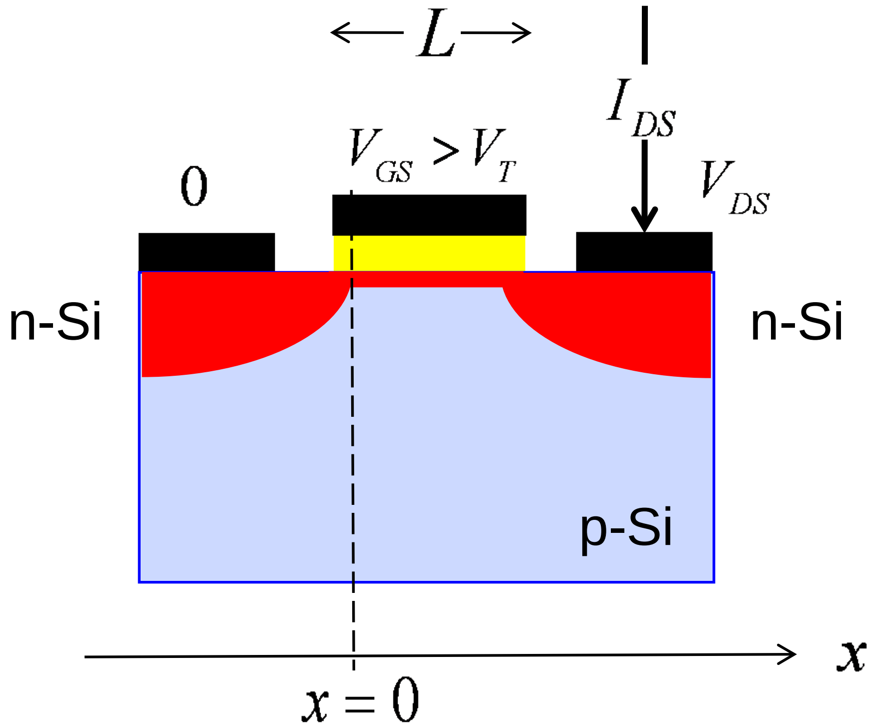
(Courtesy, Shuji Ikeda, ATDF, Dec. 2007)

# MOSFET e-band (high $V_{GS}$, low $V_{DS}$)



# MOSFET IV




current is charge per unit time

$$I_{DS} = -W\, Q_n(x) \langle \upsilon_x(x) \rangle$$

$$C \equiv \frac{Q}{V} \quad \mathrm{F}$$

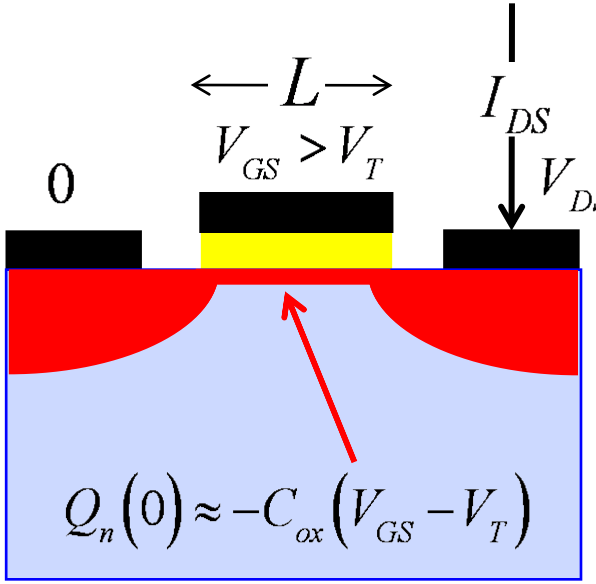
MOS electrostatics

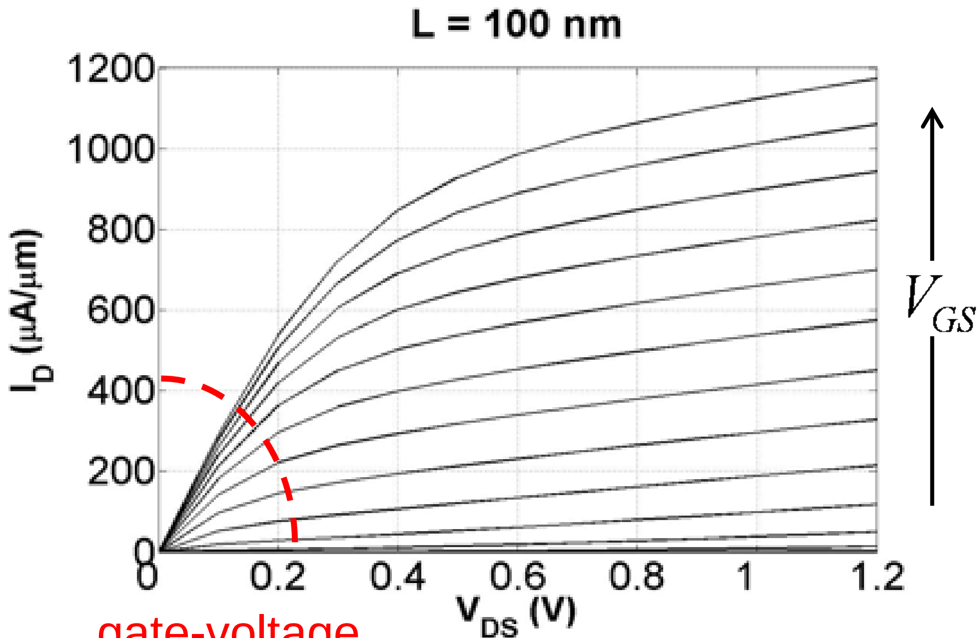
$$Q_n \approx -C_{ox}\left(V_{GS} - V_T\right) \quad \mathrm{C/cm^2}$$

