ECE 2C, notes set 2: Active Devices

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Goals of this note set:

Rough physicalsense of FET operation

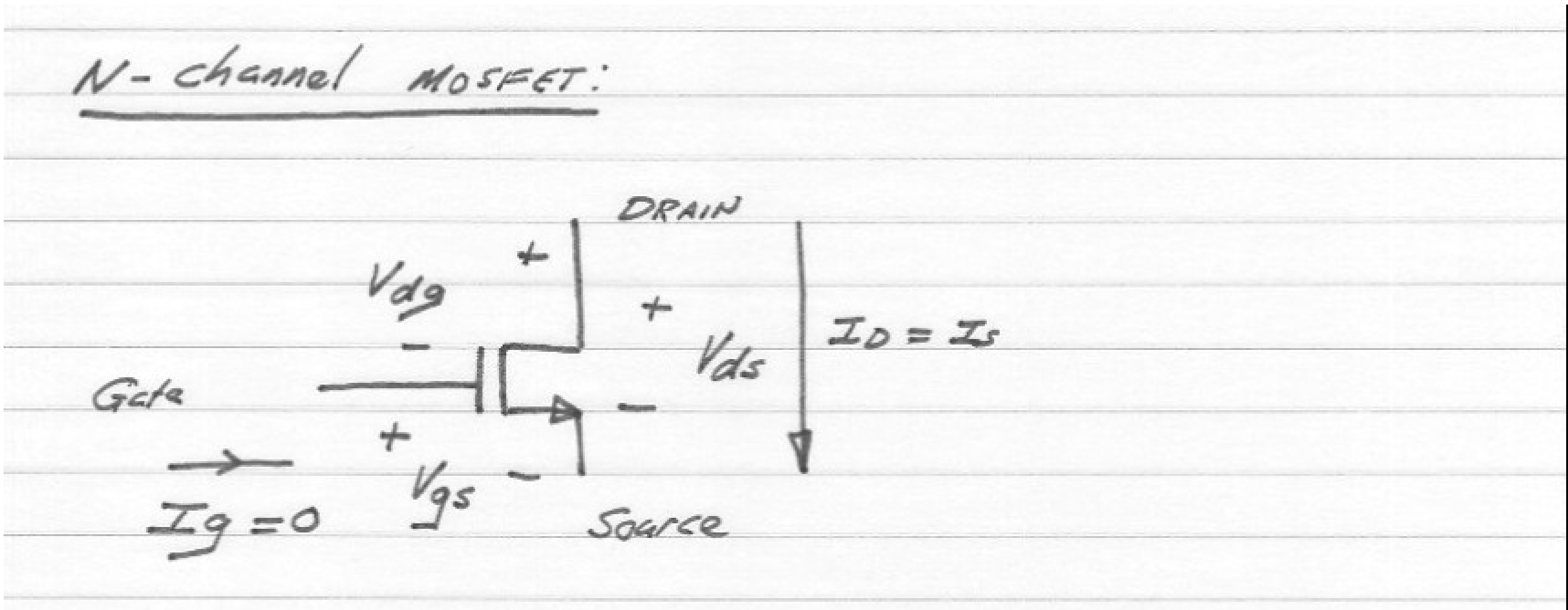
FET current - voltage characteristics.

Rough mathematical models of MOSFETs

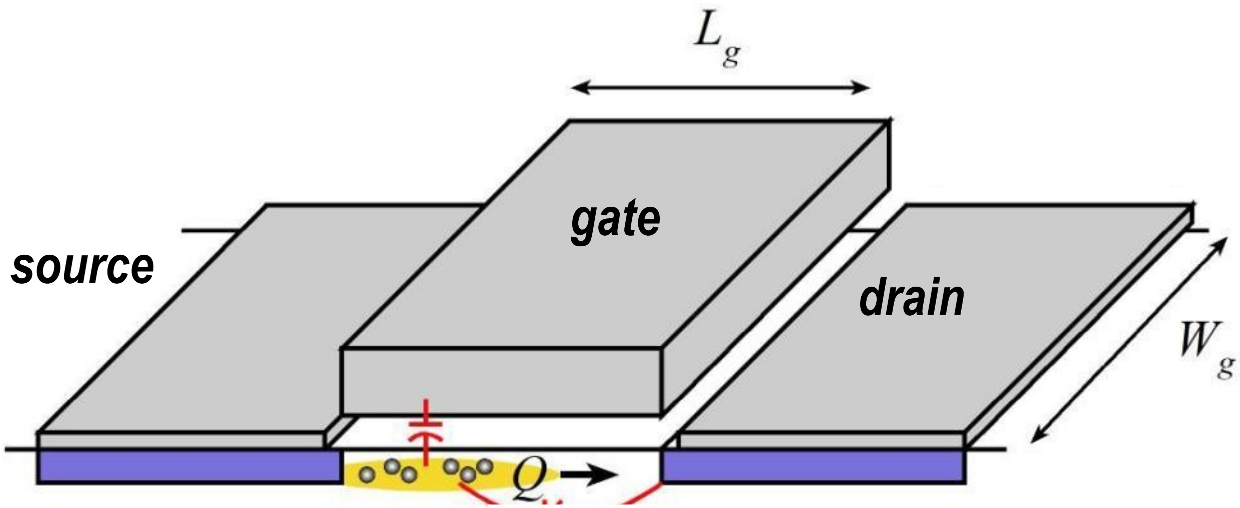
old - fashioned mobility - limited model.

