Spring 2019 Purdue University

ECE 255: L13

MOSFETs

(Sedra and Smith, 7^{th} Ed., Sec. 5.1)

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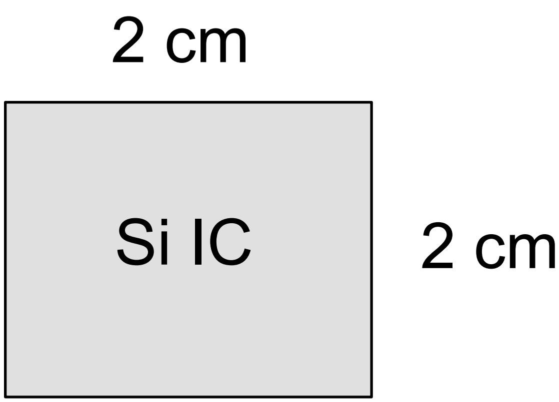
West Lafayette, IN USA

Quiz



How many kilometers of wire are there in a modern Si chip?

$1 \text{ km} = 10^5 \text{ cm}$

a) 2×10^{-5}
b) 10×10^{-5}
c) 4×10^{-2}
d) 2×10^{-1}
e) 3

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Company Information Session

Monday, February 11th
7:00 - 8:00 PM
MJIS 1001
Presentation followed by Q&A

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Visit our booth at the Professional Practice Career Fair

Tuesday February 19, 10 AM-3 PM, in PMU Ballrooms

Mon 2/18 Information Sessions HCRS 1076

8:30am Fulbright U.S. Student Program Overview

11:30am Fulbright U.S. Student Program Overview

Mon 2/18 Fulbright Program Mixer Duhme Hall Atrium

6:00pm Join us for food and drink with Purdue Fulbright alumni to hear about their experiences in the program.

Tues 2/19 Information Sessions HCRS 1066

3:30pm Research & Study Grants – guidance for graduate students

4:15pm 2020-21 English Teaching Assistant Grants

5:00pm 2020-21 Research and Study Grants

Wed 2/20 Information Sessions HCRS 1066

5:00pm 2020-21 Research and Study Grants

5:45pm 2020-21 English Teaching Assistant Grants

6:30pm Research & Study Grants – guidance for graduate students

Thurs 2/21 Information Sessions HCRS 1066

5:00pm 2020-21 English Teaching Assistant Grants

5:45pm 2020-21 Research and Study Grants

FULBRIGHT

FULBRIGHT U.S. STUDENT PROGRAM

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Juniors begin applications now for a Fulbright U.S. Student Program grant after graduation in one of 140+ countries. Seniors look ahead a year to 2020-21. Graduate students conduct thesis/ dissertation research abroad. Freshmen and sophomores explore options.

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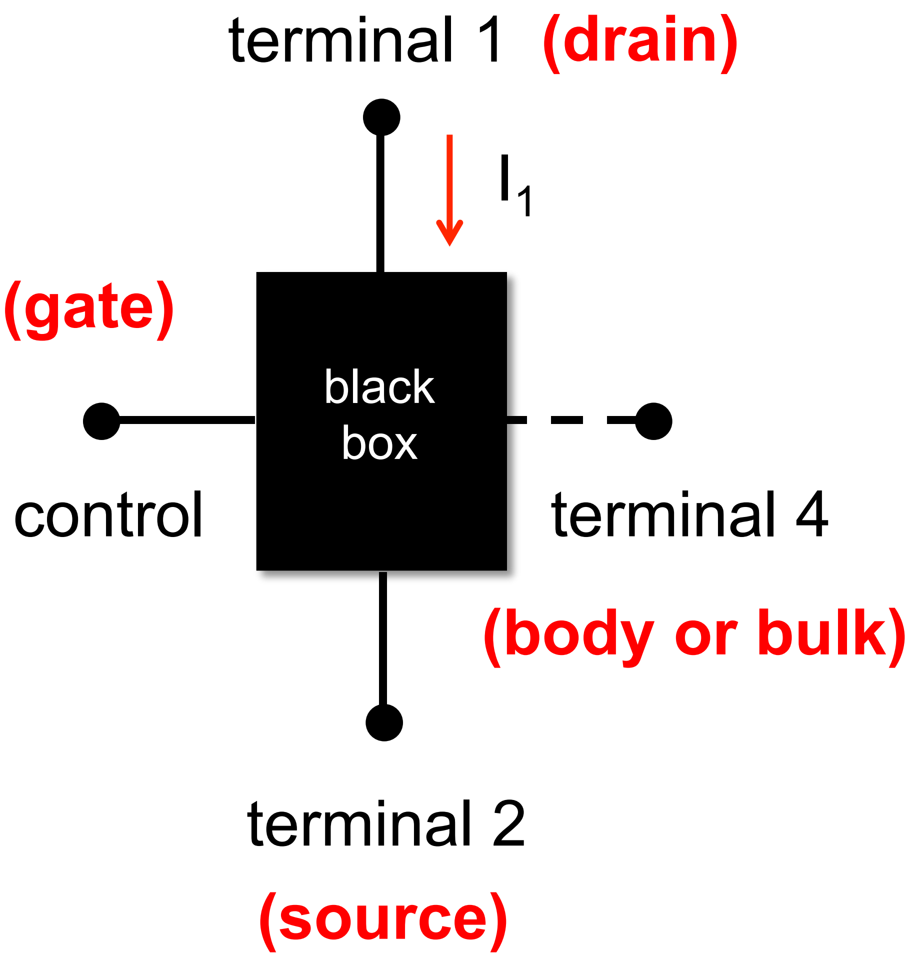
MOSFETs

1) Physical structure
2) IV characteristics (descriptive)
3) IV characteristics (energy band approach)
4) IV characteristics (mathematical model)

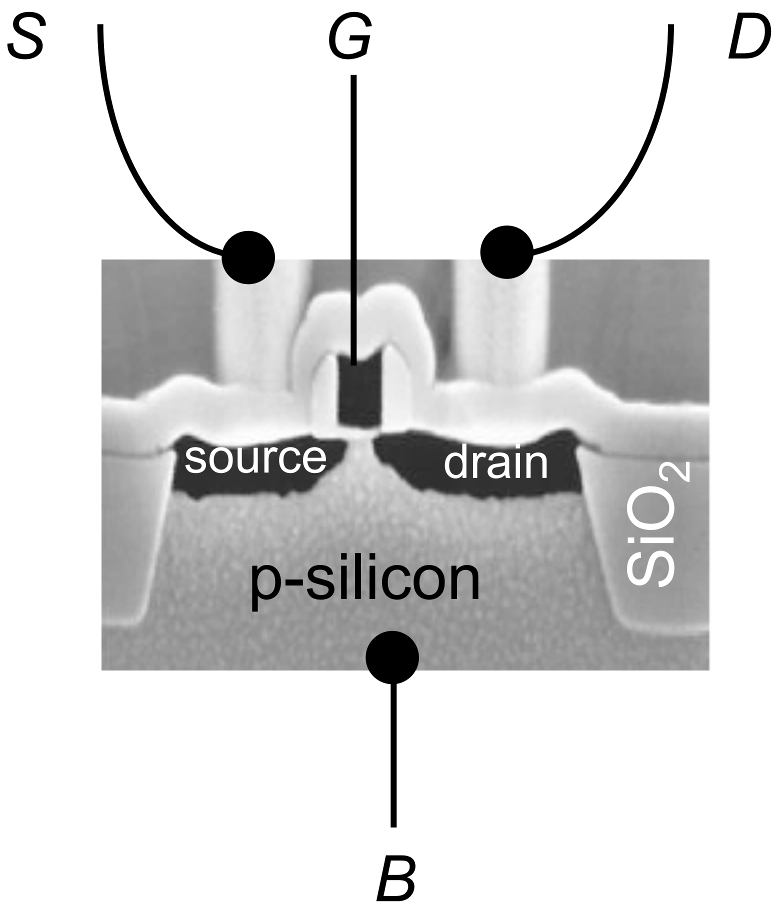
Transistor as a "black box"

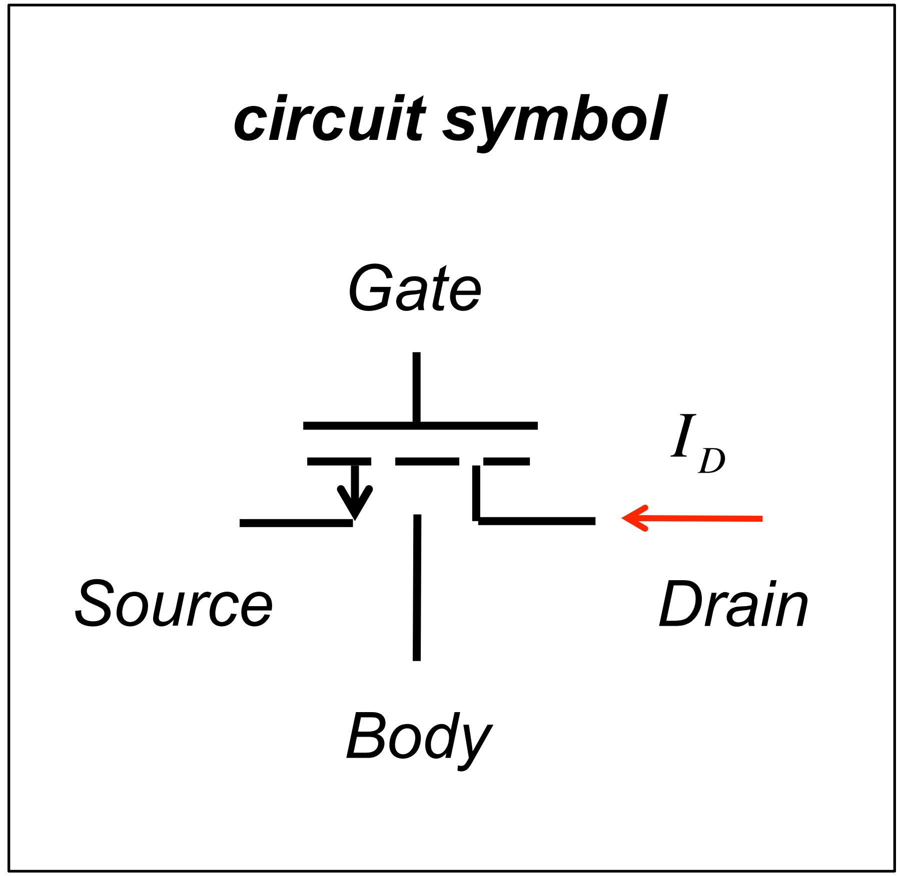


A small current (or voltage) on the control terminal controls a much larger current through two other terminals.

