Essentials of MOSFETs

Unit 2: Essential Physics of the MOSFET

Lecture 2.6: Unit 2 Recap

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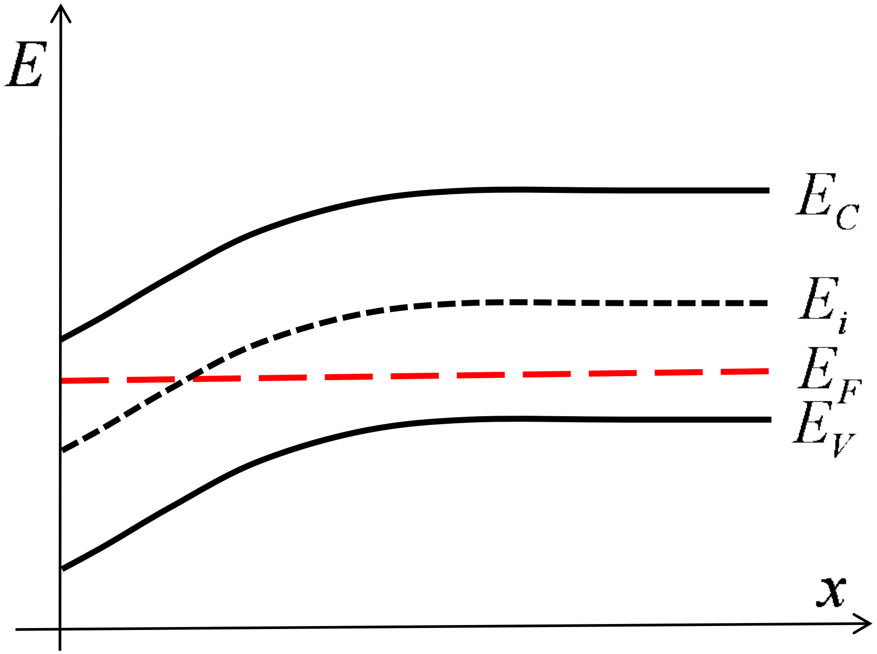
Unit 2