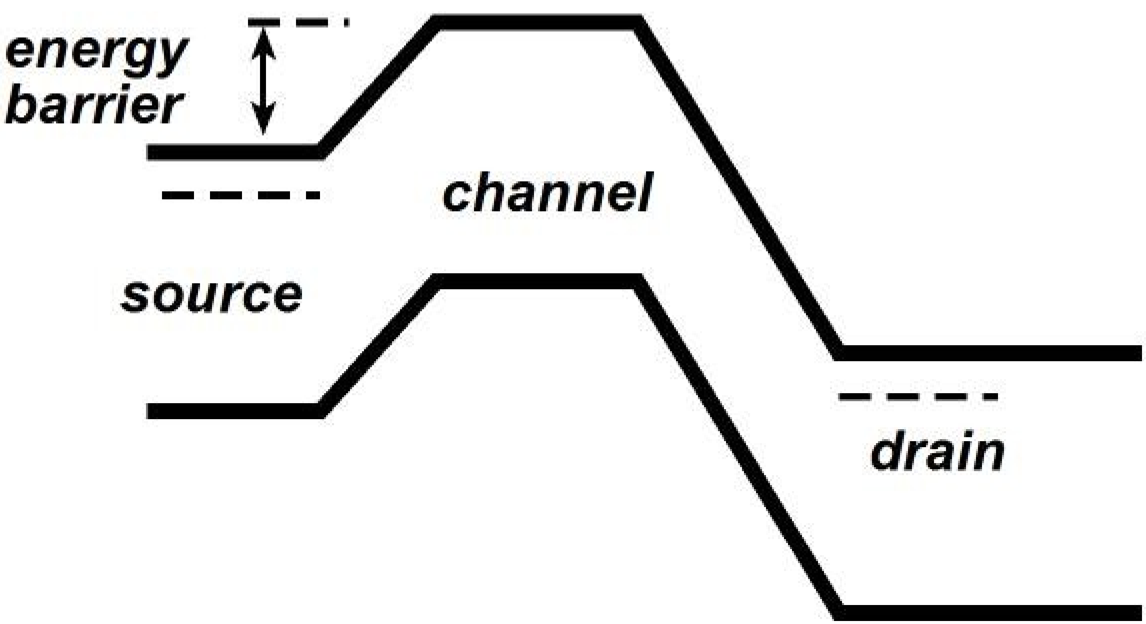
slighly less - old - fashioned velocity - limited model