Current control: BJT
Voltage control: MOSFET

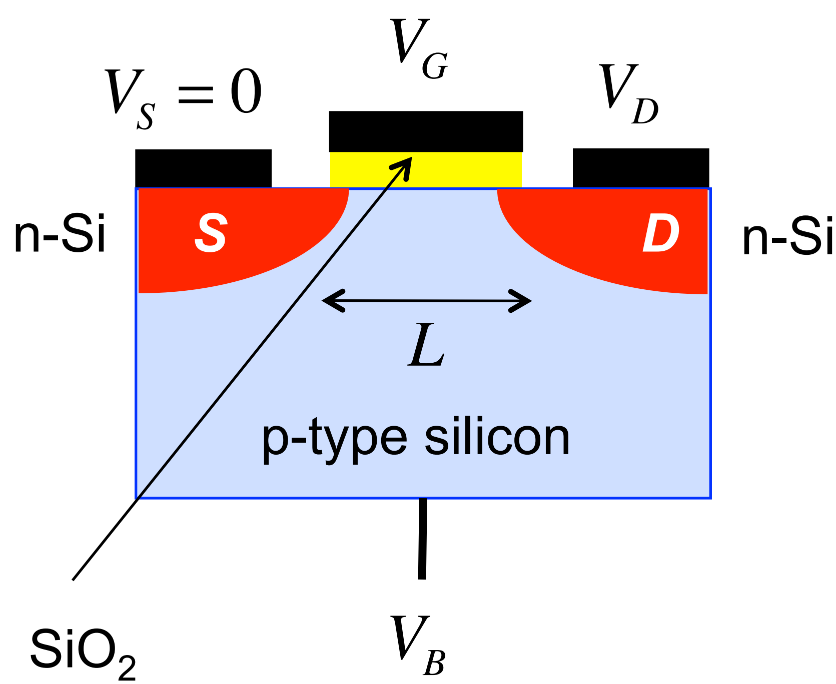
Physical structure



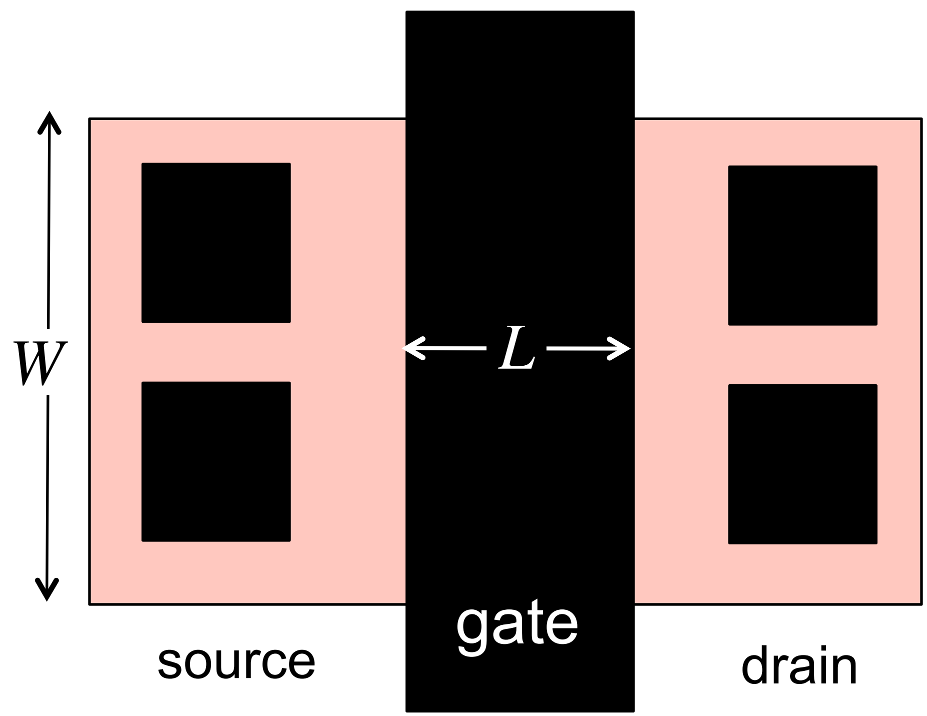


Side and top views of an n-channel MOSFET

Metal **O**xide **S**emiconductor **F**ield **E**ffect **T**ransistor



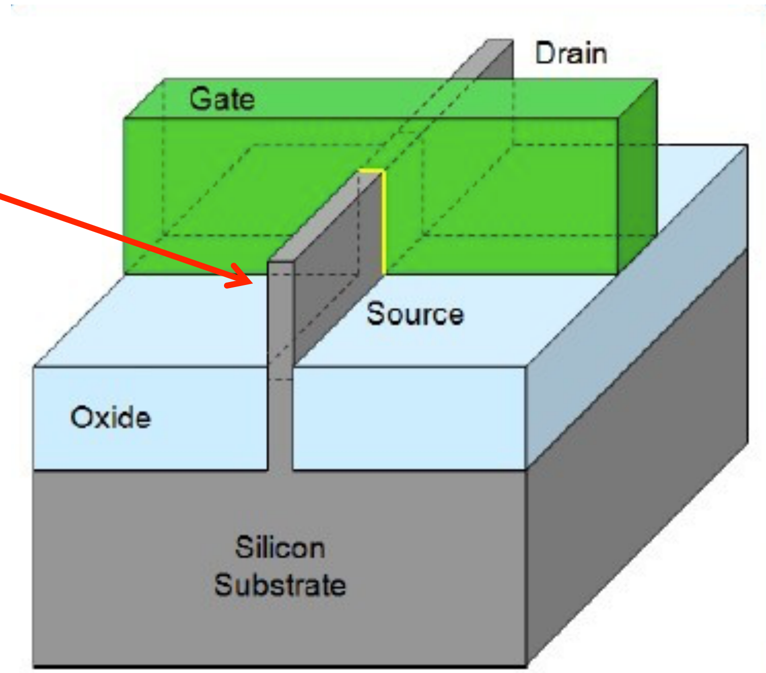
side view



top view

Modern MOSFETs: FinFETs

silicon fin

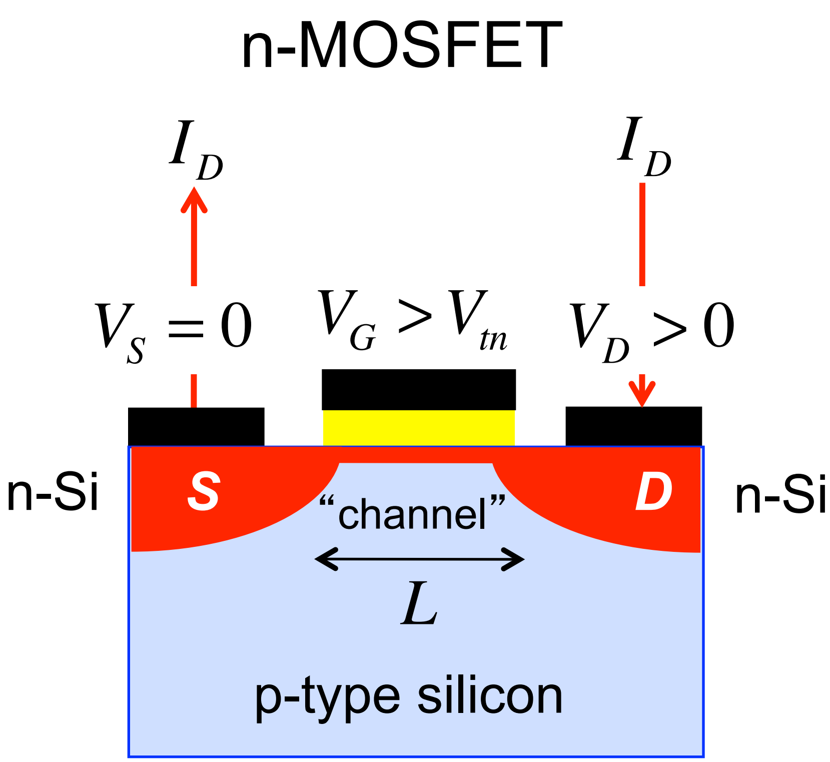


Source: Intel

SiO_2 → high k gate dielectrics

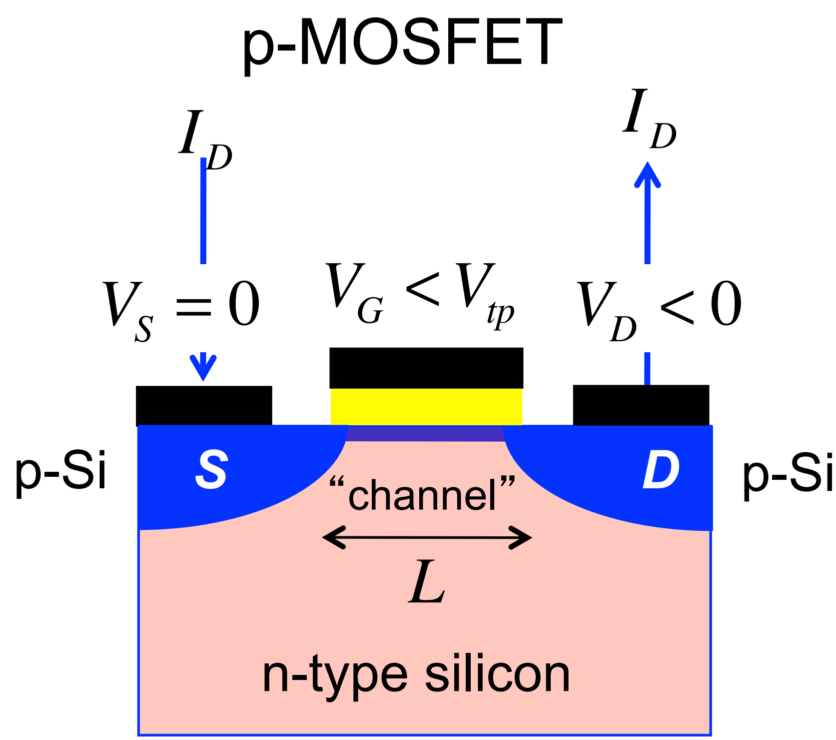
Digh Hisamoto, Wen-Chin Lee, Jakub Kedzierski, Hideki Takeuchi, Kazuya Asano, Charles Kuo, Erik Anderson, Tsu-Jae King, Jeffrey Bokor, Chenming Hu, "FinFET-a self-aligned double-gate MOSFET scalable to 20 nm," *IEEE Transactions on Electron Devices*, **47**, 2320-2325, 2000.

N-channel vs. P-channel MOSFET



side view

Current flows in the drain

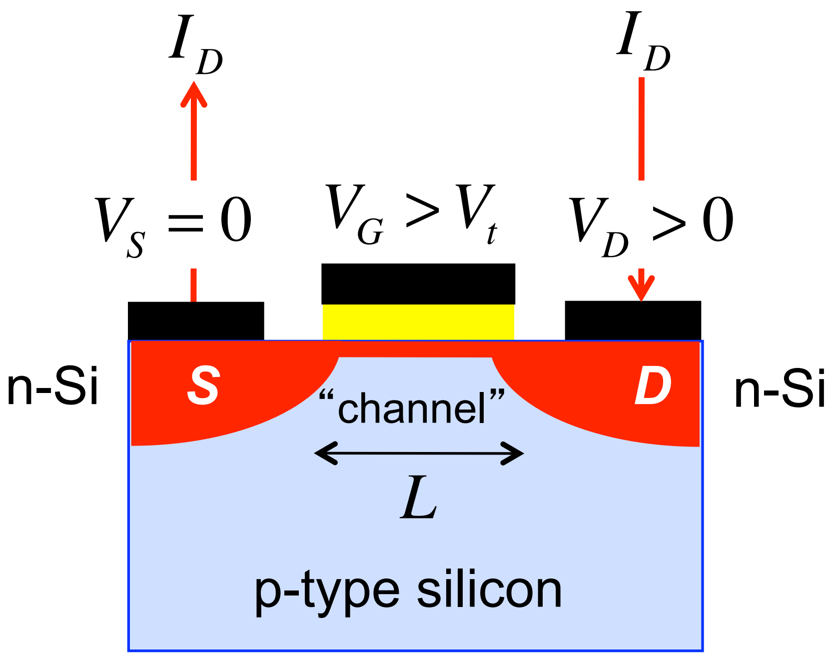


side view

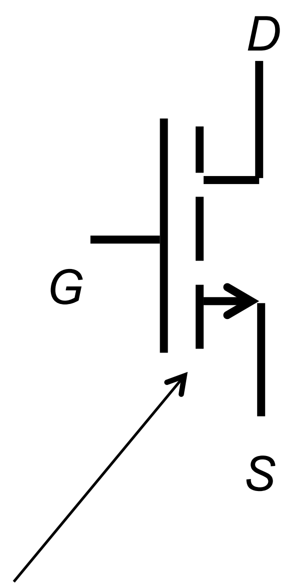
Current flows out the drain

N-channel MOSFET: circuit symbol

n-MOSFET

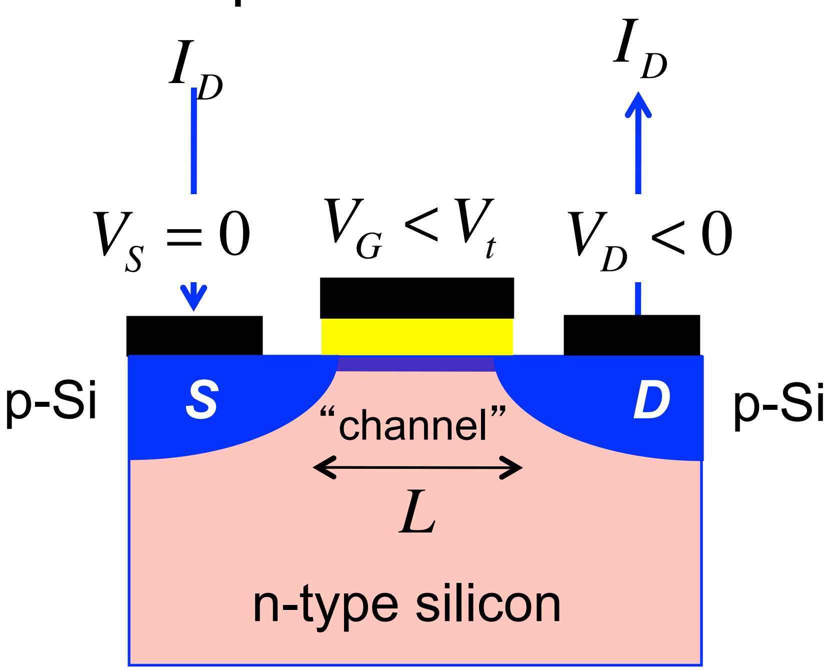


side view

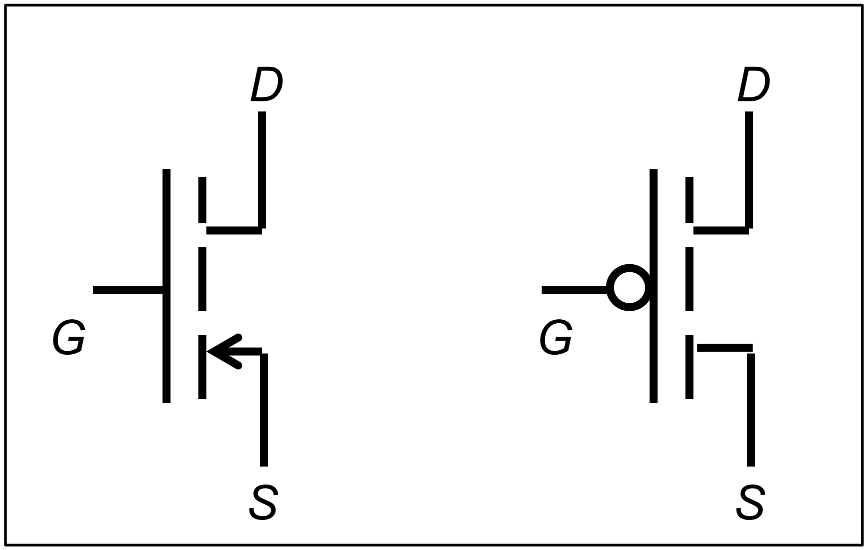


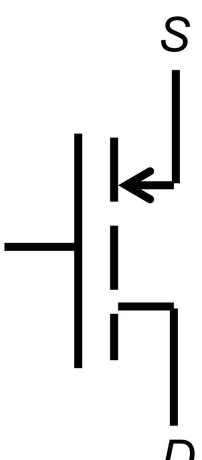
dashed line indicates an **enhancement mode** MOSFET.