Review of energy band diagrams

Draw the band diagram



$$\frac{d\mathcal{E}}{dx} = \frac{\rho(x)}{K_S \varepsilon_0}$$

Read the band diagram

$$V(x) \propto -E_C(x)$$

$$\mathcal{E} \propto dE_C(x)/dx$$

$$\log n(x) \propto E_F - E_i(x)$$

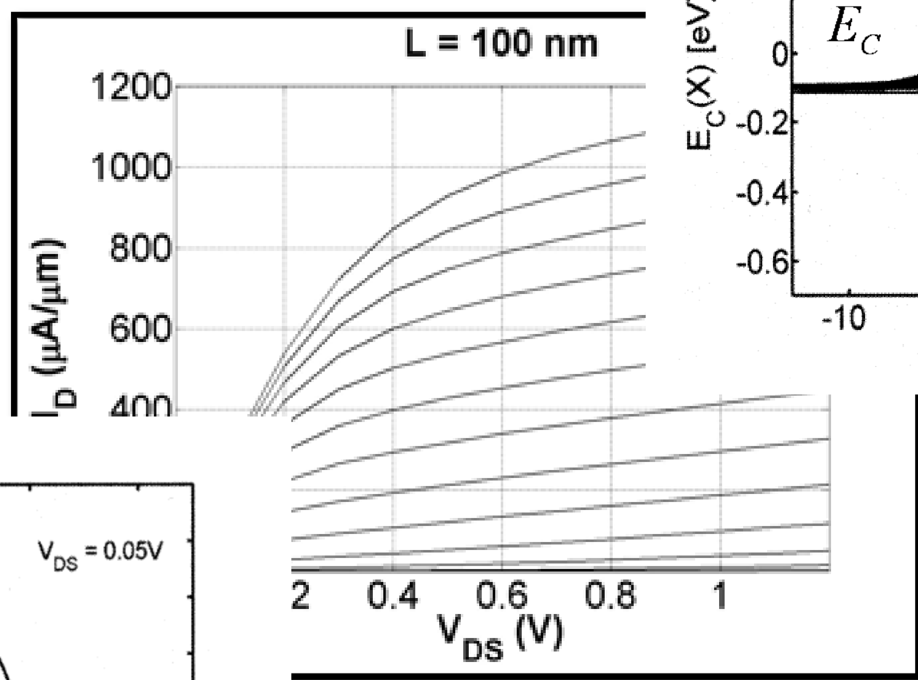
$$\log p(x) \propto E_i(x) - E_F$$

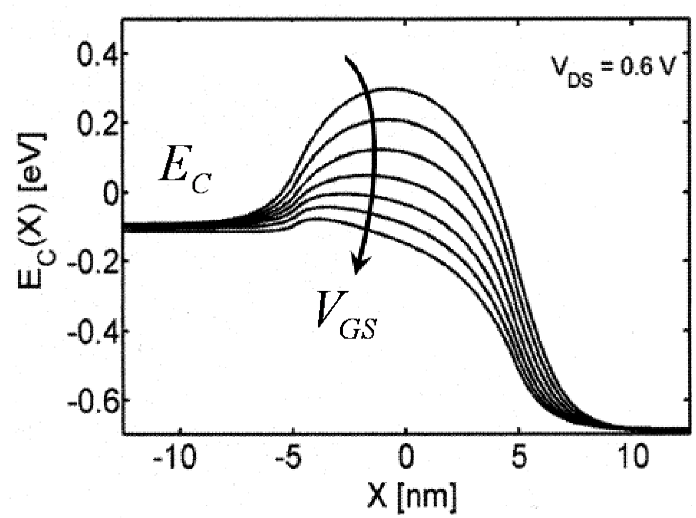
$$\rho(x) \propto \left(p - n + N_D - N_A\right)$$