N-Channel MOSFET



Field-Effect Transistor Operation



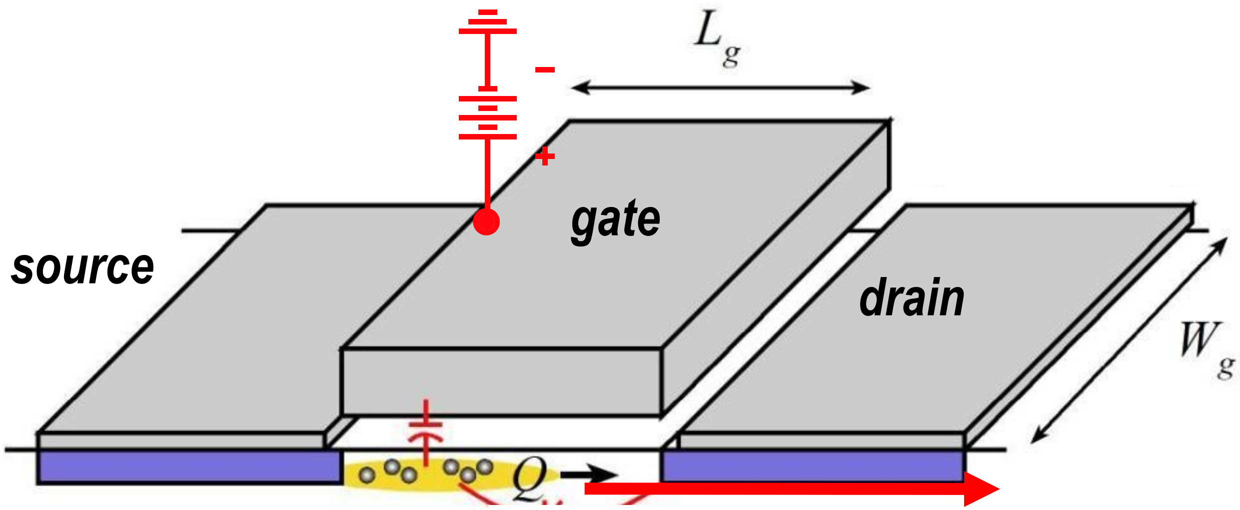


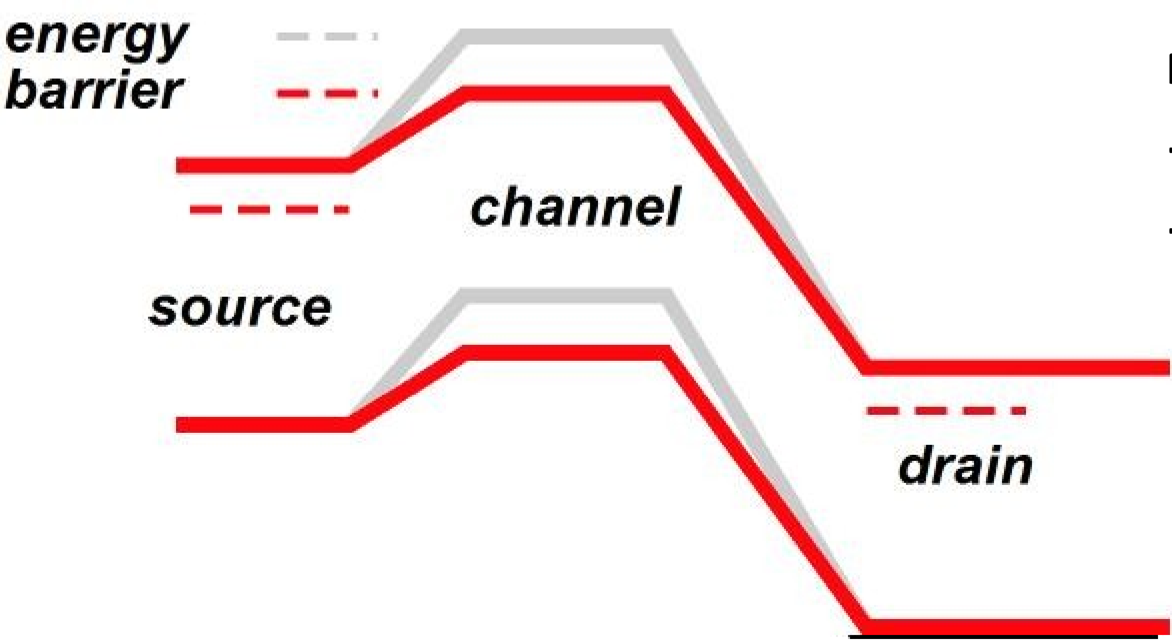
Positive Gate Voltage

→ reduced energy barrier

→ increased drain current