$$Q_n \approx 0 \quad \left(V_{GS} < V_T\right)$$

$$C_{ox} = \frac{\kappa_{ox}\varepsilon_0}{x_o} \quad \mathrm{F/cm^2}$$

# MOSFET IV: low $V_{DS}$




$$I_{DS} = -W Q_n(x) \langle \upsilon_x(x) \rangle$$

$$Q_n = -C_{ox}(V_{GS} - V_T)$$

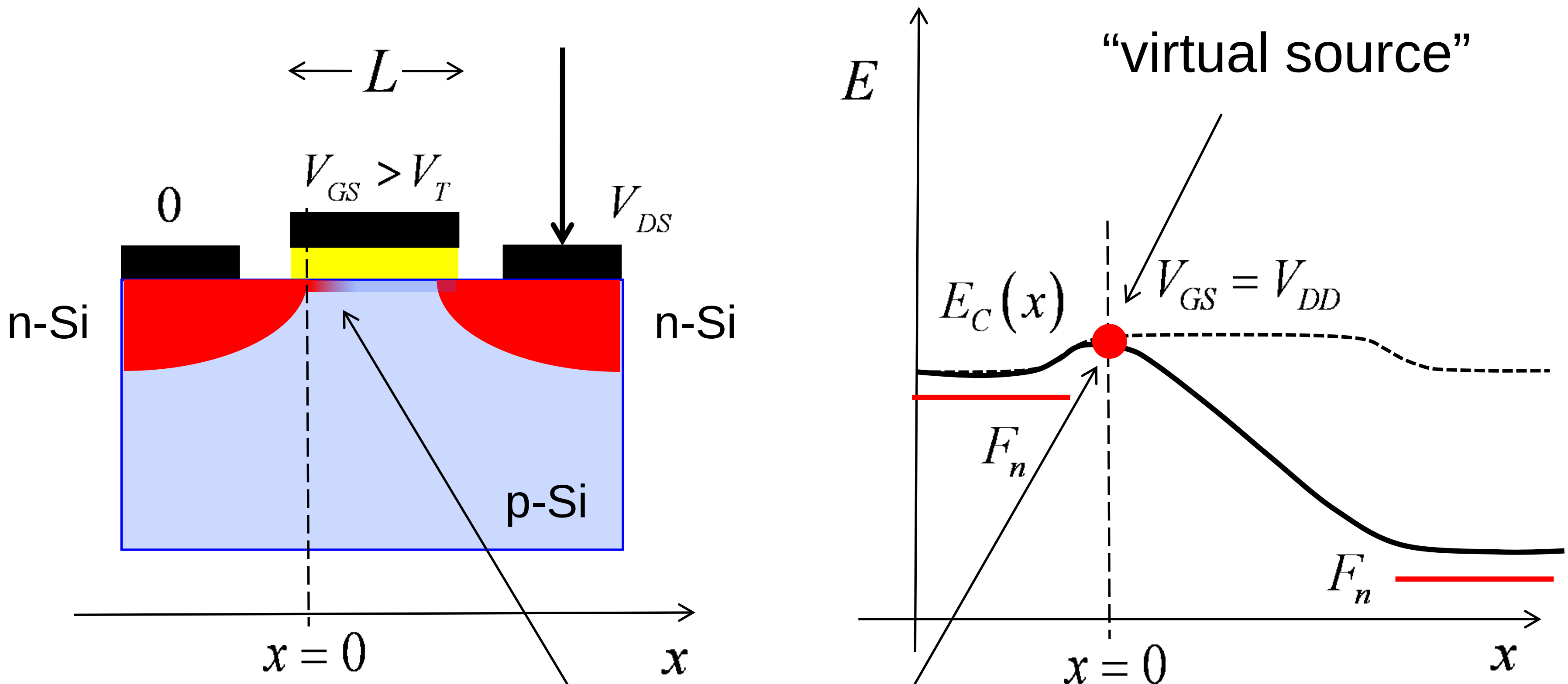
$$\langle \upsilon_x(x) \rangle = -\mu_n \mathcal{E}_x$$