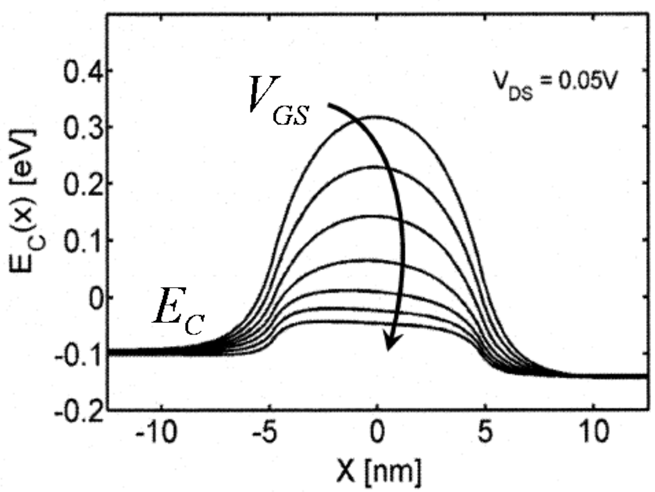
Lundstrom: 2018

How transistors work

2007 N-MOSFET



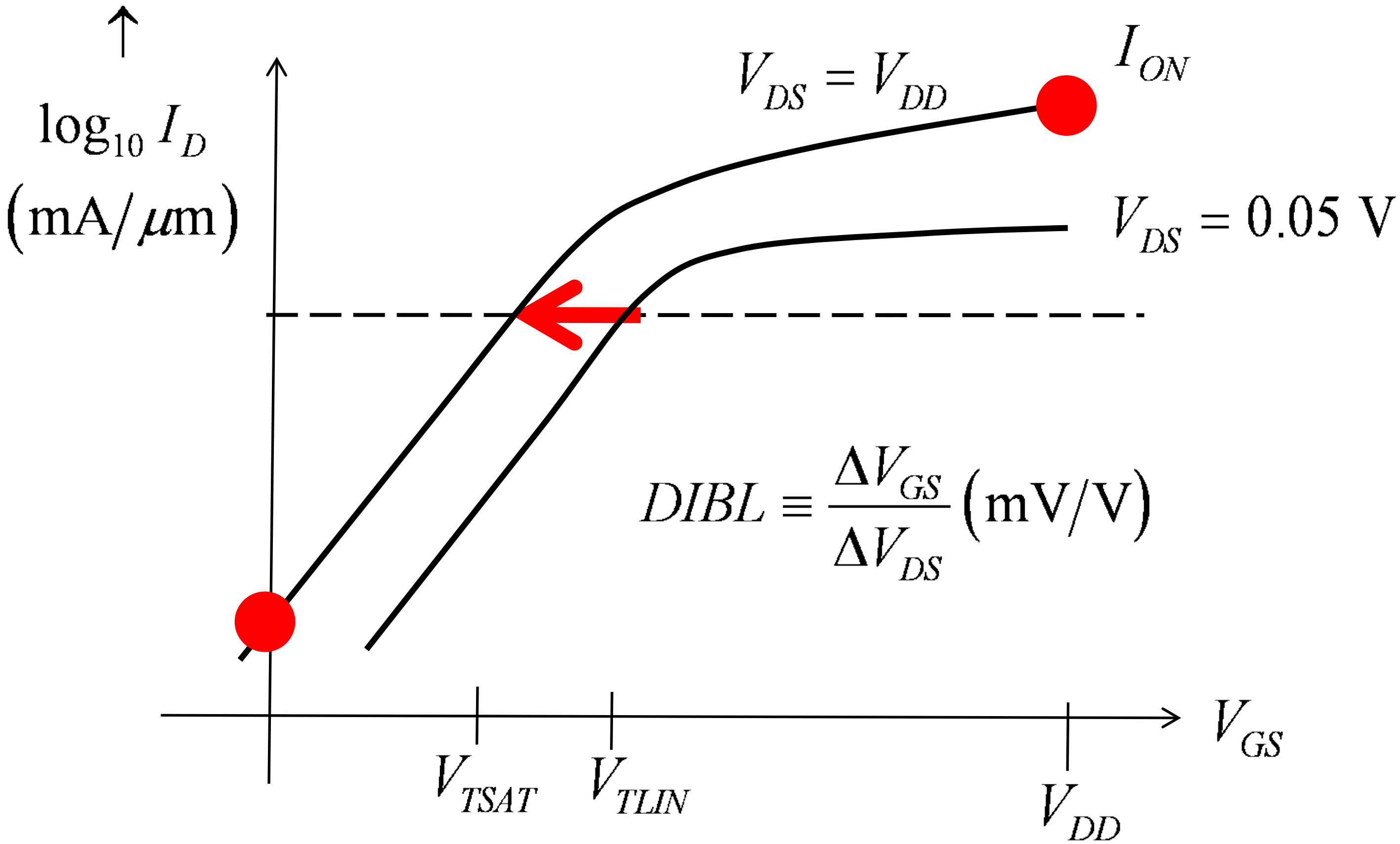




tesy, Shuji Ikeda, ATDF, Dec. 2007)

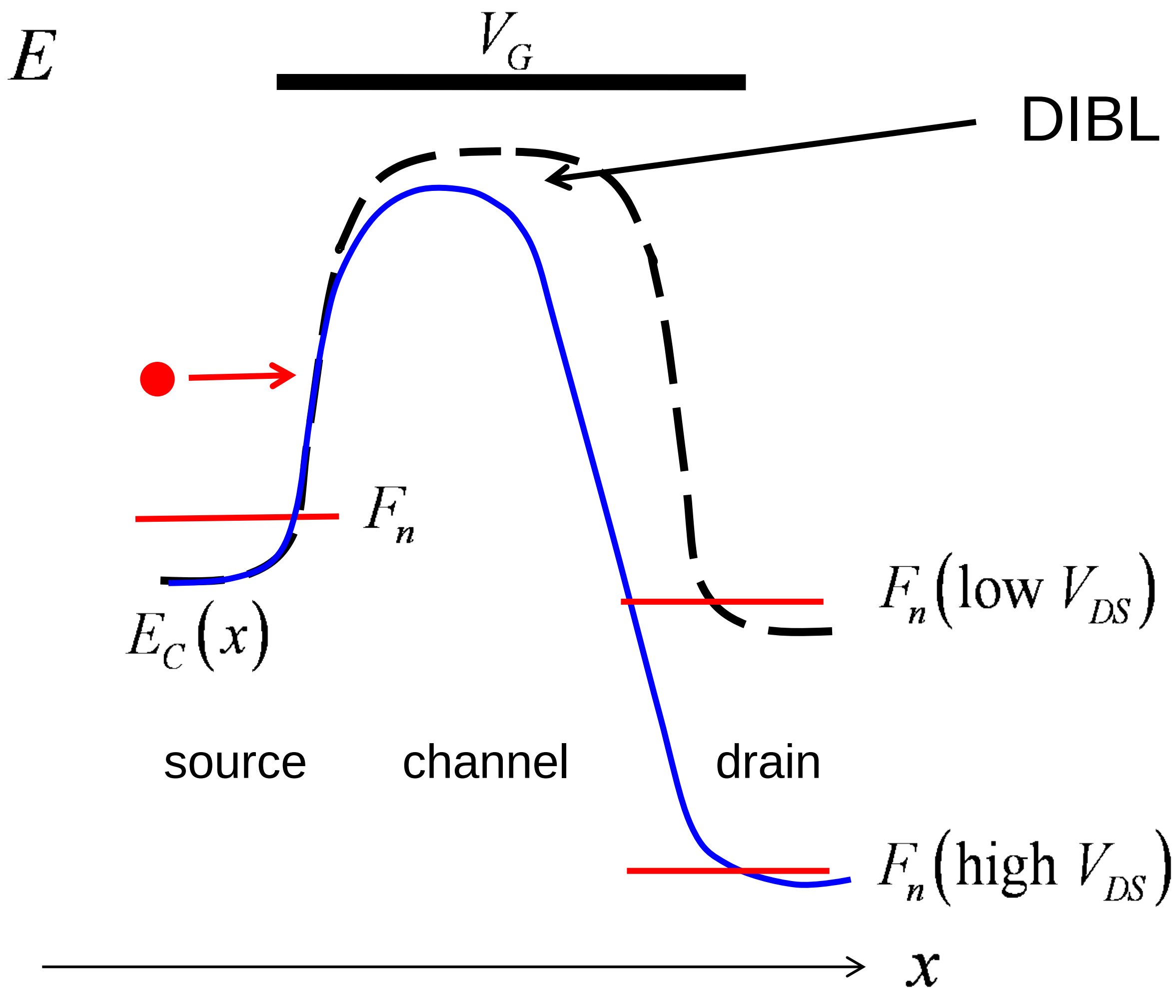
DIBL

transfer characteristics:

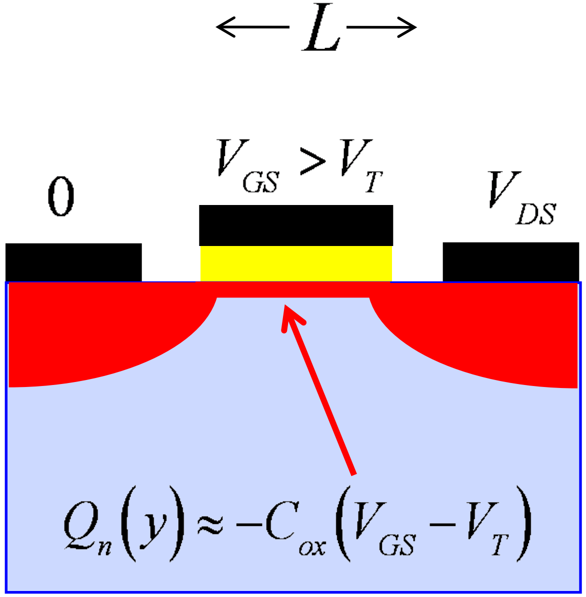


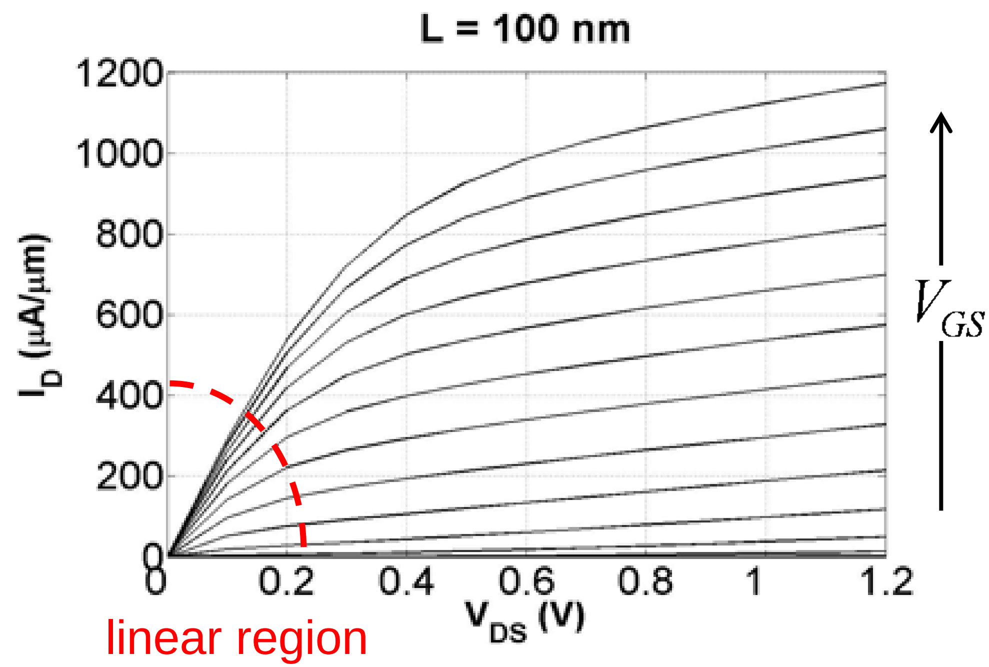
Lundstrom: 2018

Understanding DIBL with an e-band diagram



MOSFET IV: Low V_{DS} (linear region)





$$I_D = W\left|Q_n(x)\right|\langle \upsilon_x(x)\rangle$$

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

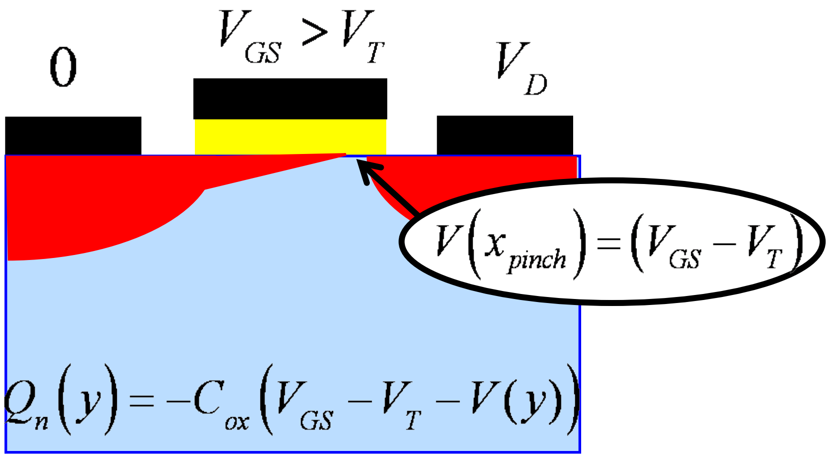
$$\langle \upsilon_x \rangle = -\mu_n \mathcal{E}_x$$