Field-Effect Transistor Operation





Positive Gate Voltage

→ reduced energy barrier

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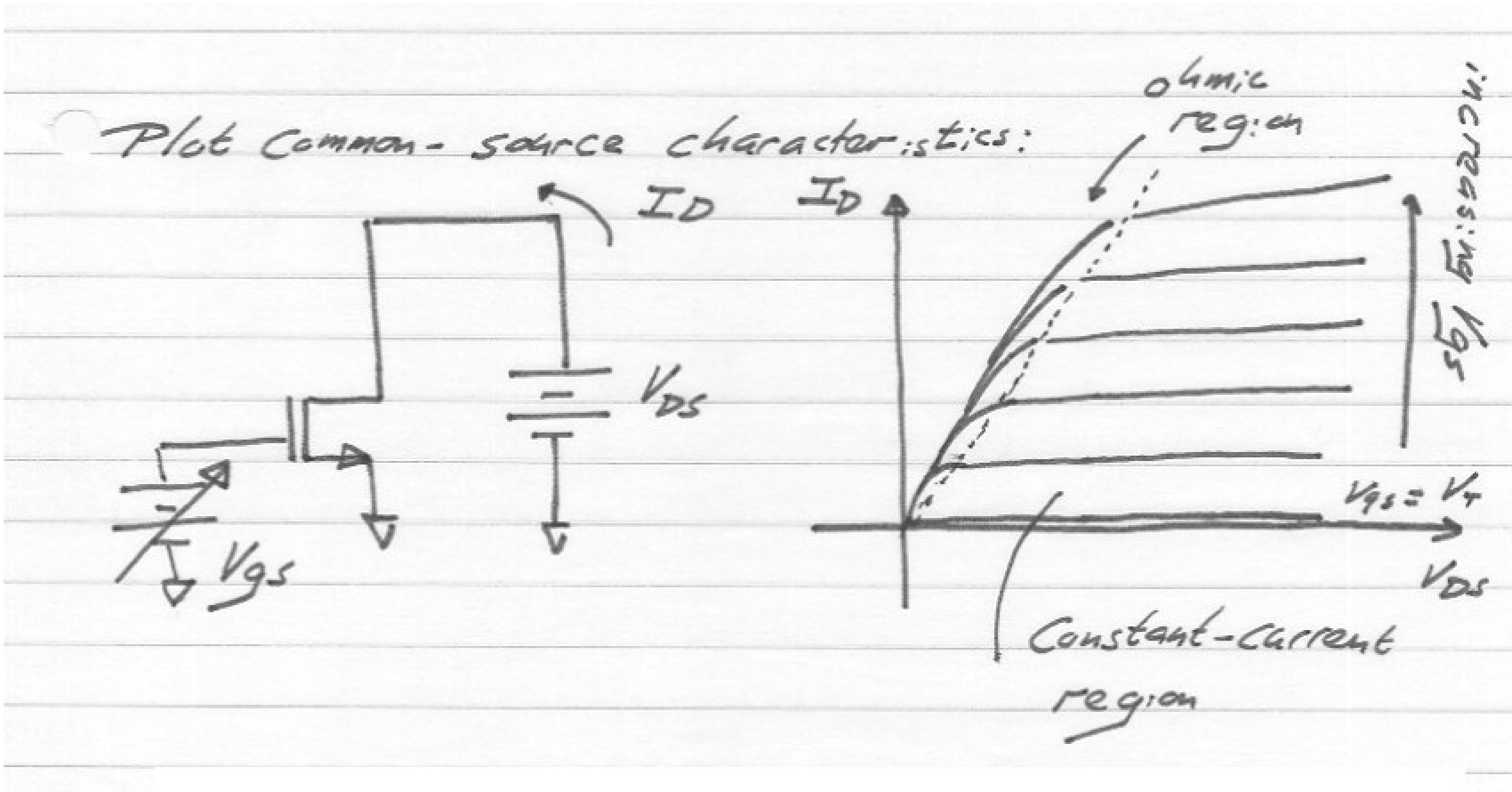
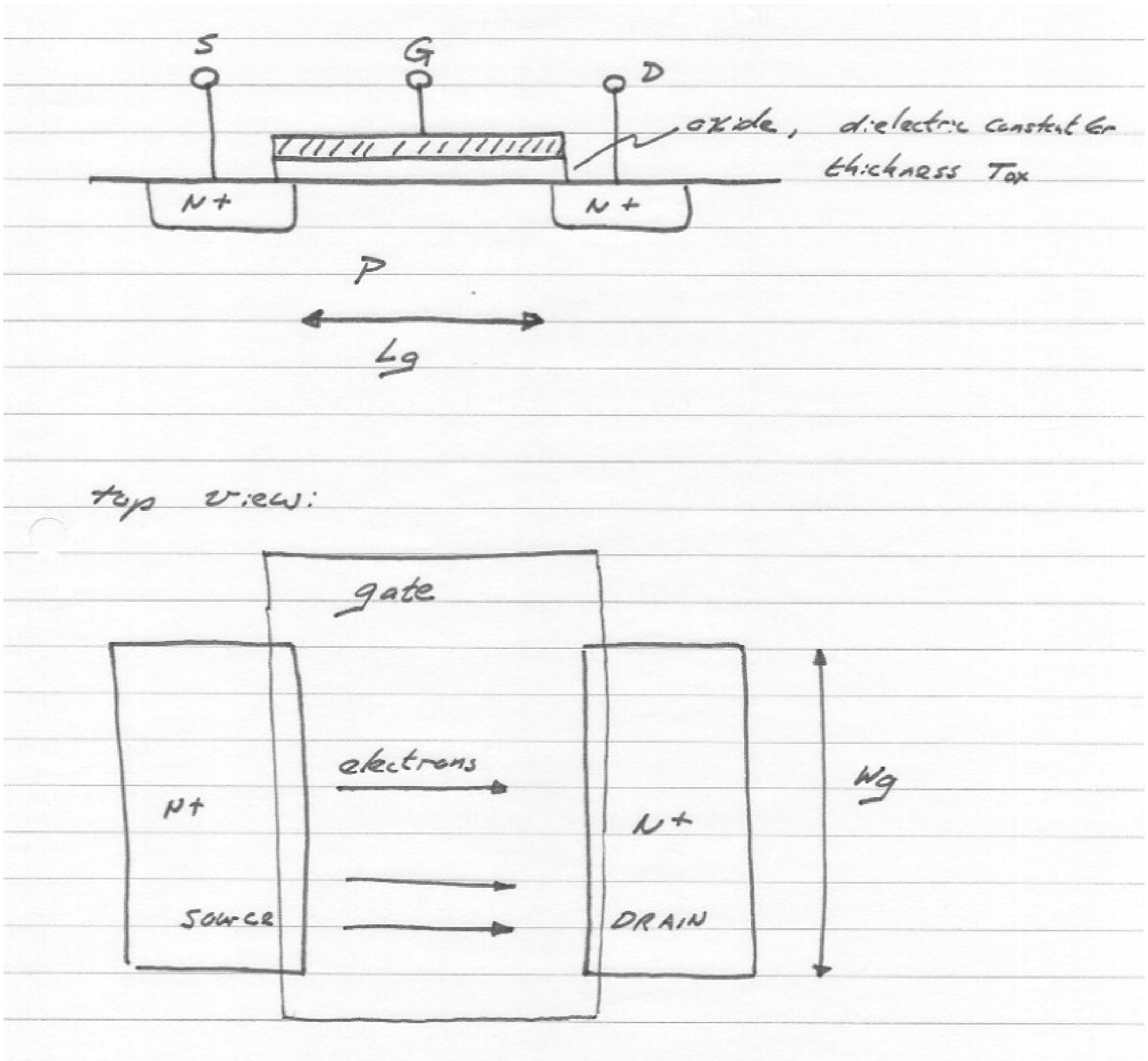
N-Channel MOSFET