$$\mathcal{E}_x = -V_{DS}/L$$

gate-voltage controlled resistor

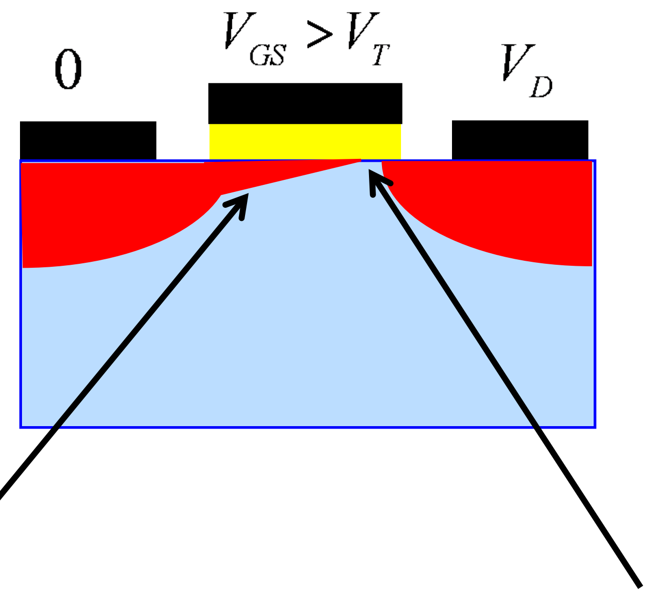
$$I_{DS} = \frac{W}{L} \mu_n C_{ox} (V_{GS} - V_T) V_{DS}$$ ✓

# MOSFET e-band (high $V_{GS}$, high $V_{DS}$)




$$Q_n \approx -C_{ox}\left(V_{GS} - V_T\right) \quad \mathrm{C/cm^2}$$

# MOSFET IV: “pinch-off” at high $V_{DS}$




$$Q_n(x) = -C_{ox}\left(V_{GS} - V_T - V(x)\right)$$

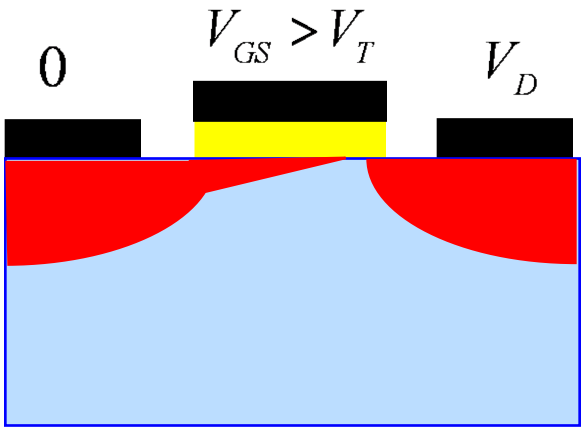
$$V\left(x_{pinch}\right) = \left(V_{GS} - V_T\right)$$