p-channel MOSFET: circuit symbol

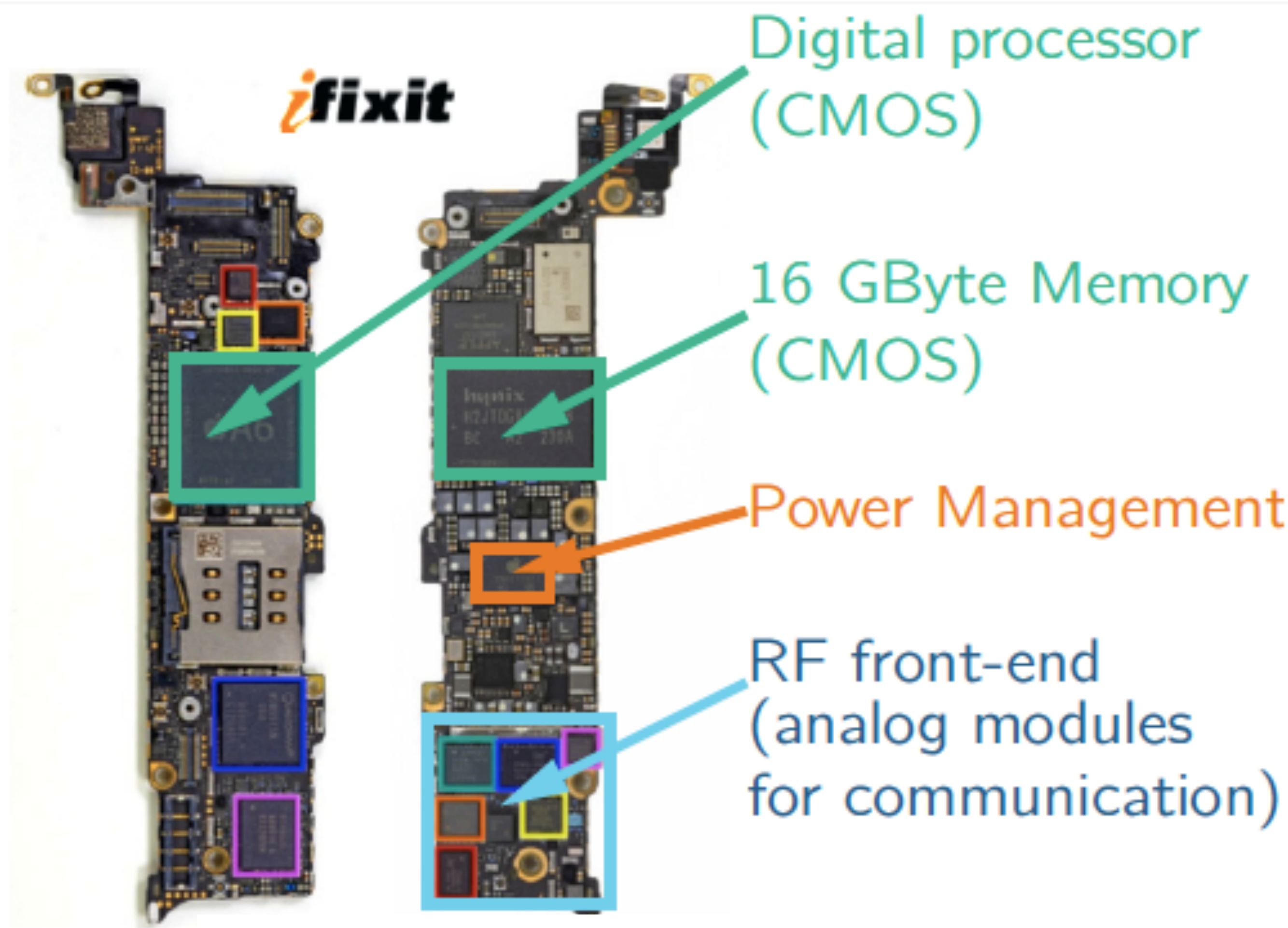


side view





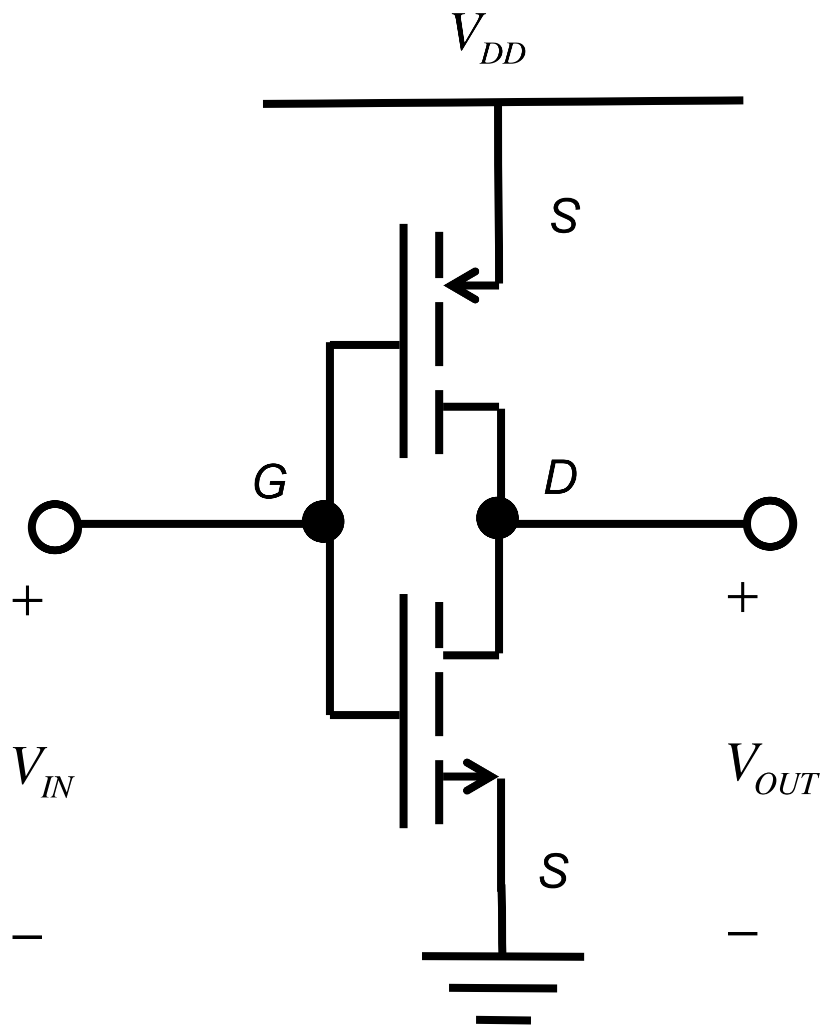
MOSFETs and BJTs



Circuit board of an iPhone 5

Lundstrom: 2019

CMOS digital technology



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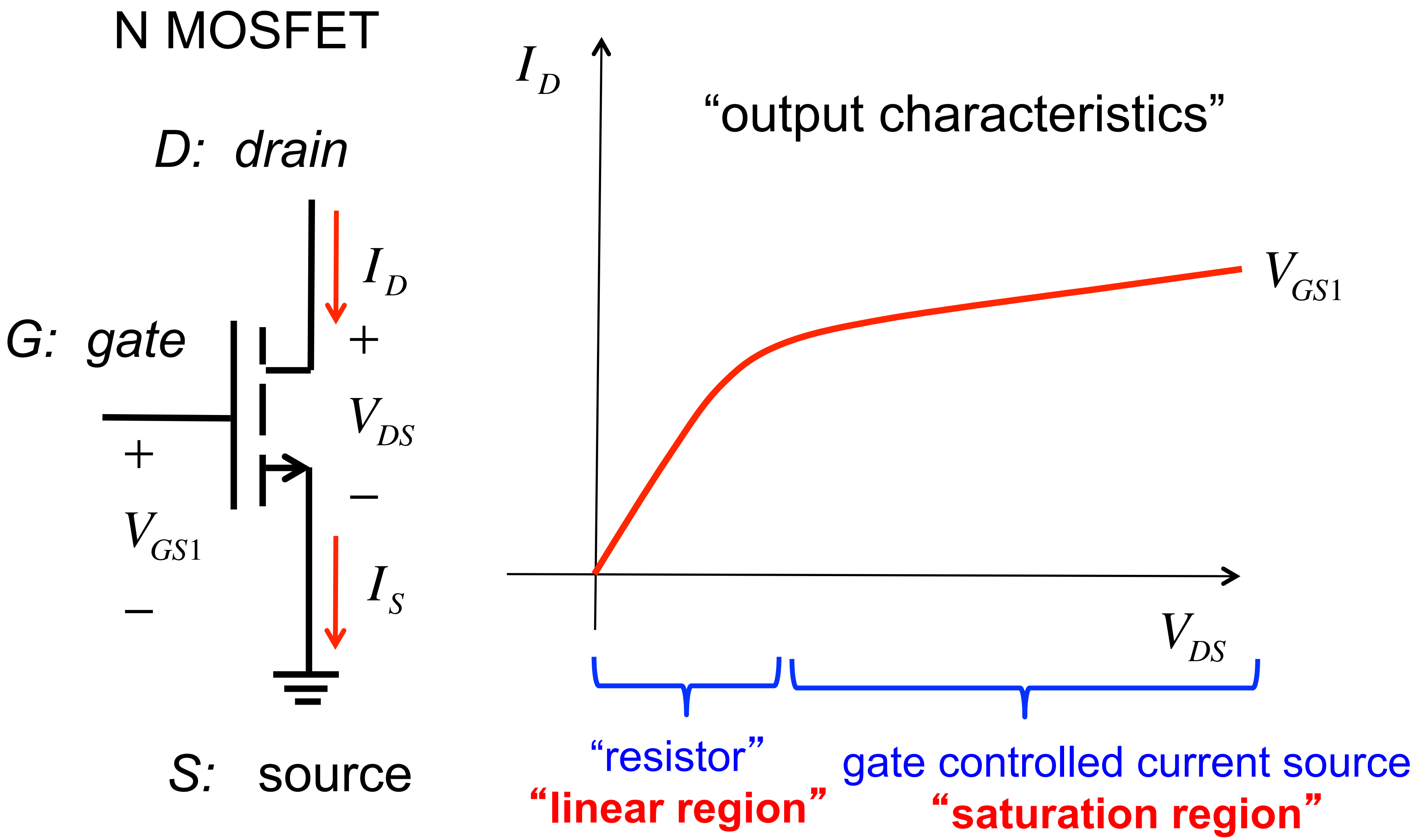
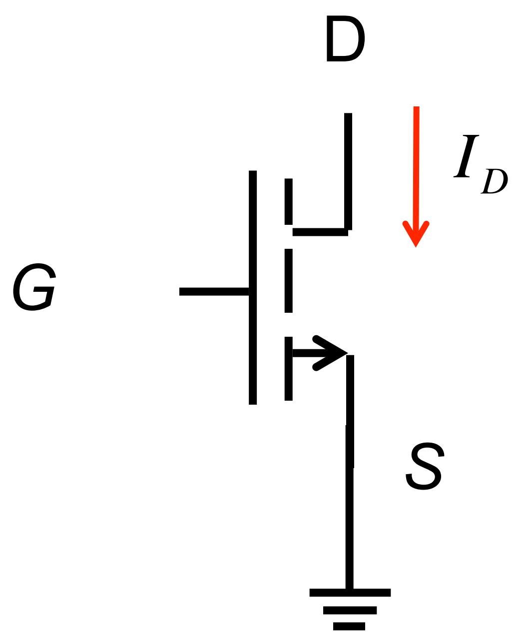
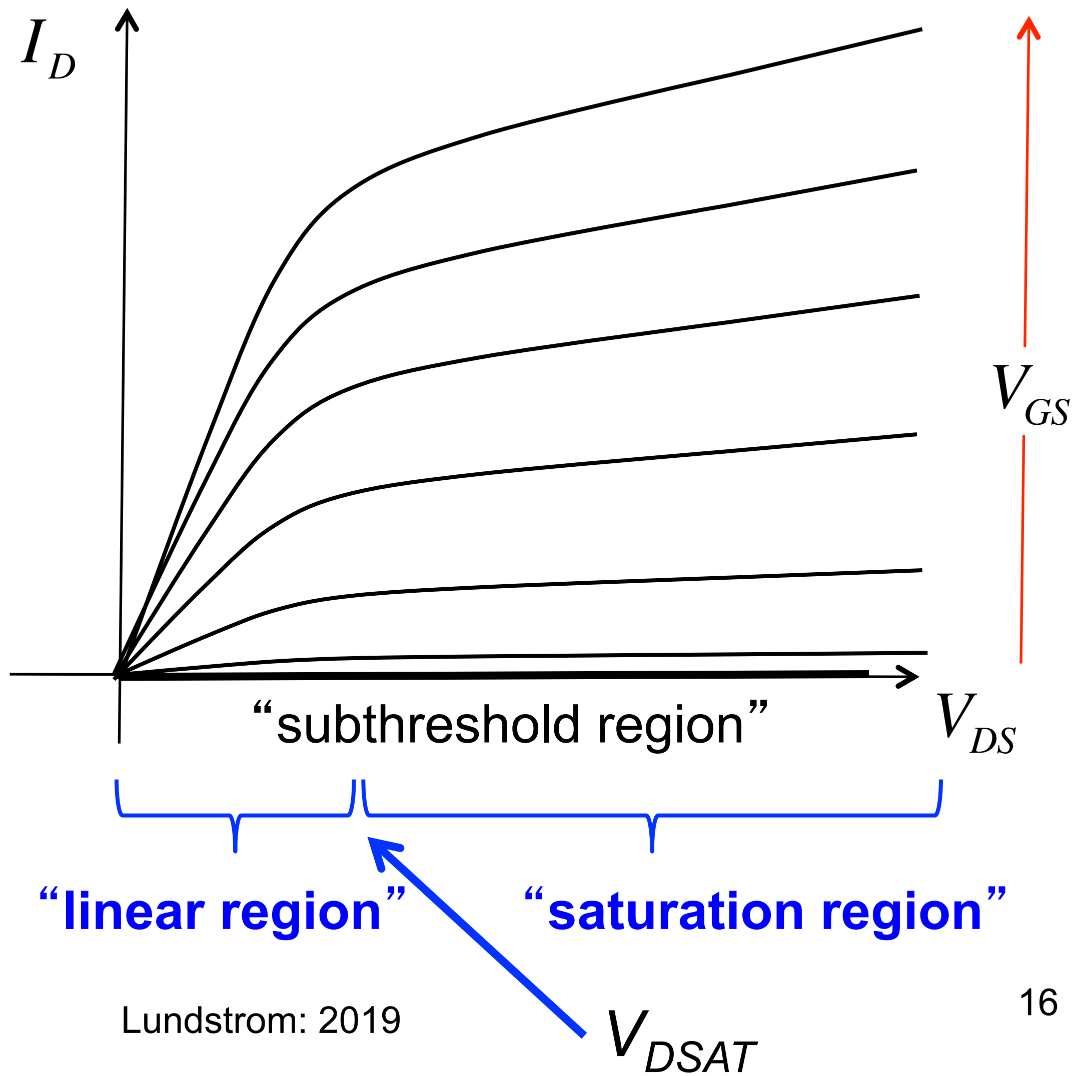
N-MOSFET IV characteristics