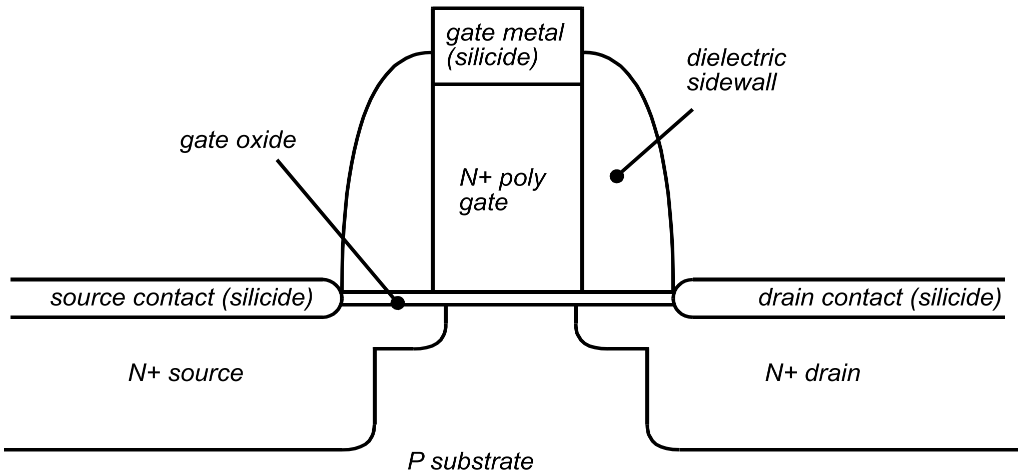


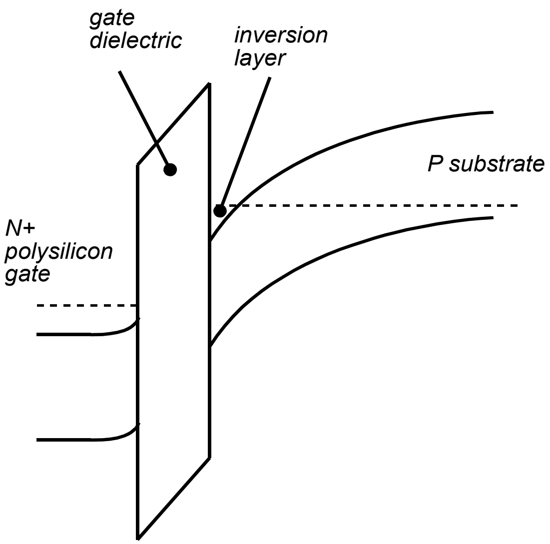
Physical Sketch



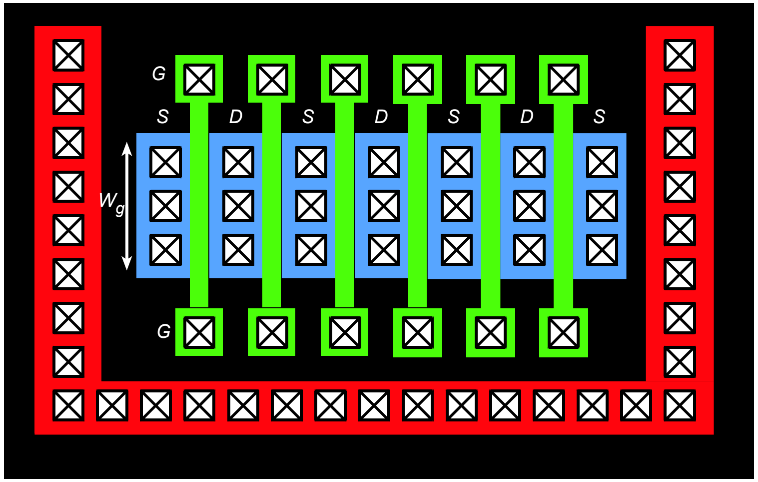
MOSFET Physical Structure

Cross-Section



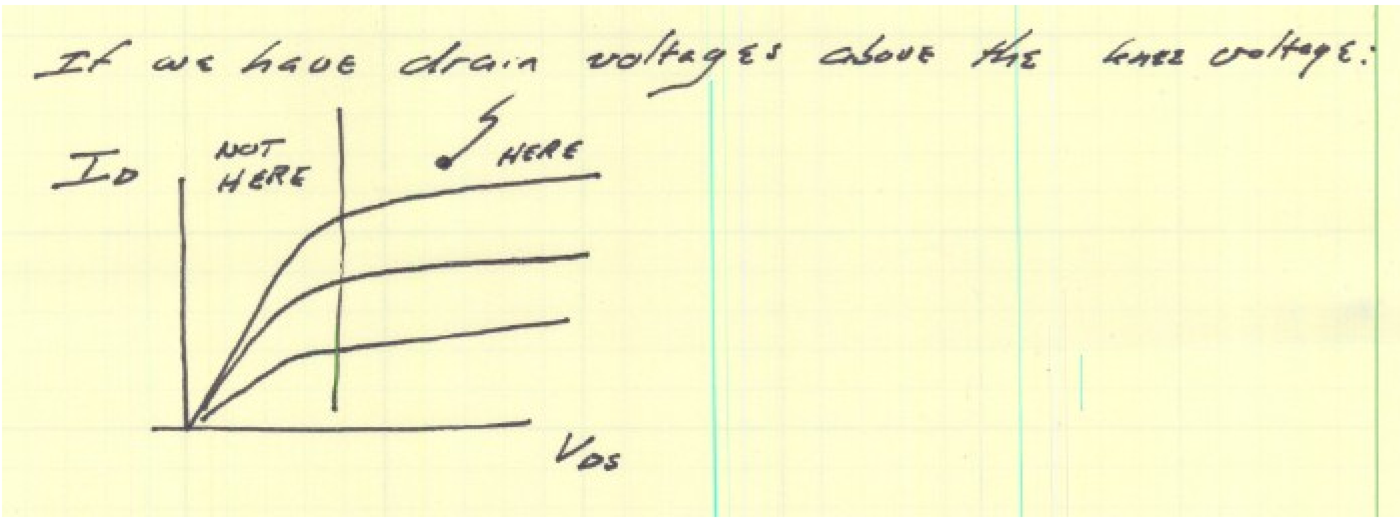


Layout



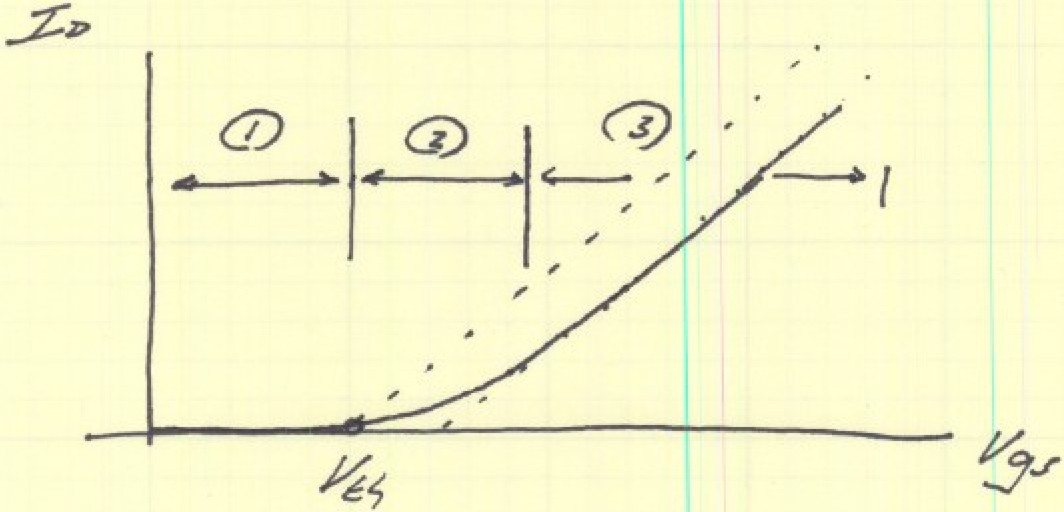
(6 FETs, each of gate width W_g , connected in parallel)