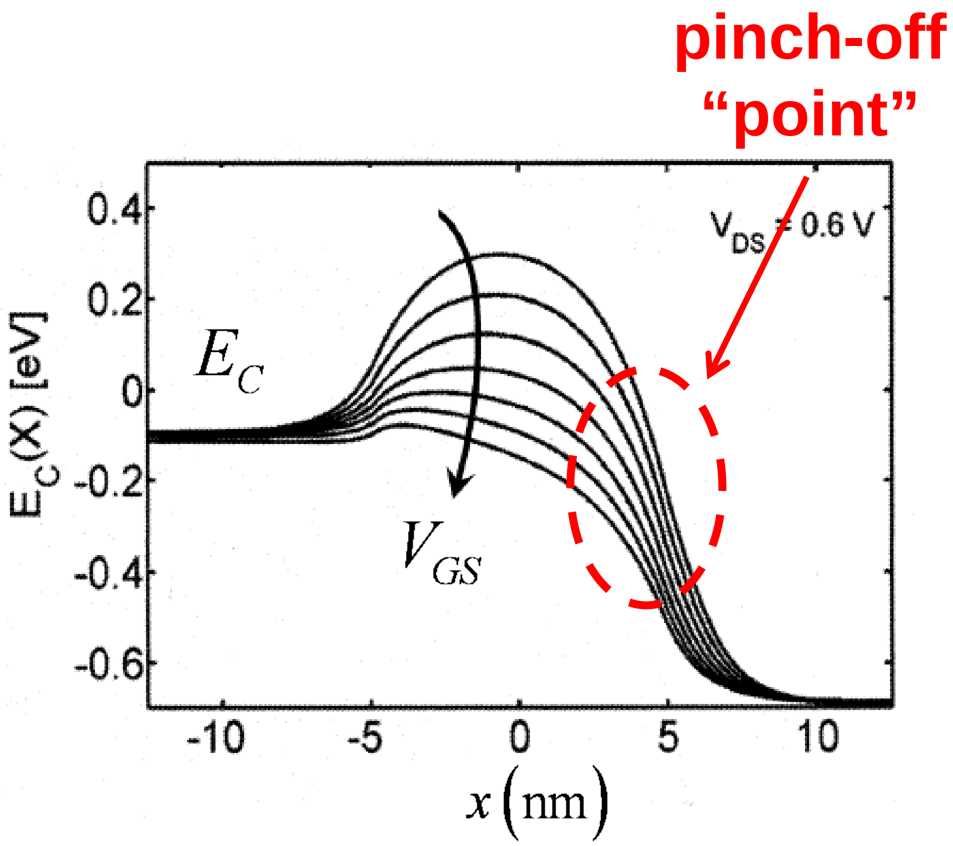
$$Q_n\left(x_{pinch}\right) \approx 0$$

Note: thickness of channel illustrates the areal density of electrons – not the actual thickness.

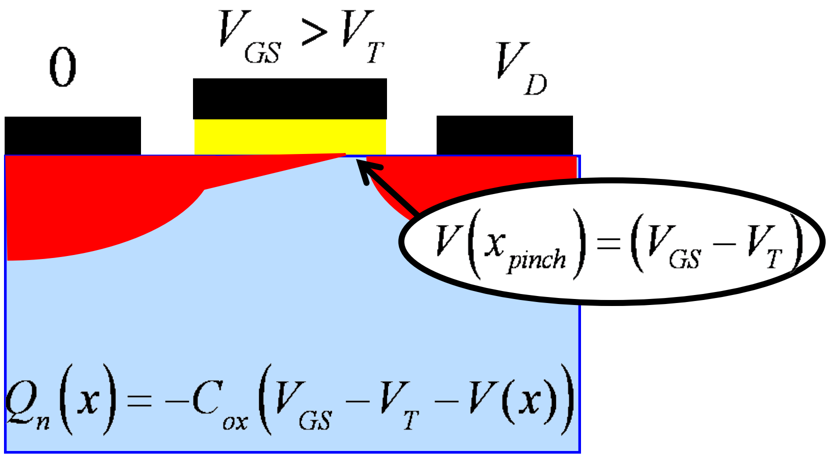
Electric field is very large in the pinch-off region.

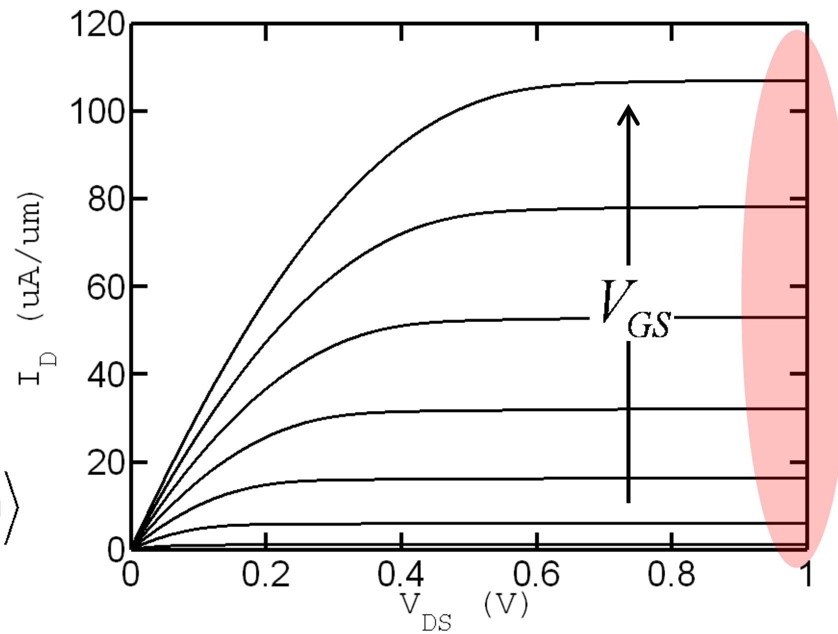
# “Pinch off” in the channel



# MOSFET IV: high $V_{DS}$




$$I_{DS} = -W\,Q_n(x)\langle \upsilon_x(x)\rangle = W\,Q_n(0)\langle \upsilon_x(0)\rangle$$