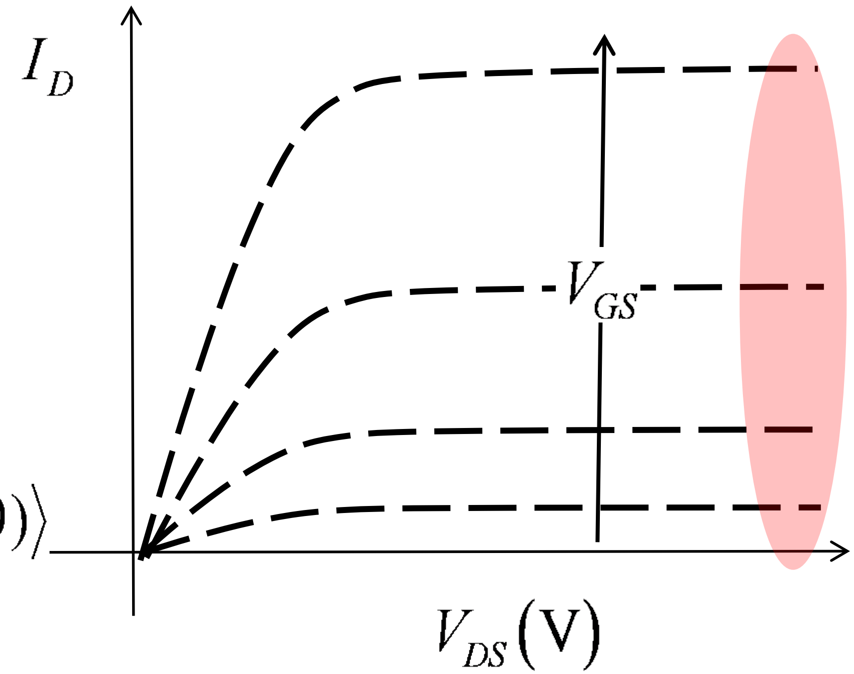
$$\mathcal{E}_x = -V_{DS}/L$$

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

✓

MOSFET IV: High V_{DS} (beyond pinch-off)





$$I_D = W\left|Q_n(x)\right|\langle \upsilon_x(x)\rangle = W\left|Q_n(0)\right|\langle \upsilon_x(0)\rangle$$

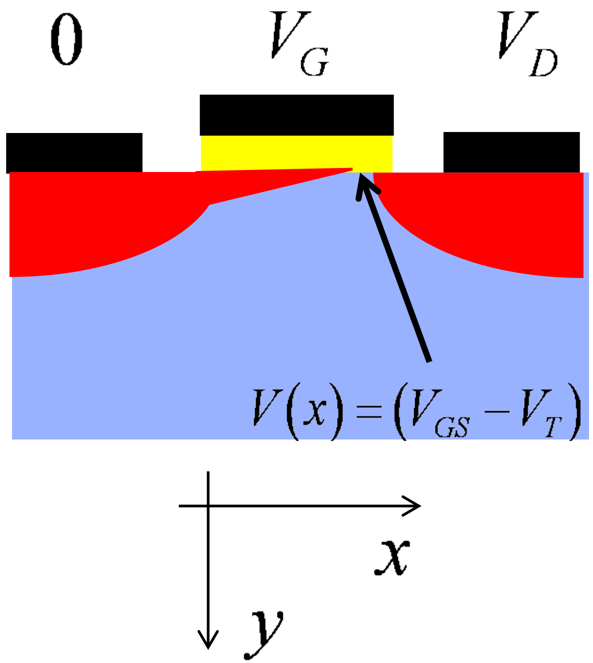
$$Q_n(0) = -C_{ox}\left(V_{GS} - V_T\right)$$