N-MOSFET output characteristics

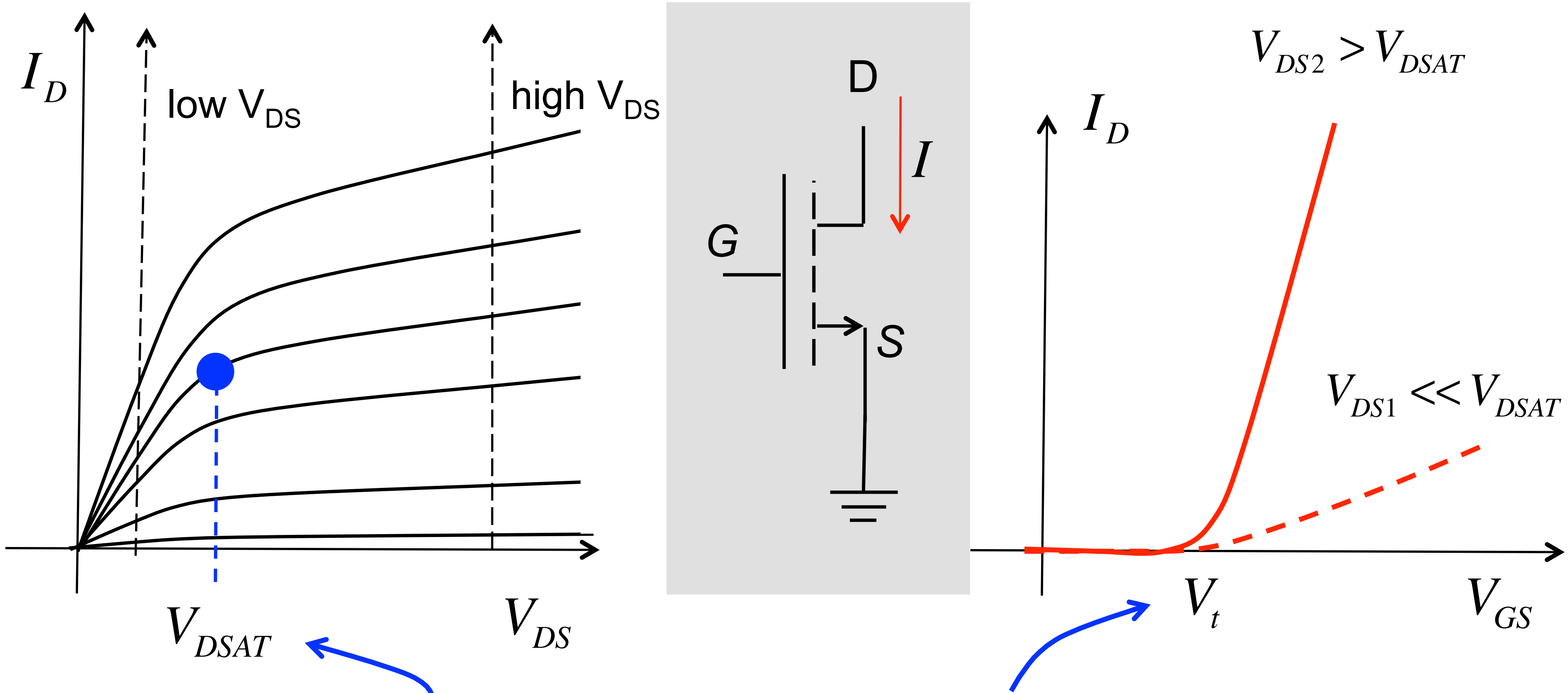


n-channel enhancement mode MOSFET



Output vs. transfer characteristics

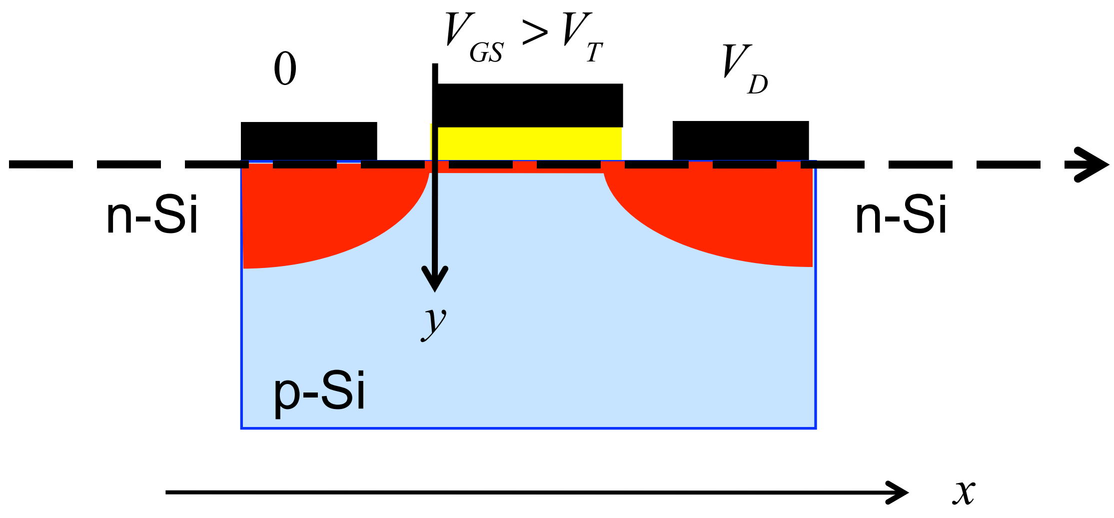
output characteristics ⟷ transfer characteristics



"saturation voltage"

"threshold voltage"

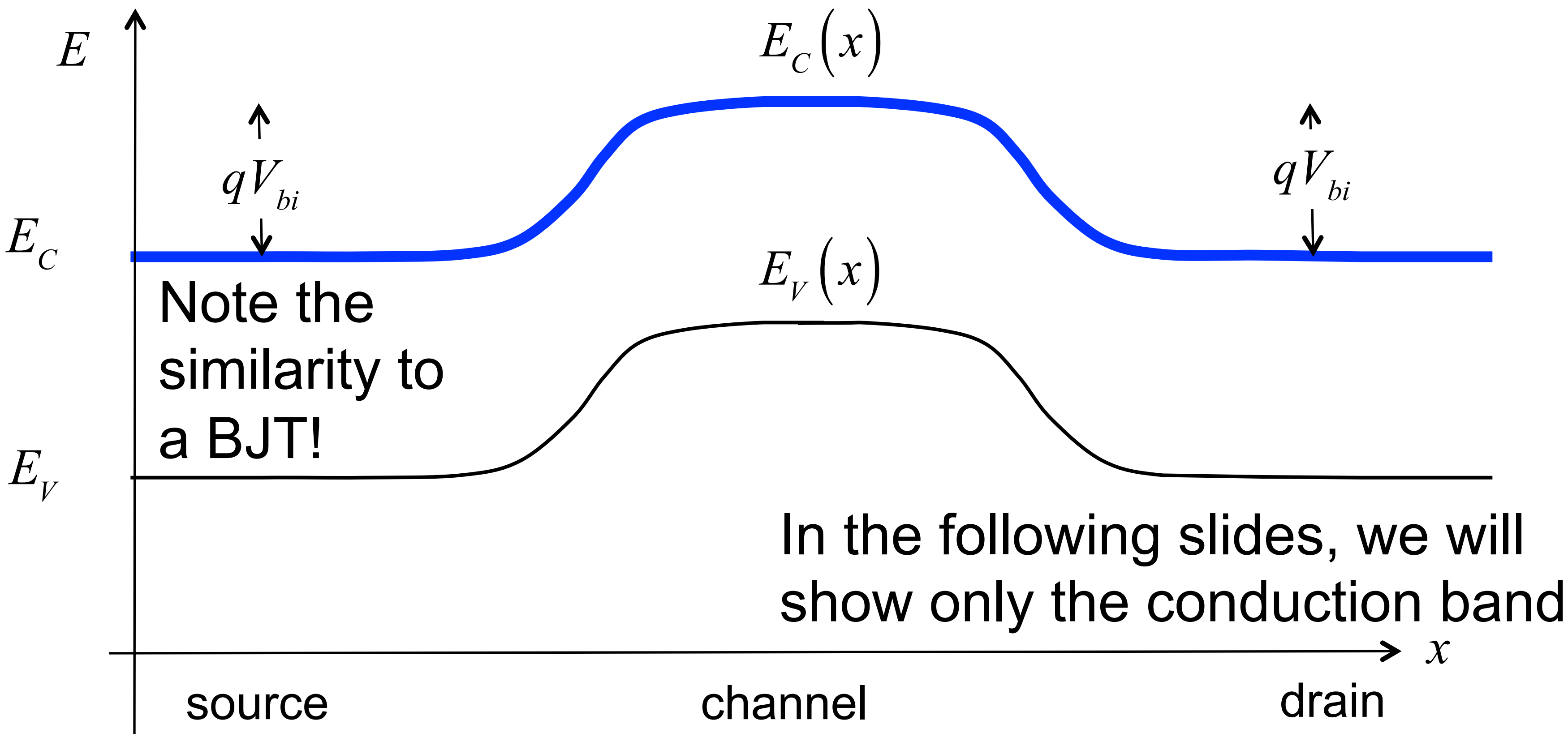
Energy band treatment of the MOSFET



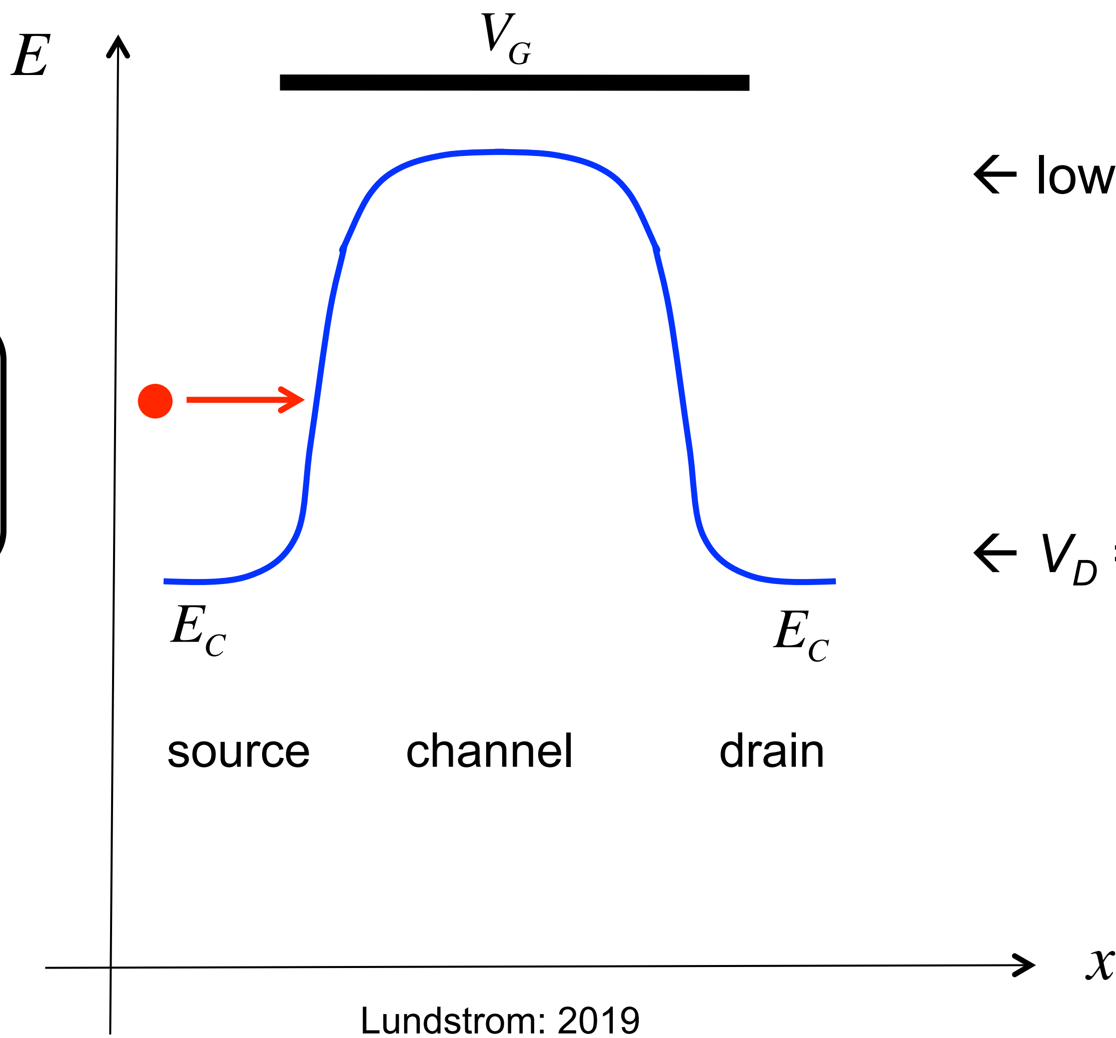
To understand this device, we should first draw an ***Energy Band Diagram*** *from the source, across the channel, and out the drain.*

Equilibrium energy band diagram

Now, what effect does a gate voltage have?