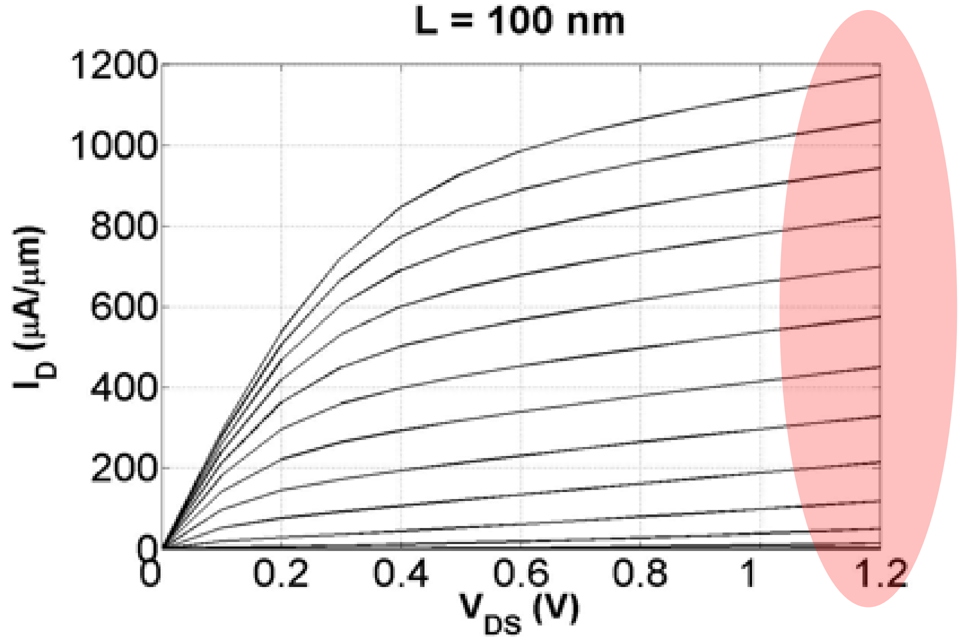
$$Q_n(0) = -C_{ox}(V_{GS} - V_T)$$

$$\langle \upsilon_x(0)\rangle = -\mu_n \mathcal{E}_x(0)$$

$$\mathcal{E}_x(0) \approx -V(x_{pinch})/L = -(V_{GS} - V_T)/L$$

$$I_{DS} = \frac{W}{2L}\mu_n C_{ox}(V_{GS} - V_T)^2$$

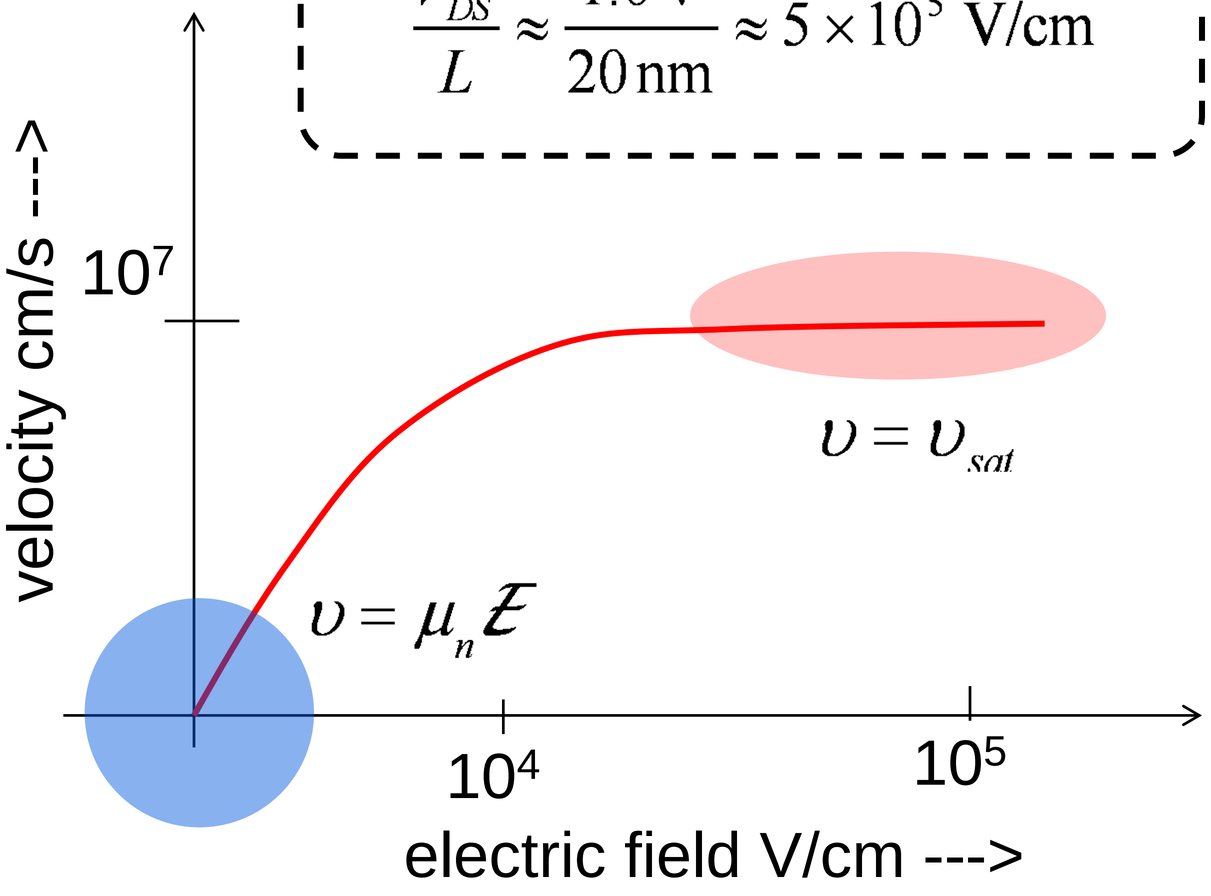
# Short channel MOSFETs



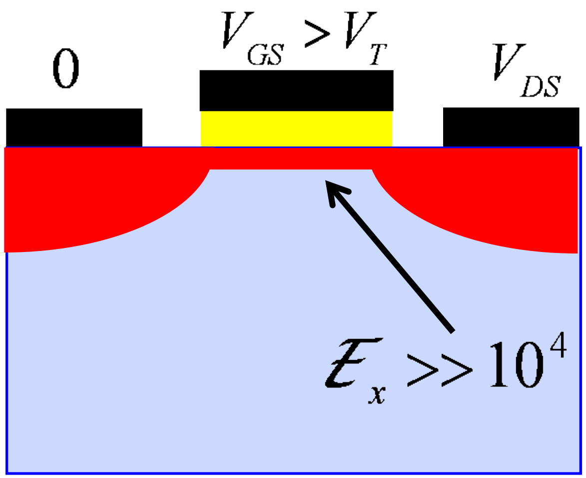