MOSFET I-V characteristics



MOSFET I-V characteristics

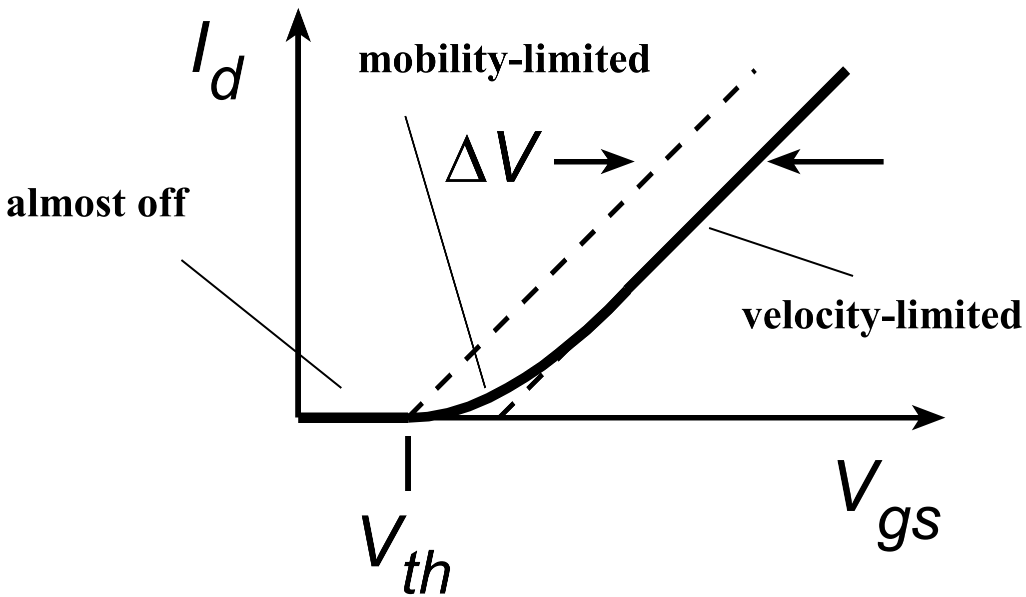
Then we can plot I_D vs V_{gs}:



There are 3 regions in the $I_D - V_{gs}$ curve:

1) subthreshold = almost off
2) mobility-limited: $I_d \sim (V_{gs} - V_{th})^2(1 + \lambda V_{DS})$
3) velocity-limited: $I_d \sim (V_{gs} - V_{th})^1(1 + \lambda V_{DS})$