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

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

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

Complete IV characteristic



$$V_{GS} > V_T$$

$$V_{DS} < V_{GS} - V_T$$

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

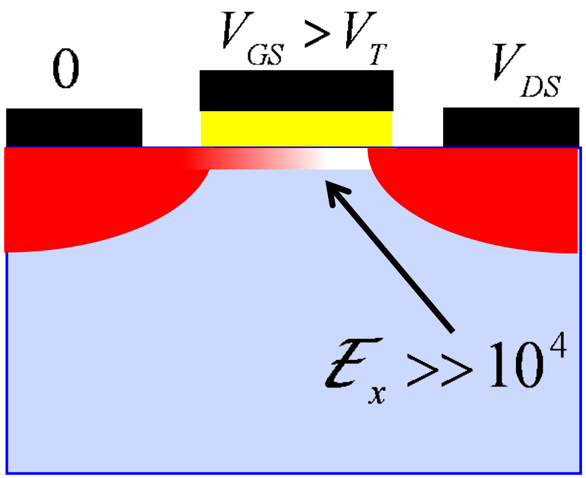
$$V_{GS} > V_T$$

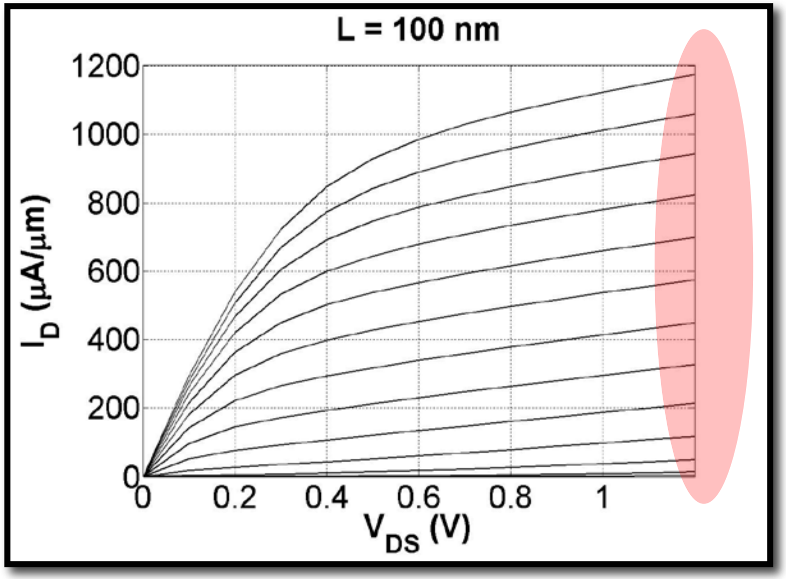
$$V_{DS} > V_{GS} - V_T$$

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

Lundstrom: 2018

MOSFET IV: High V_{DS} (velocity saturation)





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

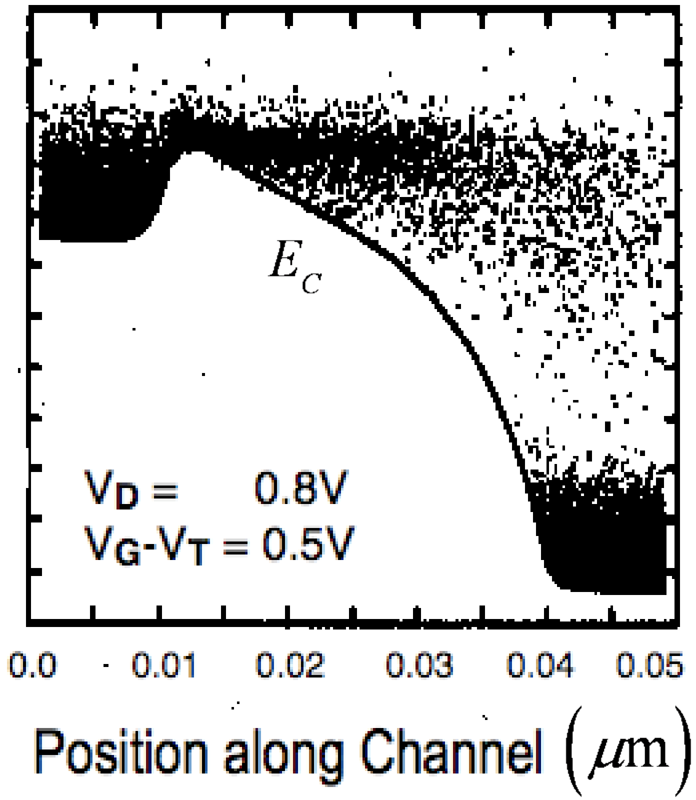
$$I_D = W\left|Q_n(x)\right|\left\langle \upsilon_y(x)\right\rangle$$