The MOSFET as a barrier controlled device



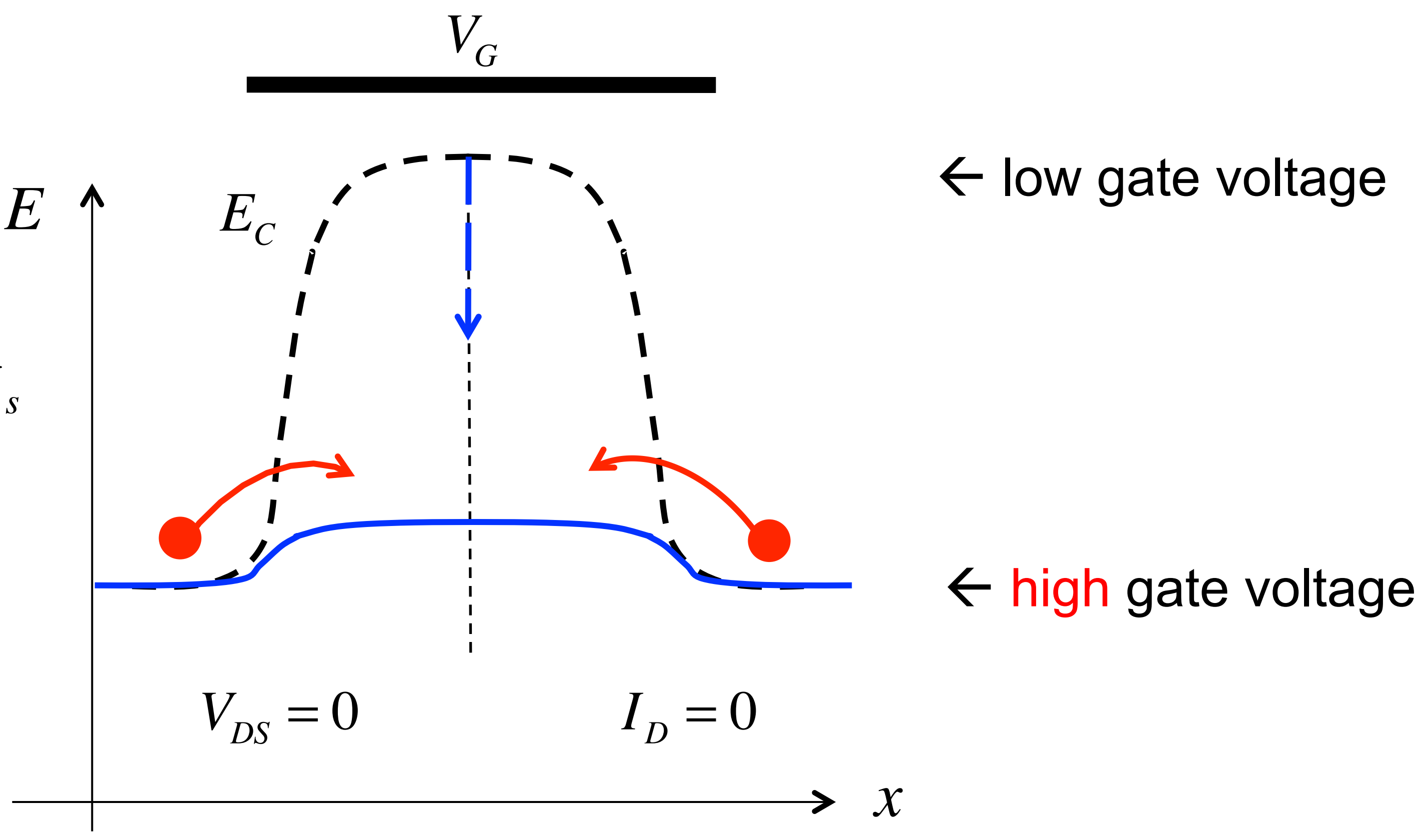
$$E = -qV$$

← low gate voltage

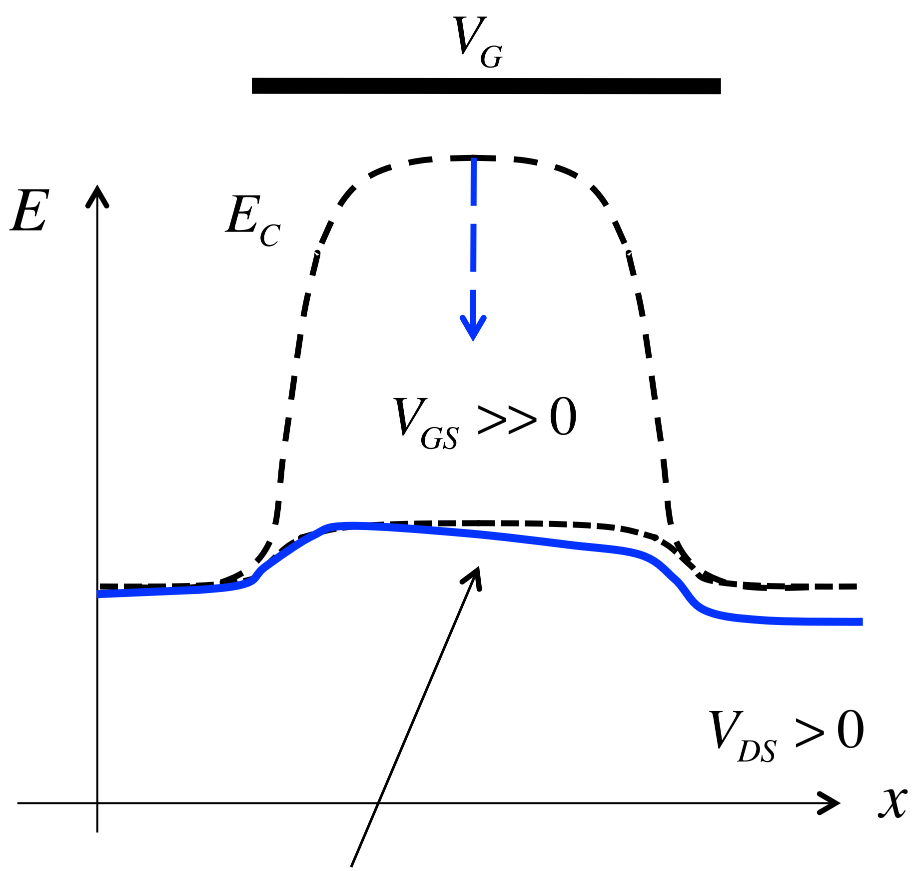
← $V_D = V_S = 0$

Examine effect of gate voltage first

$$E_C = E_{C0} - q\psi_s$$



Now add a small drain voltage



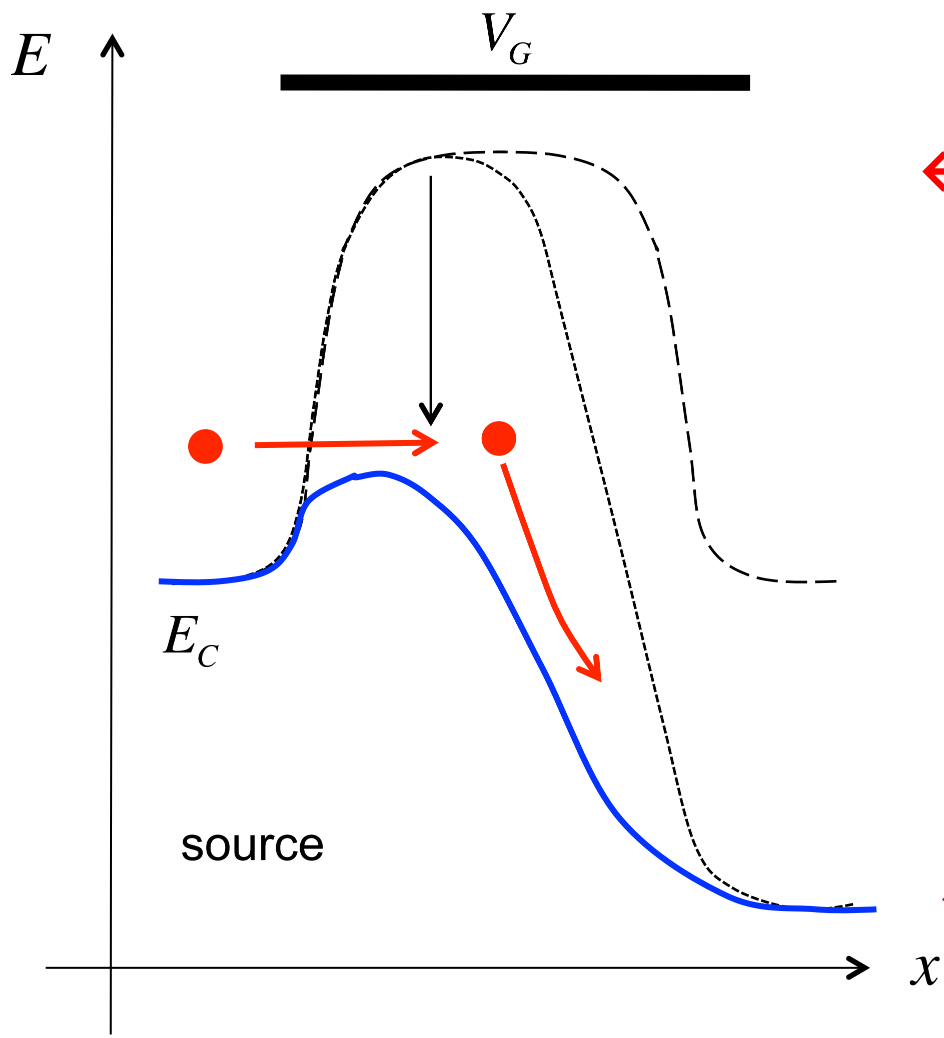
constant electric field and
substantial electron density

What if we apply a small positive voltage to the drain?

The conduction band in the drain is lowered.

Now increase the drain voltage

ON-state



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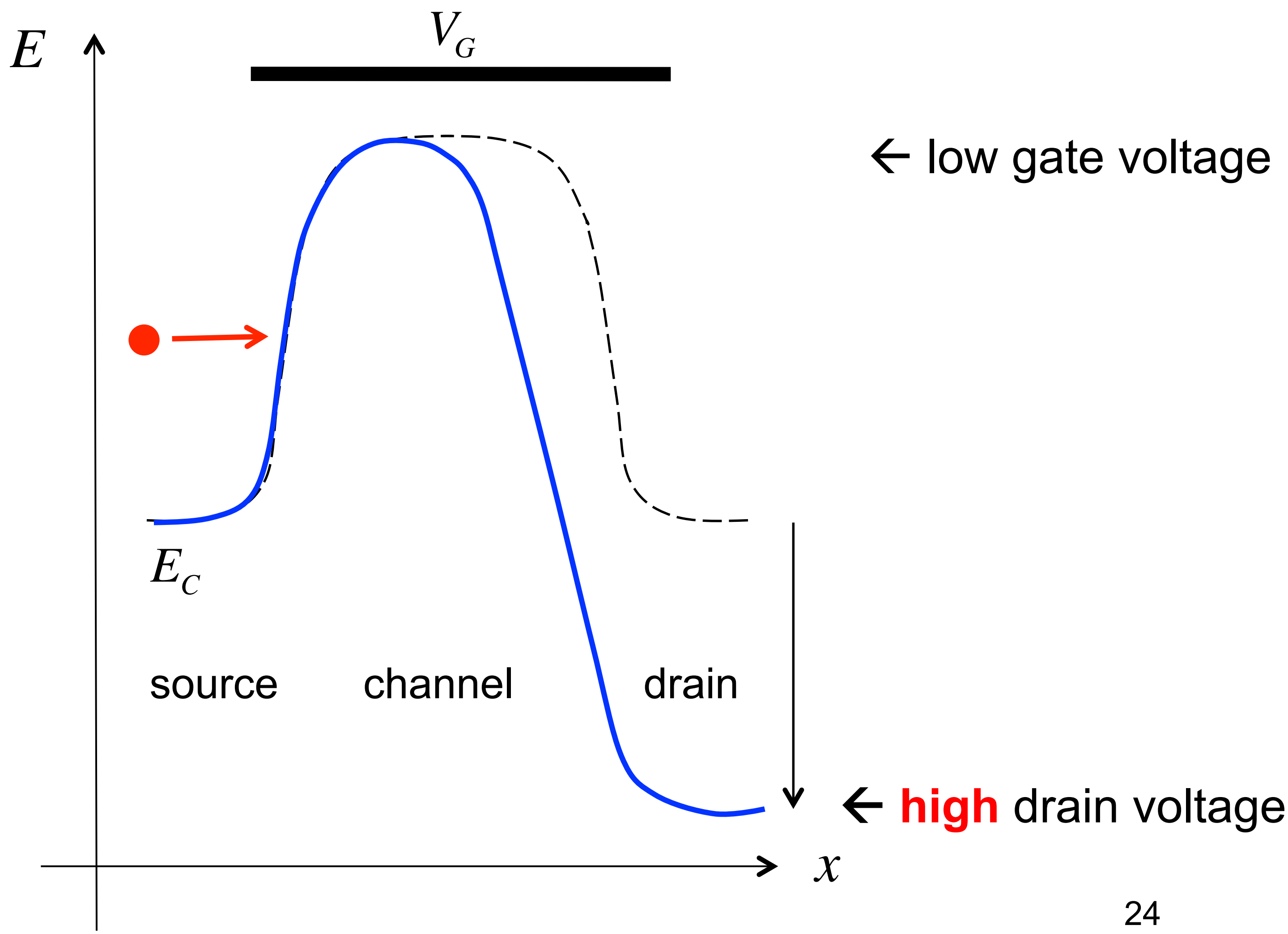
Now remove the gate voltage