MOSFETs: Three Regions of Gate Voltage



$$\Delta V = v_{sat} L_g / \mu$$

When V_{gs} is less than threshold, transistor is (almost) off : "subthreshold"

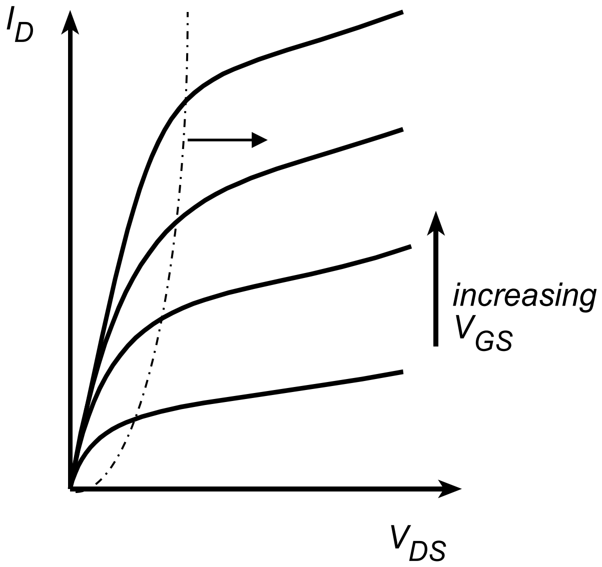
When V_{gs} is a little above threshold, current is mobility – limited

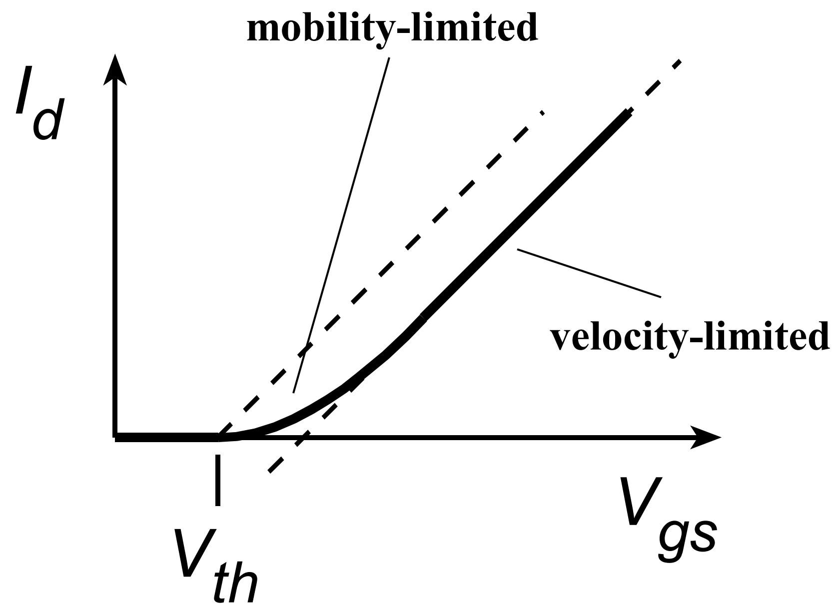
$$I_{D,\mu} \propto (V_{gs} - V_{th})^2$$