$$I_{DSAT} \propto \left(V_{GS} - V_T\right)$$

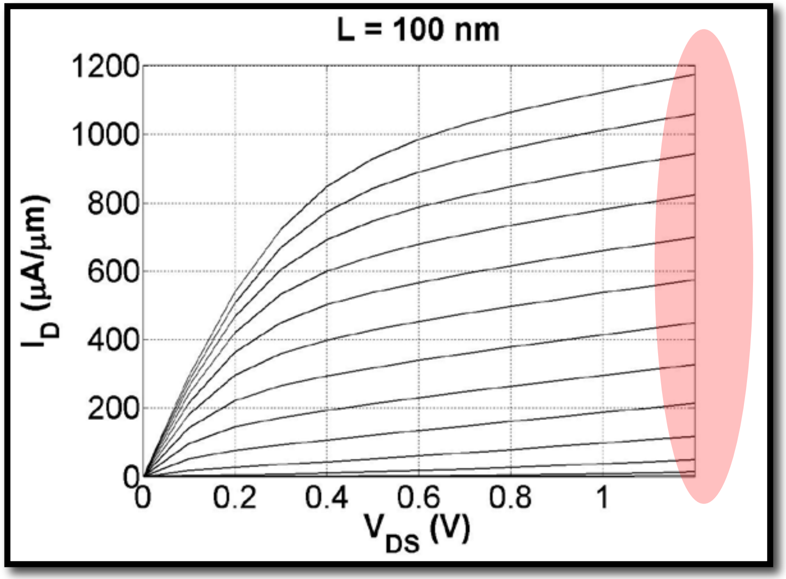
# High $V_{DS}$: velocity saturation

$$\frac{V_{DS}}{L} \approx \frac{1.0\,\text{V}}{20\,\text{nm}} \approx 5\times 10^{5}\ \text{V/cm}$$



# MOSFET IV: velocity saturation




(Courtesy, Shuji Ikeda, ATDF, Dec. 2007)