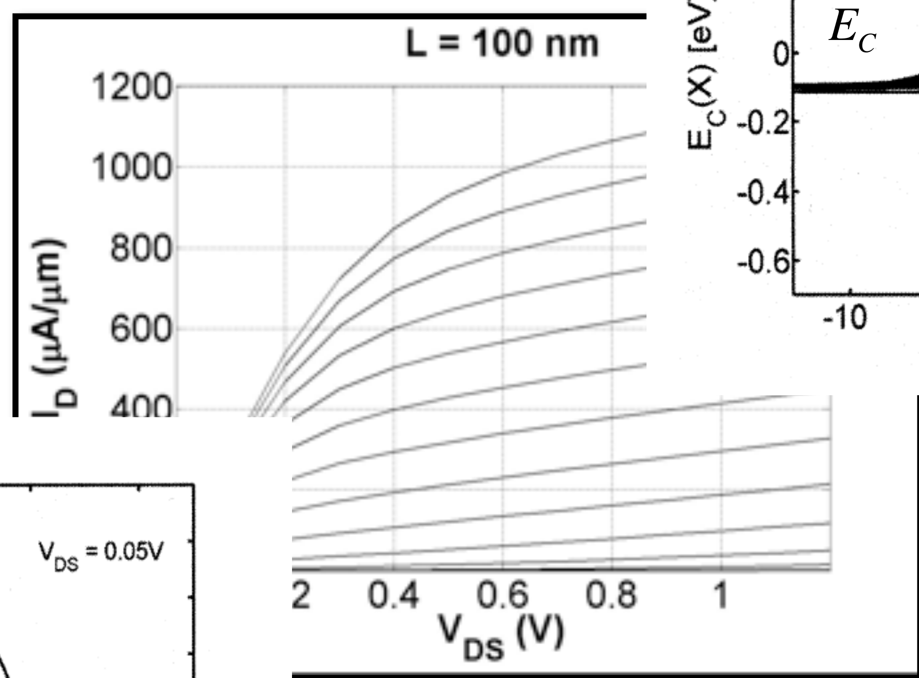
OFF-state

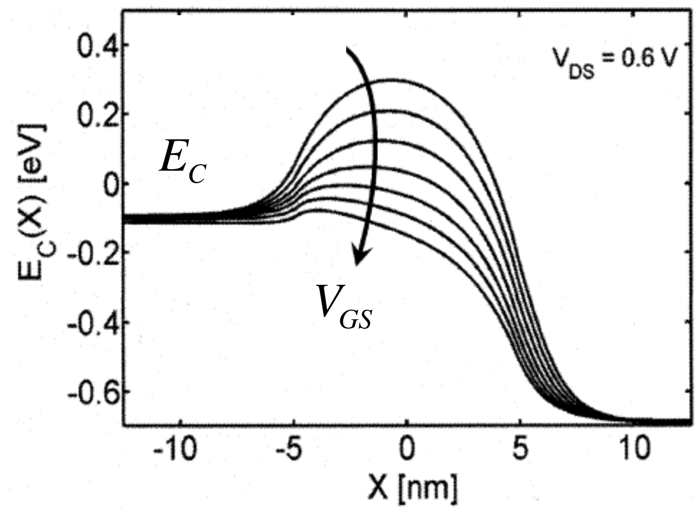


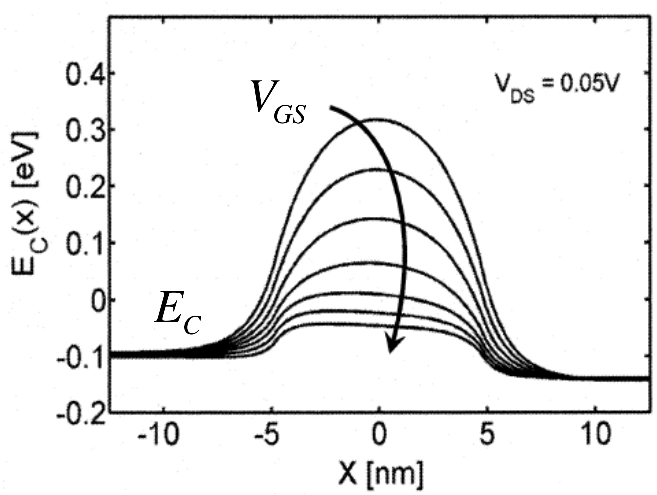
Lundstrom: 2019

How MOSFETs work

2007 N-MOSFET

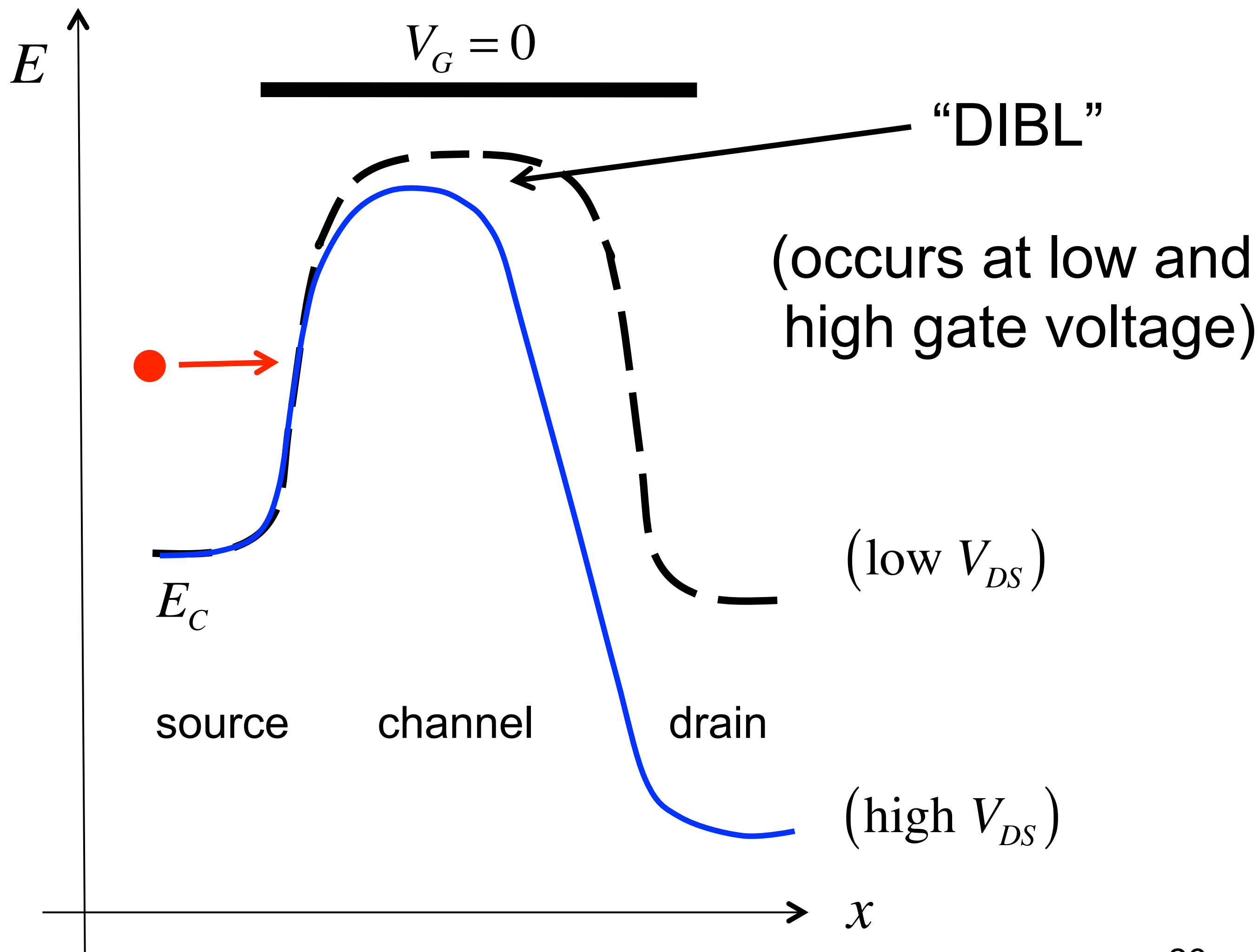






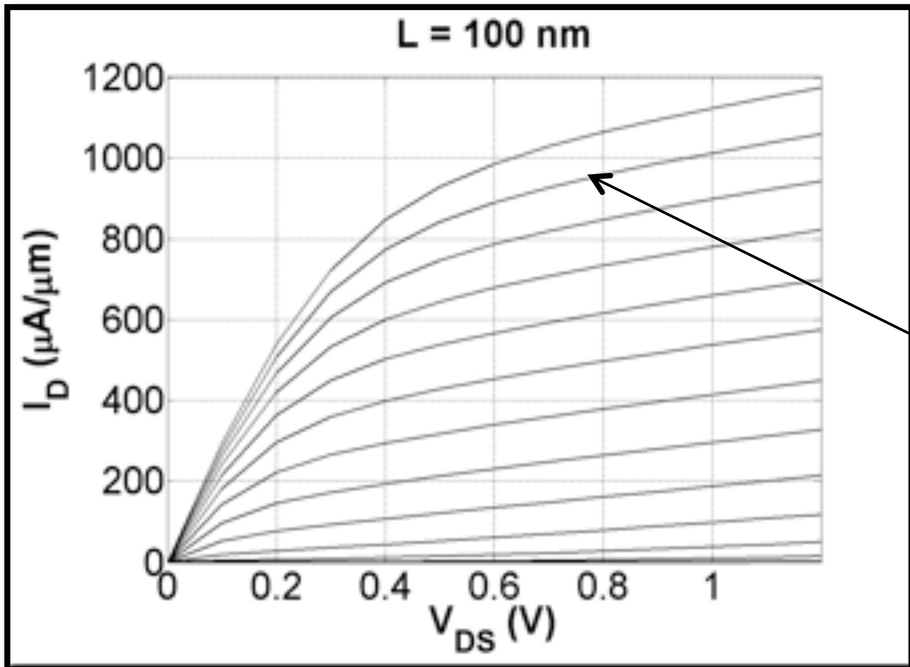
rtesy, Shuji Ikeda, ATDF, Dec. 2007)

Effect of drain voltage



Output conductance

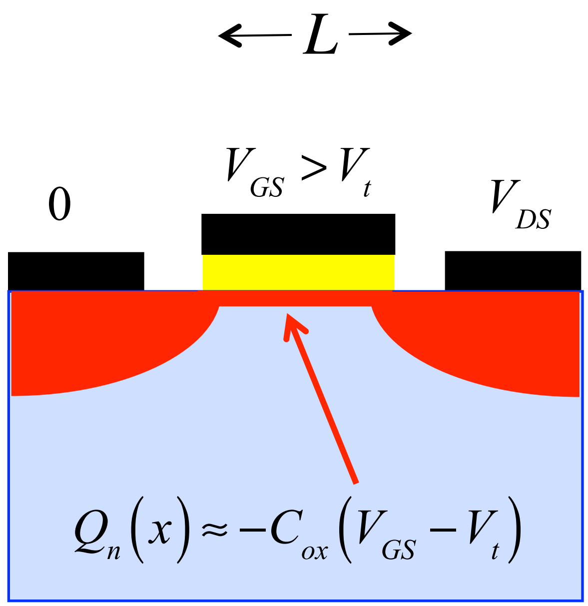
2007 N-MOSFET



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

DIBL explains the slope in the saturation region

Mathematical treatment: Small V_{DS}



$$V_{OV} = (V_{GS} - V_t)$$

Sedra and Smith

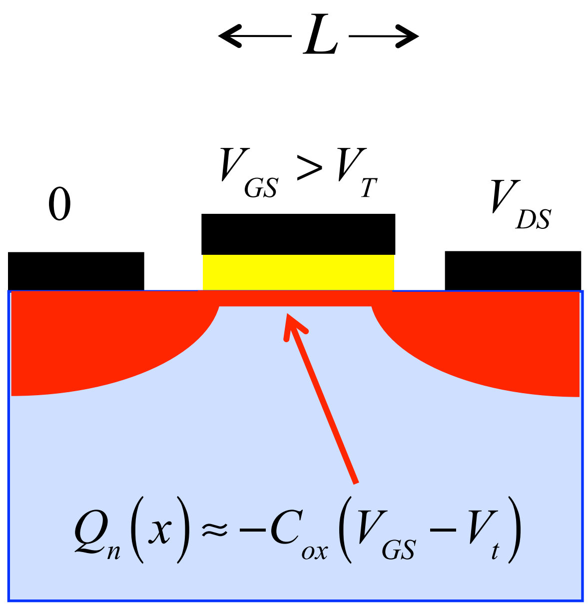
$$Q = CV$$

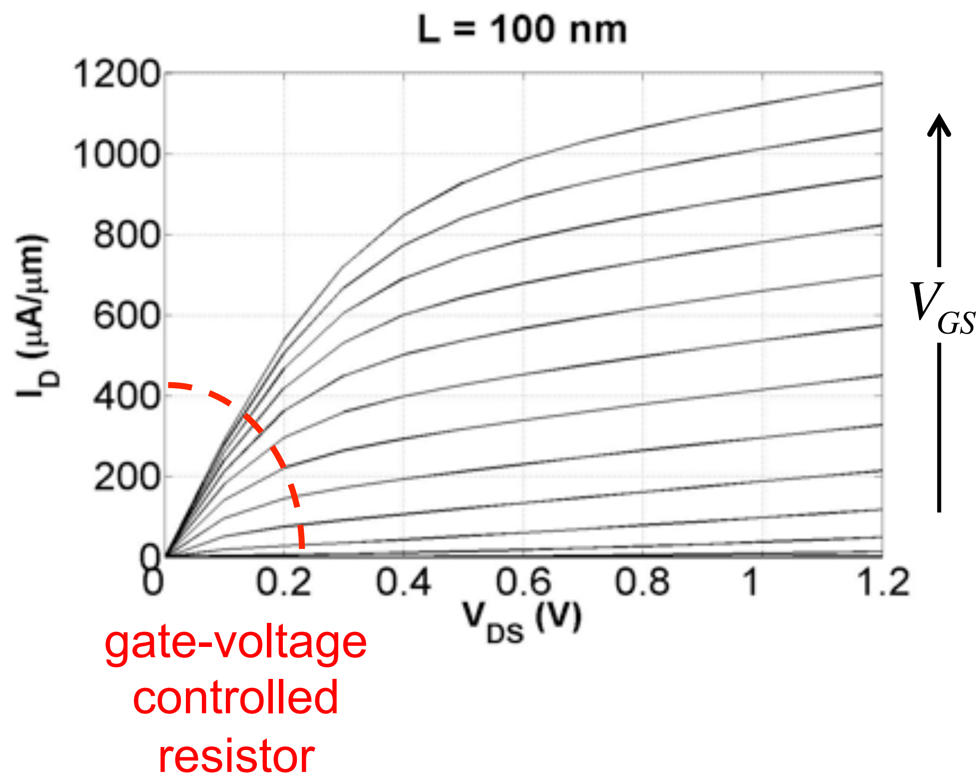
$$C = \frac{\kappa_{ox}\varepsilon_0}{t_{ox}} A = \frac{\varepsilon_{ox}}{t_{ox}} A \quad \text{F}$$

$$C_{ox} = \frac{C}{A} = \frac{\kappa_{ox}\varepsilon_0}{t_{ox}} \quad \frac{\text{F}}{\text{cm}^2}$$

$$Q_n(x) \approx -C_{ox}(V_{GS} - V_t) \quad \frac{\text{C}}{\text{cm}^2}$$

Mathematical treatment: Small V_{DS}





$$I_D = -W\, Q_n(x)\langle \upsilon_x(x)\rangle$$

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

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

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

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

✓

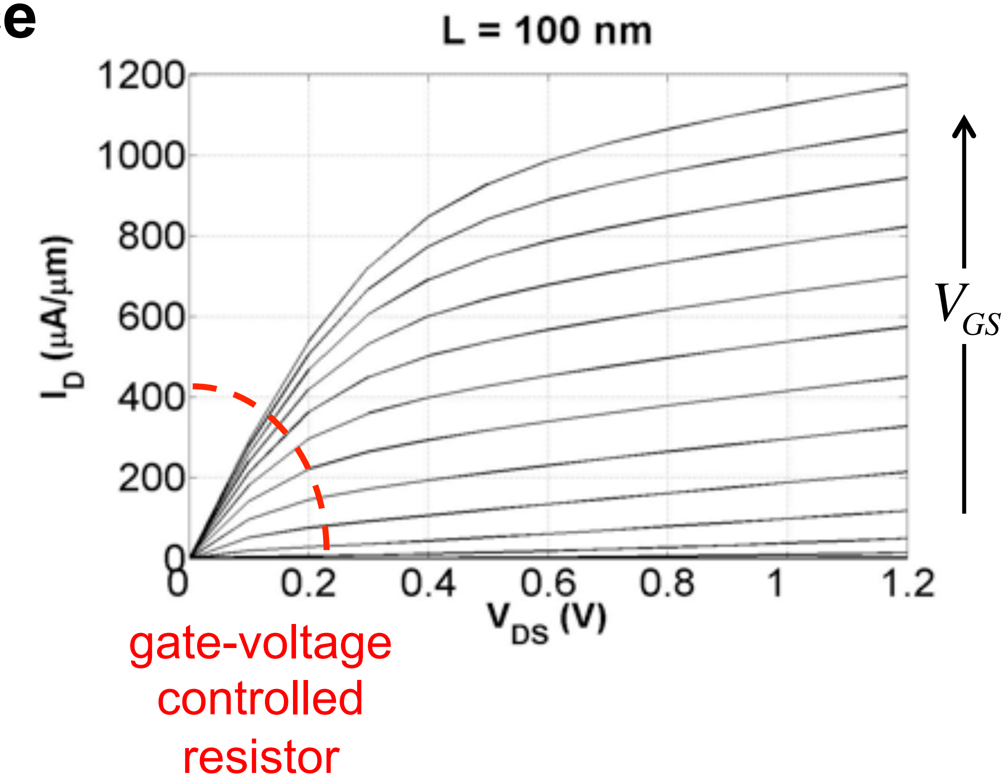
The transconductance parameter

MOSFET transconductance parameter:

$$k_n = \frac{W}{L}\mu_n C_{ox}$$

$$k_n' = \mu_n C_{ox}$$

$$k_n = k_n' \frac{W}{L}$$



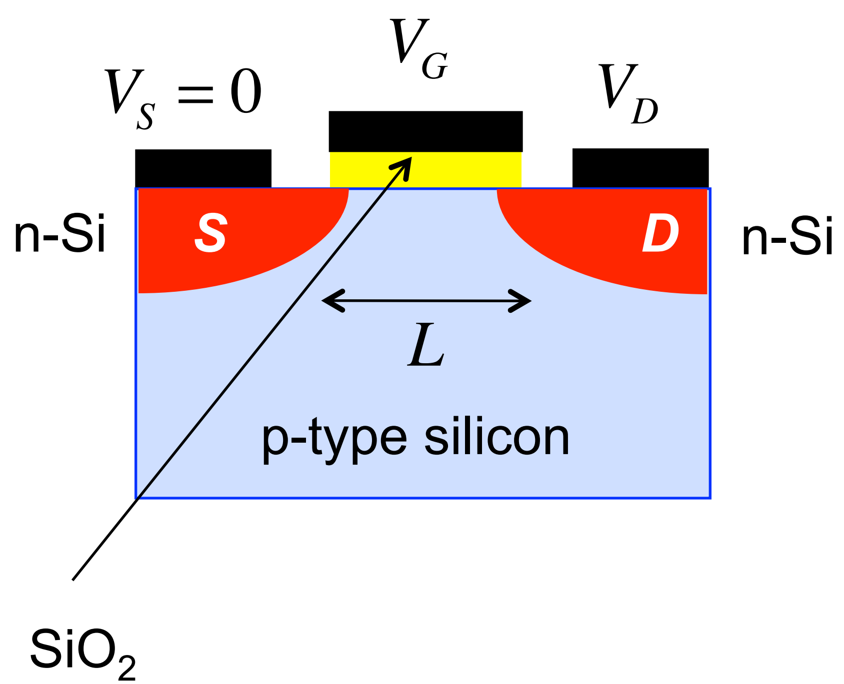
MOSFET aspect ratio: W/L

$$I_D = \frac{W}{L} k_n' \left(V_{GS} - V_t\right) V_{DS}$$

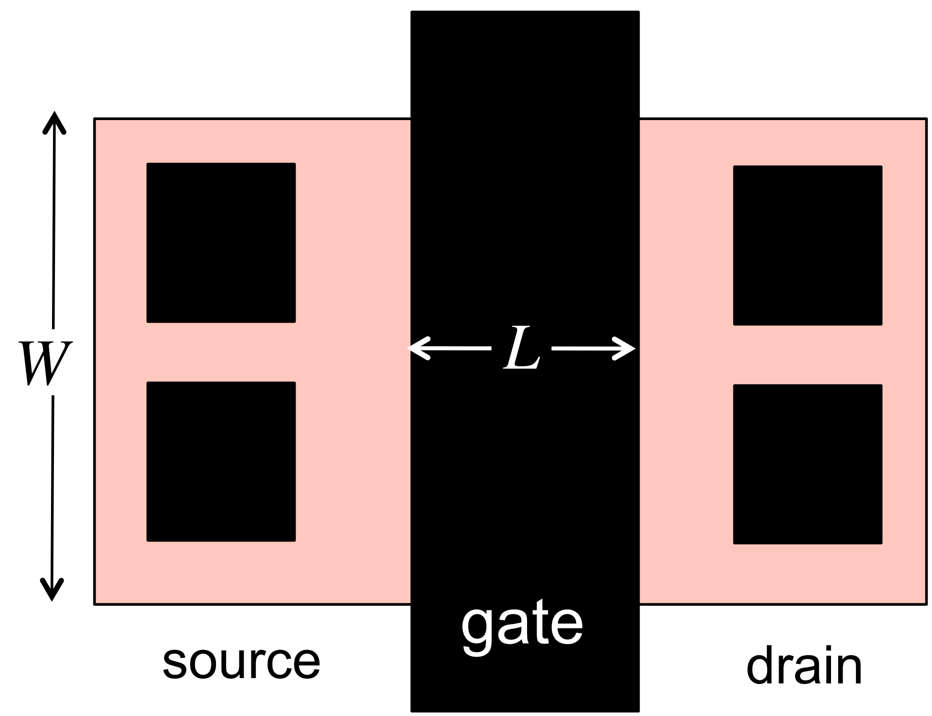
Lundstrom: 2019

Aspect ratio

Metal **O**xide **S**emiconductor **F**ield **E**ffect **T**ransistor

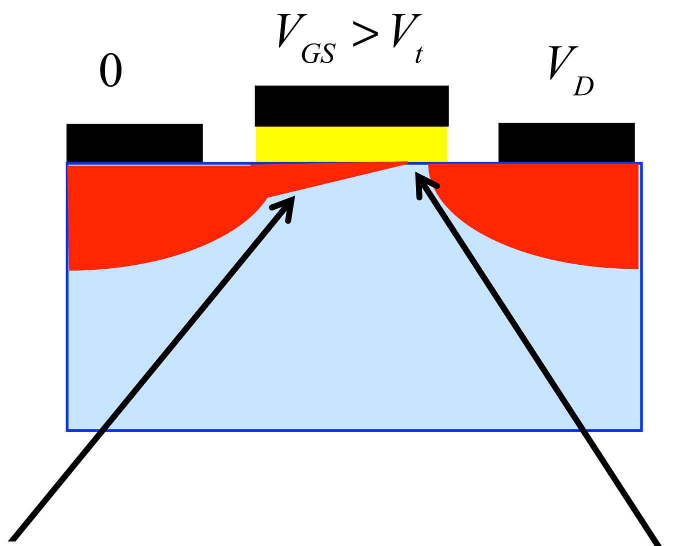


side view



top view

Mathematical treatment: Large V_{DS}



"pinch-off"