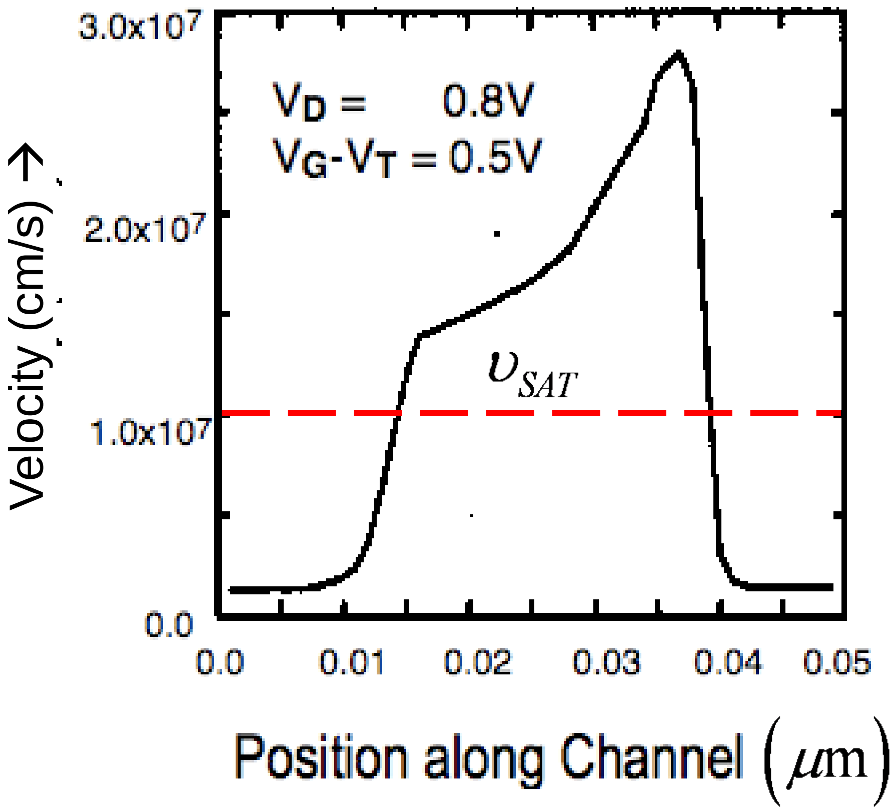
$$Q_n = -C_{ox}\left(V_{GS} - V_T\right)$$

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

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

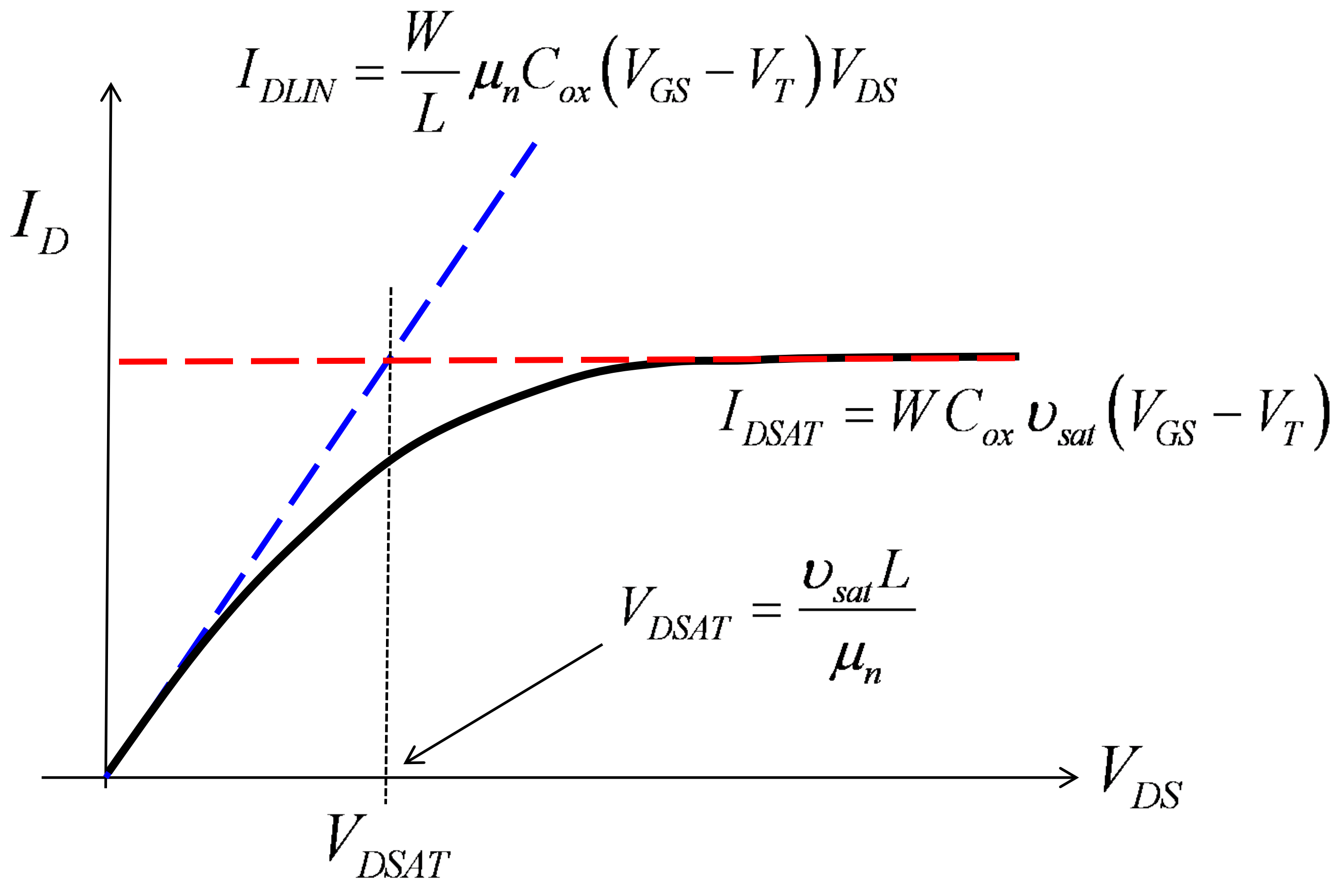
Velocity overshoot





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

From two-piece to continuous model



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

Simple (Level 0) VS model

1) $I_D/W = \left|Q_n\left(V'_{GS}\right)\right|\left\langle \upsilon\left(V'_{DS}\right)\right\rangle$