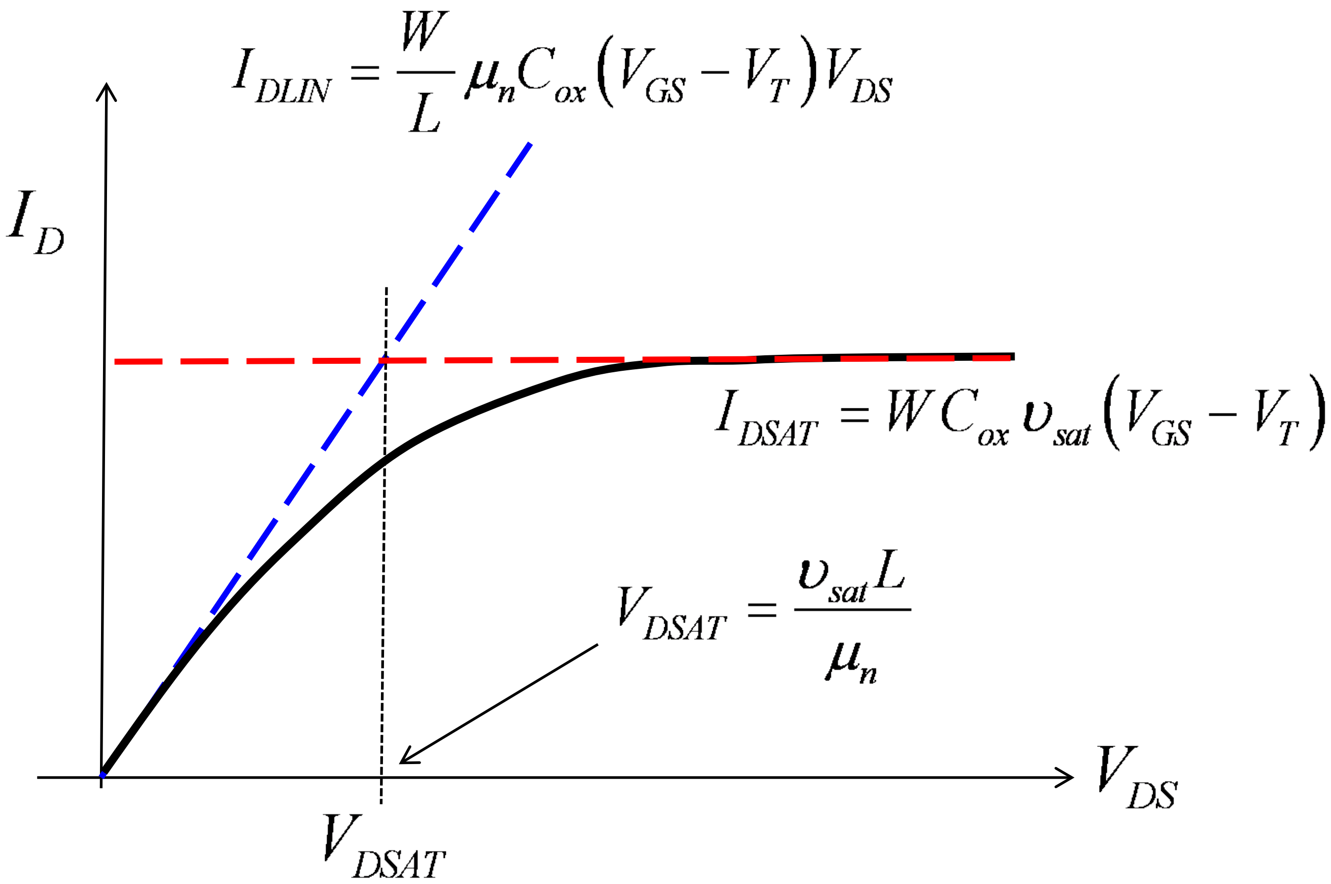
$$I_{DS} = -W\, Q_n(x) \langle \upsilon_x(x) \rangle$$

$$Q_n = -C_{ox}\left(V_{GS} - V_T\right)$$

$$\langle \upsilon_x \rangle = \upsilon_{sat}$$

$$I_{DS} = W\, C_{ox}\, \upsilon_{sat}\left(V_{GS} - V_T\right)$$ ✓

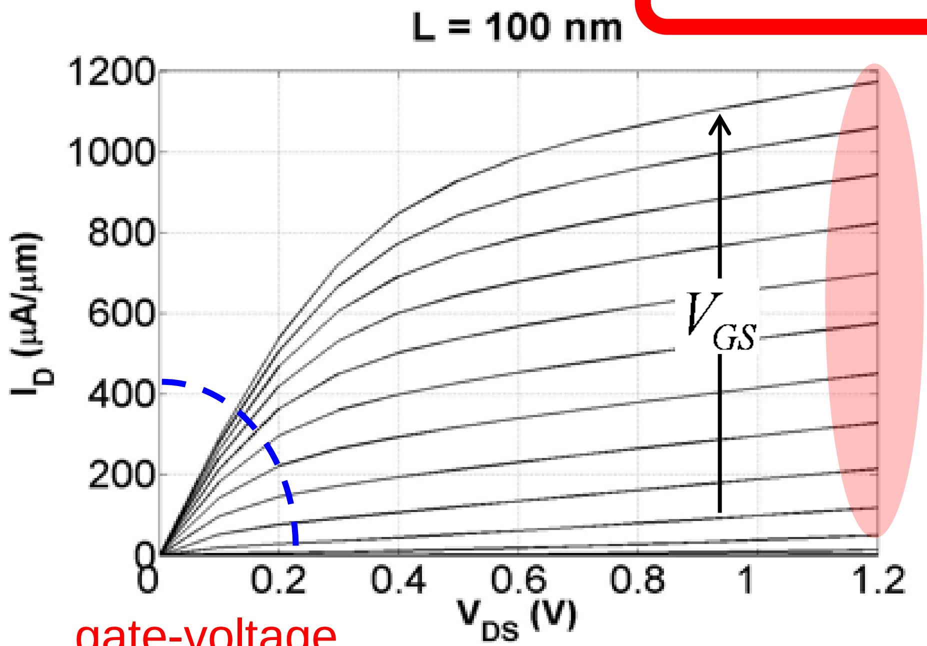
# MOSFET: IV (re-cap)




We have developed a 2-piece approximation to the MOSFET IV characteristic.