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

$$0 \le V(x) \le V_{GS} - V_t$$

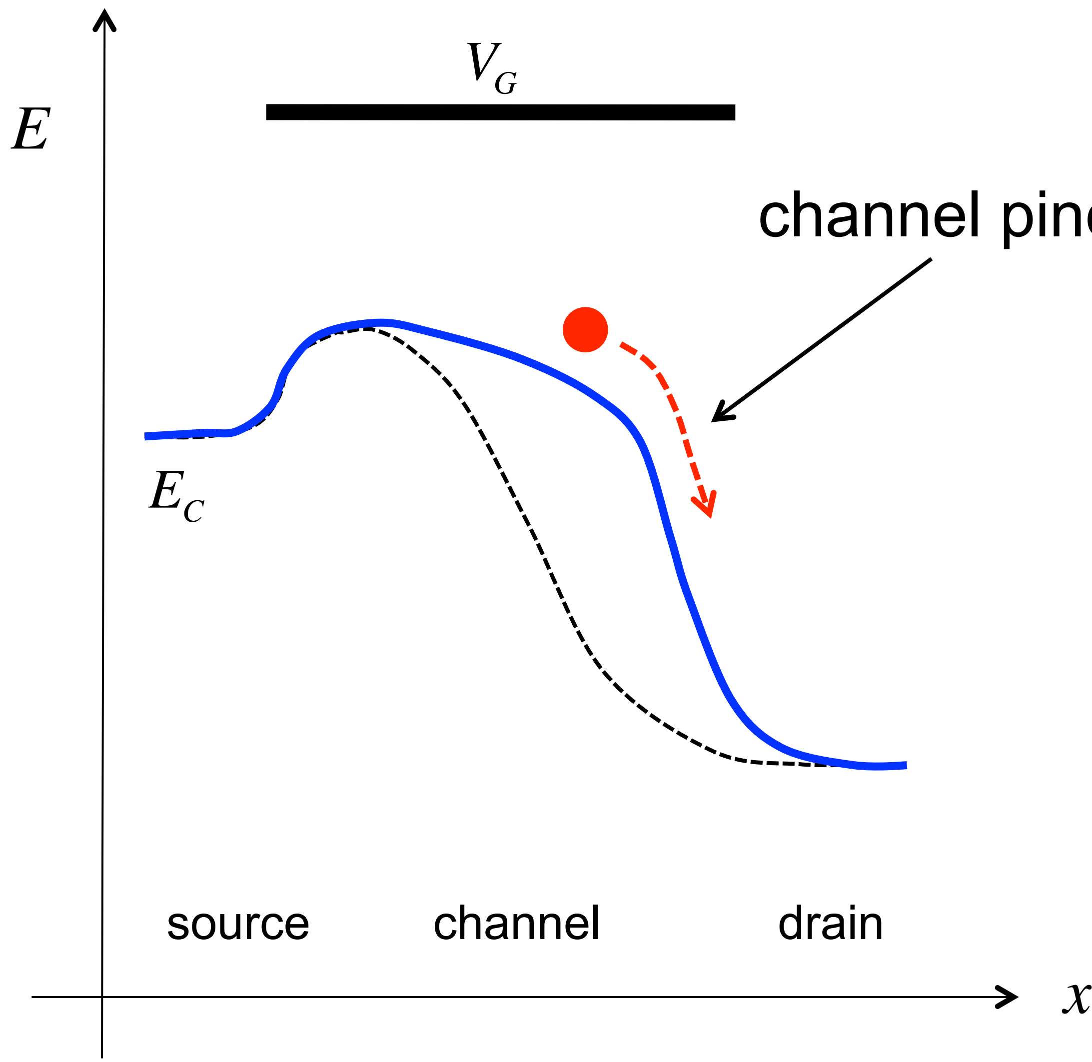
$$V\left(x_{pinch}\right) = \left(V_{GS} - V_t\right)$$

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

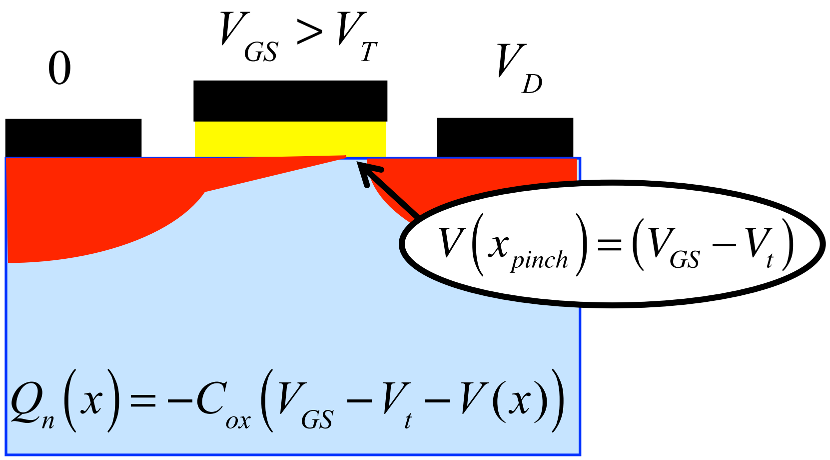
Note: thickness of channel illustrates the areal density of electrons – not the actual thickness.

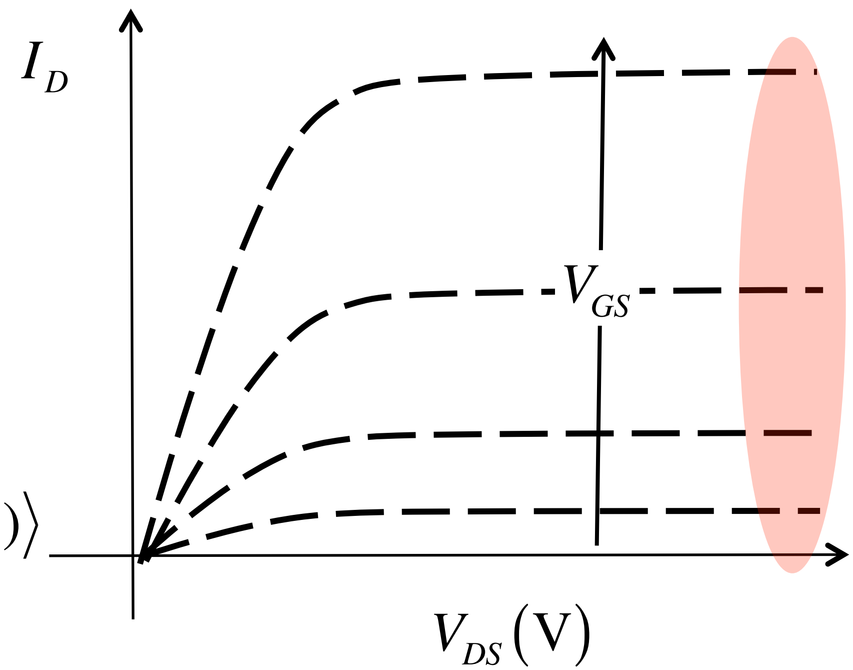
Electric field is very large in the pinch-off region.

"Pinch off" on an energy band diagram



Square law MOSFET





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

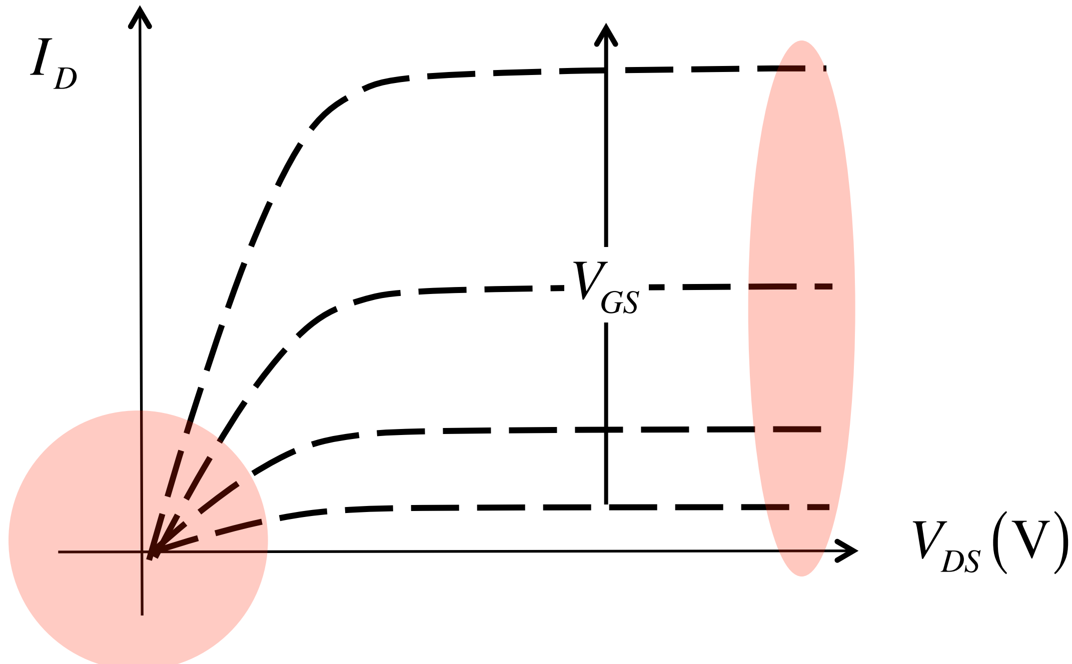
$$Q_n\left(0\right) = -C_{ox}\left(V_{GS} - V_t\right)$$

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

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

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

Square law MOSFET



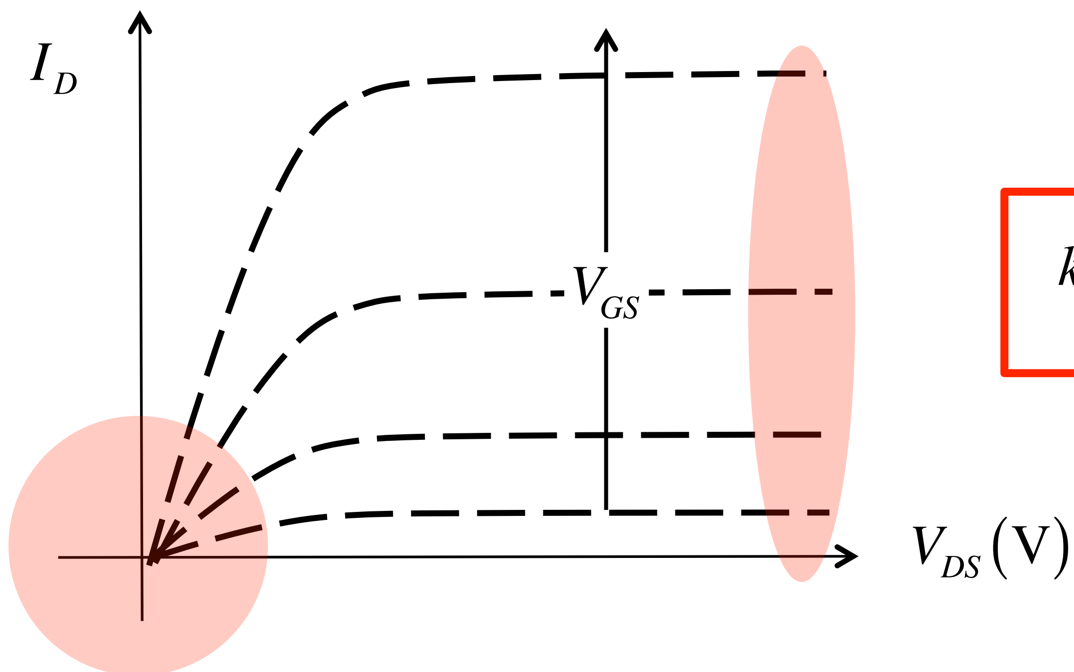
$$I_D = \frac{W}{L}\mu_n C_{ox}\left(V_{GS} - V_t\right)V_{DS}$$