2) $Q_n\left(V'_{GS}\right) = -C_{ox}\left(V'_{GS} - V_T\right) \qquad \left(V'_{GS} > V_T\right)$

$V_T = V_{T0} - \delta V'_{DS}$

3) $\left\langle \upsilon\left(V'_{DS}\right)\right\rangle = F_{SAT}\left(V'_{DS}\right)\upsilon_{sat}$

4) $F_{SAT}\left(V'_{DS}\right) = \dfrac{V'_{DS}/V_{DSAT}}{\left[1+\left(V'_{DS}/V_{DSAT}\right)^{\beta}\right]^{1/\beta}}$

5) $V_{DSAT} = \dfrac{\upsilon_{sat} L}{\mu_n}$

There are only 8 device-specific parameters in this model:

$$C_{ox}, V_{T0}, \delta, \upsilon_{sat}, \mu_n, L$$

$$R_{SD} = R_S + R_D$$

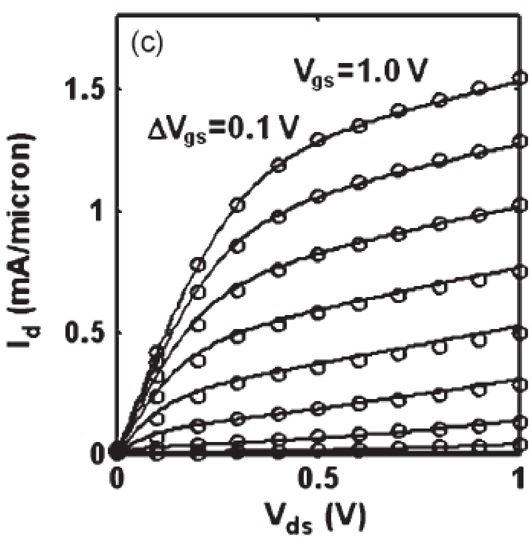
$$+ \quad \beta$$

The MIT VS Model

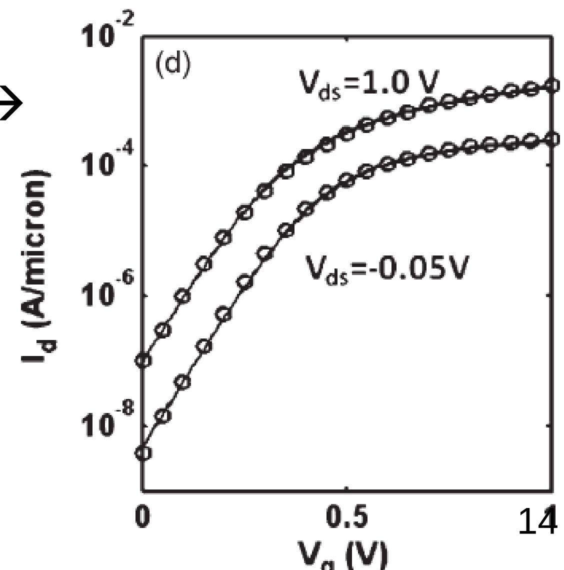
1674 IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 56, NO. 8, AUGUST 2009

A Simple Semiempirical Short-Channel MOSFET Current–Voltage Model Continuous Across All Regions of Operation and Employing Only Physical Parameters

Ali Khakifirooz, *Member, IEEE*, Osama M. Nayfeh, *Member, IEEE*, and Dimitri Antoniadis, *Fellow, IEEE*



← 32 nm technology →



The MIT VS Model

In this course, we will show that the mobility and high-field saturation velocity should be re-interpreted:

$$\frac{1}{\mu_n} \rightarrow \frac{1}{\mu_{app}}$$ "apparent mobility"

$$\upsilon_{sat} \rightarrow \upsilon_{inj}$$ "injection velocity"

We will show that these two parameters have clear, well-defined physical interpretations.

https://nanohub.org/resources/21703

Unit 3

Before we discuss carrier transport in nanoscale MOSFETs (e.g. mobility and saturation velocity), we will examine the important topic of **MOS electrostatics**.

MOS electrostatics describe the influence of the terminal voltages on the energy barrier between the source and drain.

Properly designed MOSFETs have “electrostatic integrity”:

$$Q_n(x=0) \approx -C_{ox}\left(V_{GS}-V_T\right) \quad \mathrm{C/cm^2}$$