# MOSFET IV

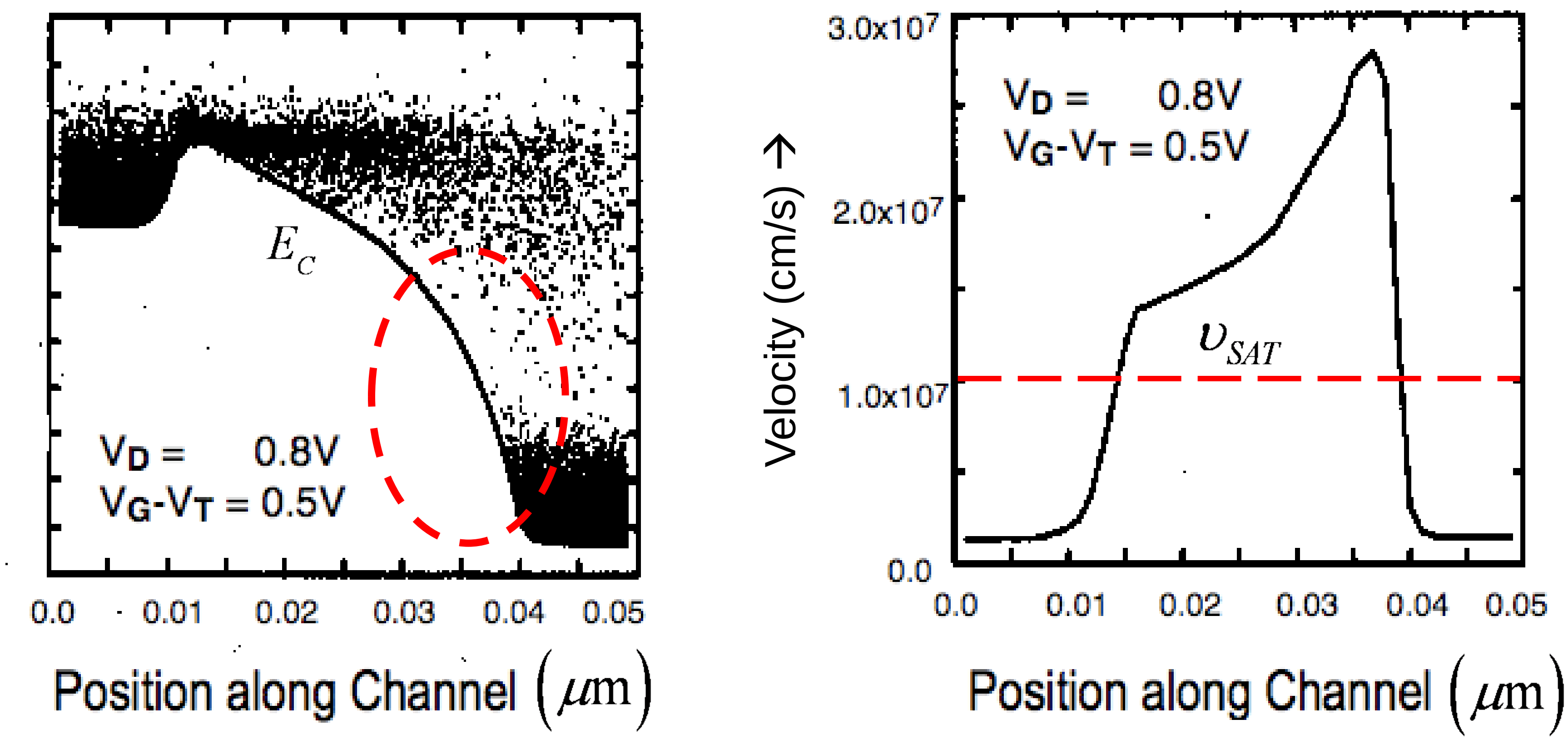
$$I_D = W C_{ox} \upsilon_{sat} \left(V_{GS} - V_T\right)$$




gate-voltage
controlled resistor

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

# “Velocity overshoot”




D. Frank, S. Laux, and M. Fischetti, Int. Electron Dev. Mtg., Dec., 1992.

# Summary

Surprisingly, our simple, traditional model seems to work pretty well  - even though it is clearly based on erroneous physics.

One goal of this course, is to explain why this is the case.

**Next up:**  Extend the two-piece model into a full model for the IV characteristics.