$V_{GS} > V_t \qquad V_{DS} << V_{GS} - V_t$

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

$V_{GS} > V_t \qquad V_{DS} > V_{GS} - V_t$

Square law MOSFET (technology constant)



$$k_n' \equiv \mu_n C_{ox}$$

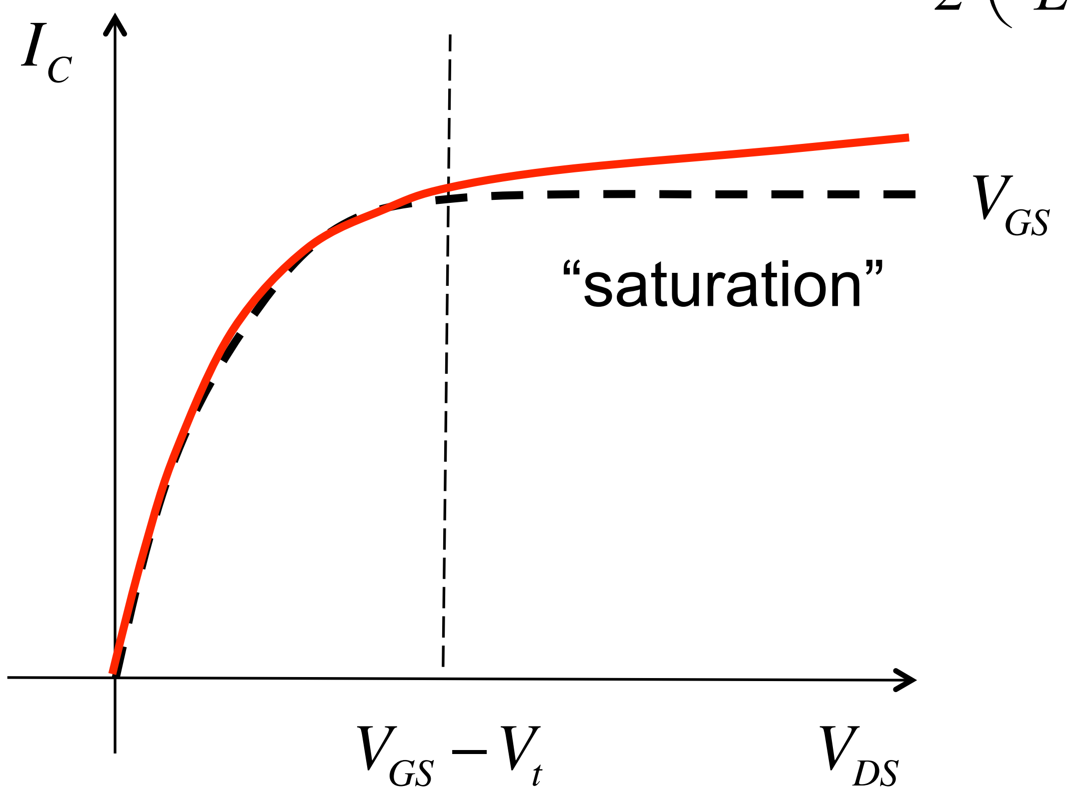
$$I_D = \frac{W}{L} k_n' \left(V_{GS} - V_t\right) V_{DS}$$

$V_{GS} > V_t \qquad V_{DS} << V_{GS} - V_t$

$$I_D = \frac{W}{L} \frac{k_n'}{2} \left(V_{GS} - V_t\right)^2$$

$V_{GS} > V_t \qquad V_{DS} > V_{GS} - V_t$

Output resistance



$$I_D = \frac{k_n'}{2}\left(\frac{W}{L}\right)\left(V_{GS} - V_t\right)^2\left(1 + \lambda V_{DS}\right)$$

$$\lambda = \frac{1}{V_A}$$

Like the Early voltage for a BJT.

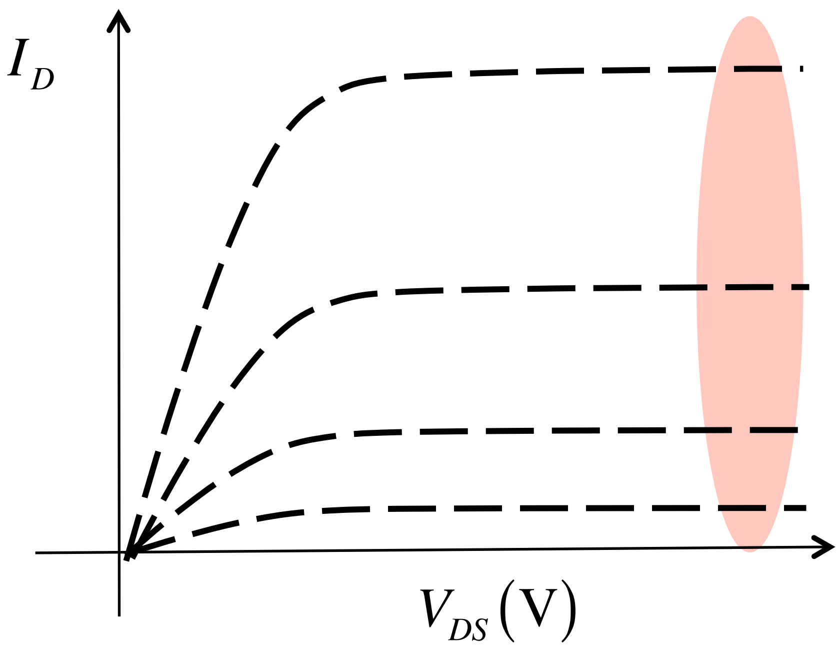
Long vs. Short Channel MOSFETs

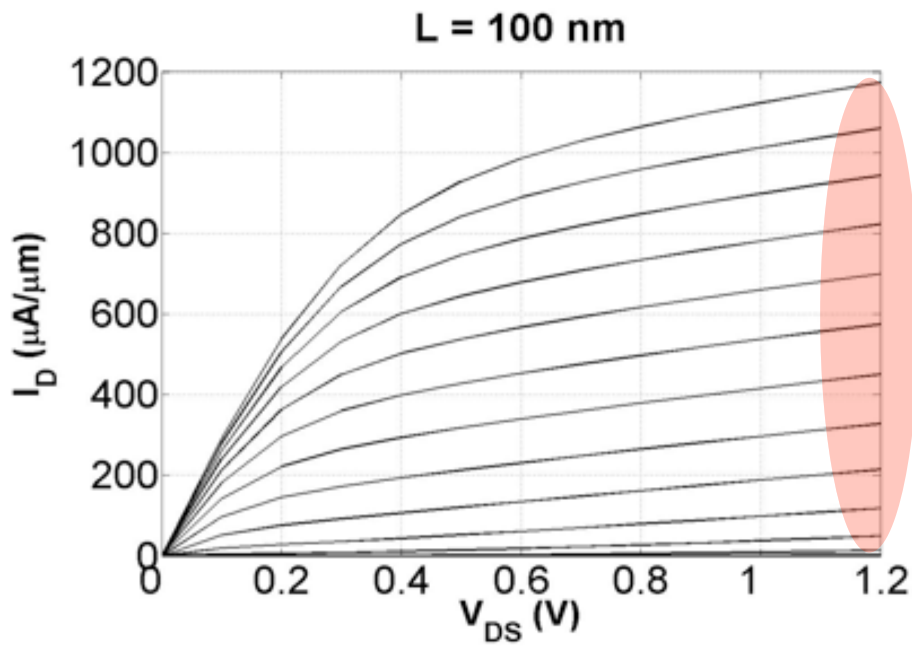
Square Law

$$I_{DSAT} \propto (V_{GS} - V_t)^2$$

"Velocity saturated"

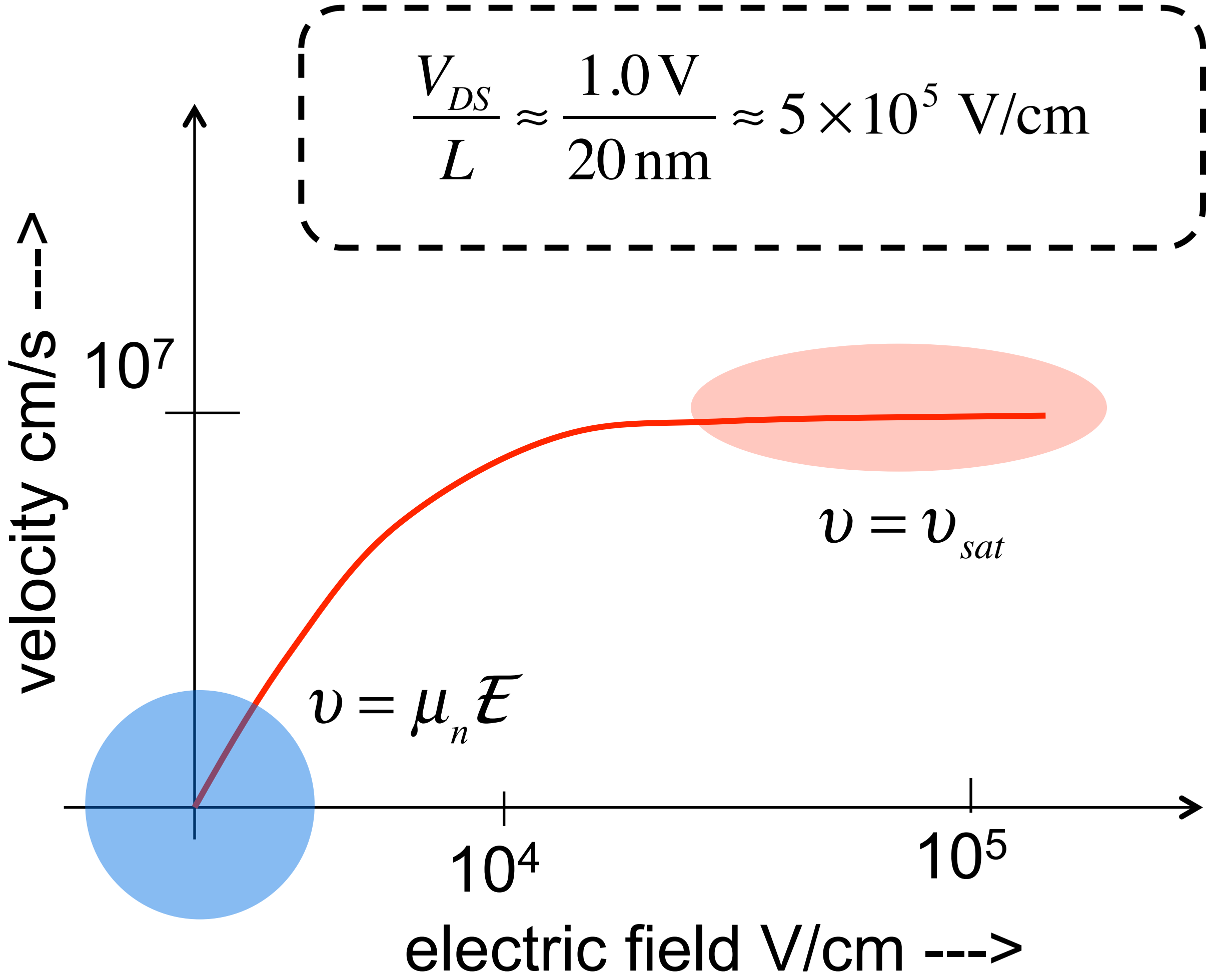
$$I_{DSAT} \propto (V_{GS} - V_t)$$





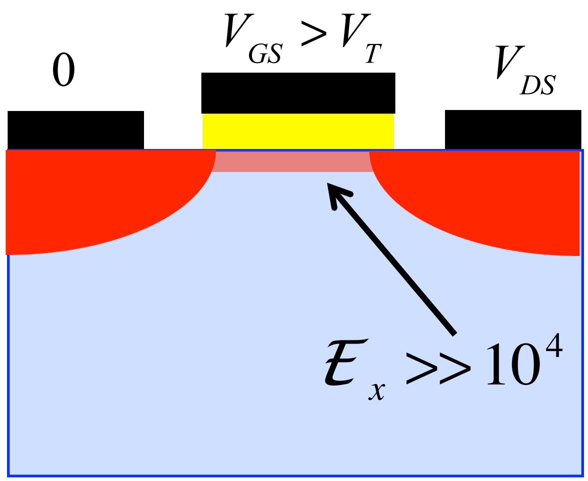
Lundstrom: 2019

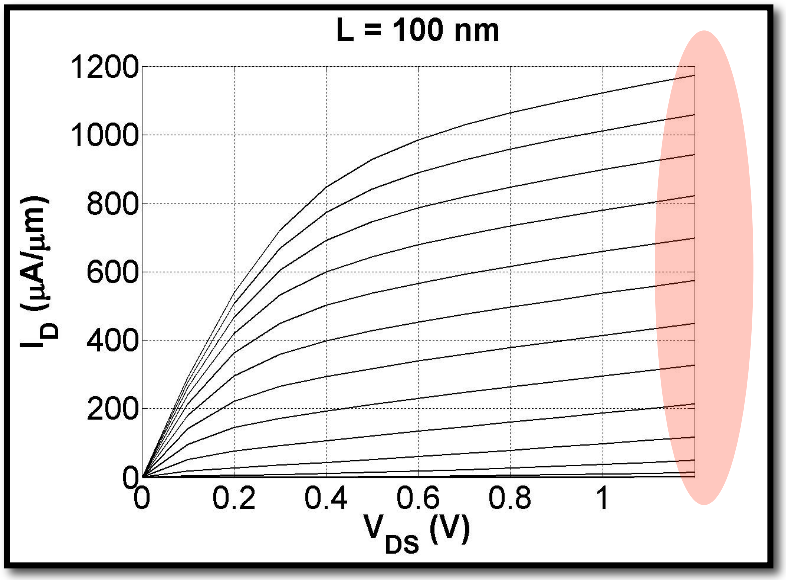
High V_{DS}: Velocity saturation



Lundstrom: 2019

MOSFET IV: velocity saturation





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

$$I_D = -W\,Q_n(x)\langle \upsilon_x(x)\rangle$$

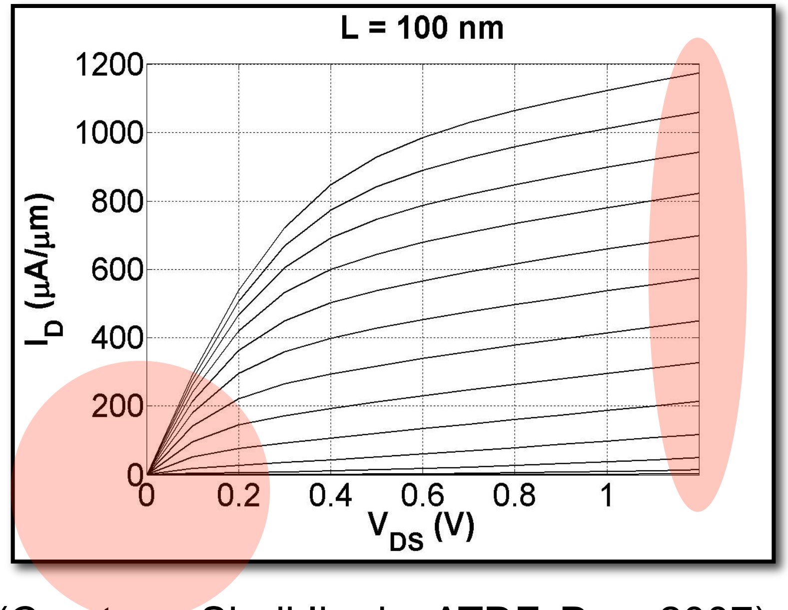
$$Q_n = -C_{ox}\left(V_{GS} - V_t\right)$$

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

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

✓

The velocity saturated MOSFET



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

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

$$V_{GS} > V_t \qquad V_{DS} << V_{GS} - V_t$$

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

$$V_{GS} > V_t \qquad V_{DS} > V_{GS} - V_t$$

Summary

A MOSFET is a barrier controlled transistor (just like a BJT).

MOSFETs come in two flavors − N-channel (NPN) and P-channel (PNP).

In the **saturation region**, the gate to source voltage is greater than the **threshold voltage**, and the drain voltage is greater than the **drain saturation voltage**.

In the **linear region**, the gate to source voltage is greater than the **threshold voltage**, and the drain voltage is **much less than** the drain saturation voltage.

MOSFETs

1) Physical structure
2) IV characteristics (descriptive)
3) IV characteristics (energy band approach)
4) IV characteristics (mathematical model)