When V_{gs} is far above threshold, current is velocity – limited

$$I_{D,v} \propto (V_{gs} - V_{th} - \Delta V)$$

MOSFET DC Characteristics: Mobility-Limited Case



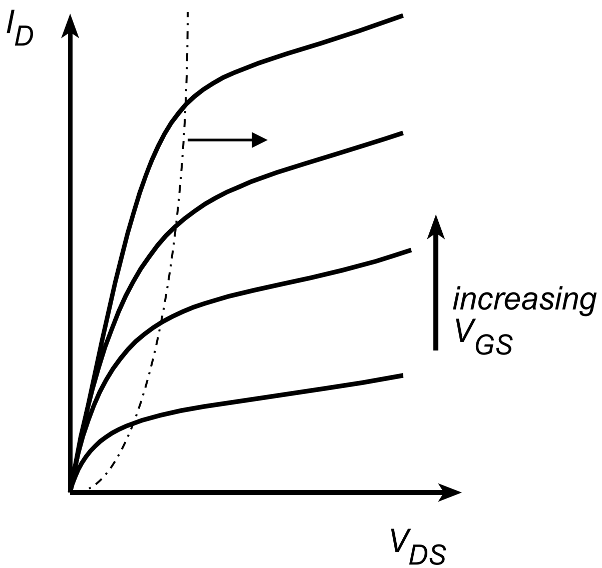


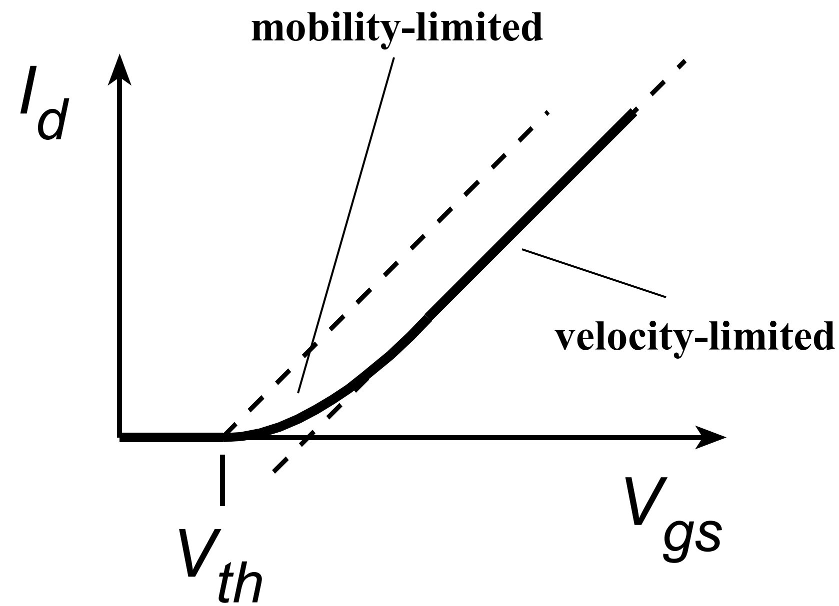
mobility – limited current :

$$I_{D,\mu} = (\mu c_{ox} W_g / 2L_g)(V_{gs} - V_{th})^2 (1 + \lambda V_{DS})$$

Applies for drain voltages larger than the knee voltage,

MOSFET DC Characteristics: Velocity-Limited Case



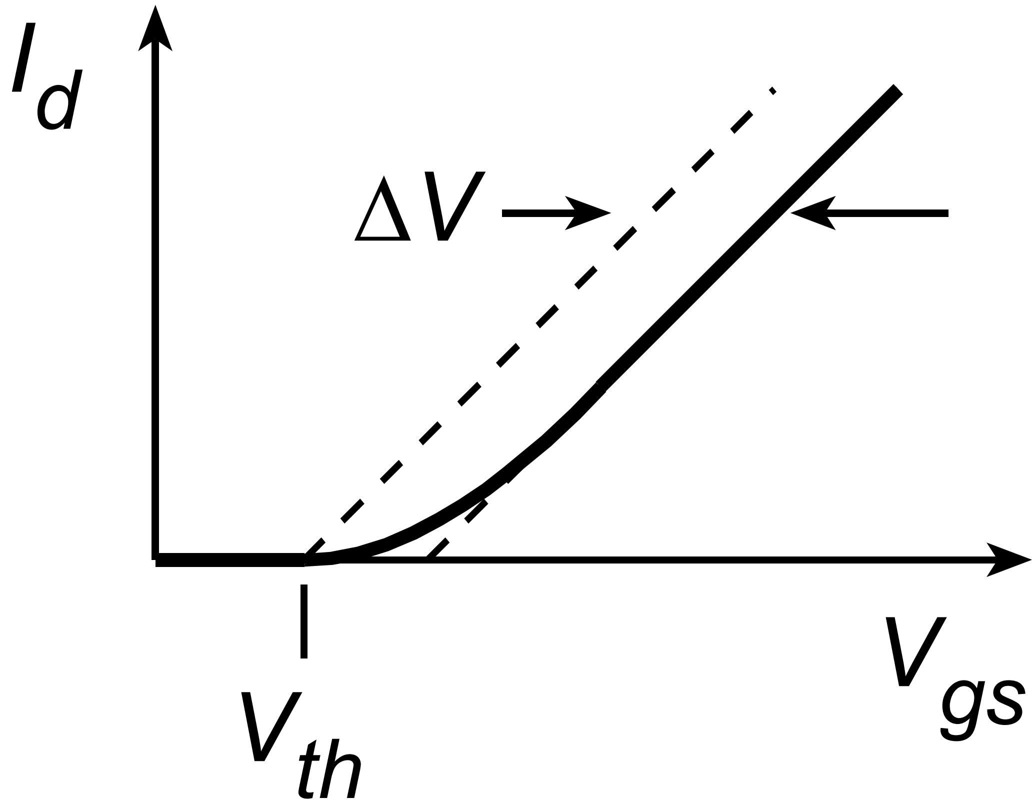


velocity – limited current

$$\boxed{I_{D,v} = c_{ox} W_g v_{sat} (1 + \lambda V_{DS})(V_{gs} - V_{th} - \Delta V)} \qquad \Delta V = v_{sat} L_g / \mu$$

Applies for drain voltages larger than the knee voltage,

DC Characteristics---Far Above Threshold



$$I_D \approx c_{ox} W_g v_{sat} (V_{gs} - V_{th} - \Delta V) \text{ for } (V_{gs} - V_{th}) / \Delta V >> 1$$

where $\Delta V = v_{sat} L_g / \mu$

We will ignore the ΔV term in ece2C, but please use it in your more advanced classes.

Paramers and Typical #s

v_{sat} = saturation drift velocity ~ 10^7 cm/s for N-MOSFETs

μ = carrier mobility at surface ~ 300 – 400 cm^2/(V-s) for N-MOSFET

For P-channel FETs, both v_{sat} and μ are about half that of N-FETs

c_{ox} = gate capacitance per unit area = $\varepsilon_r \varepsilon_0 / T_{ox}$ ($\varepsilon_r = 3.8$ for SiO_2)

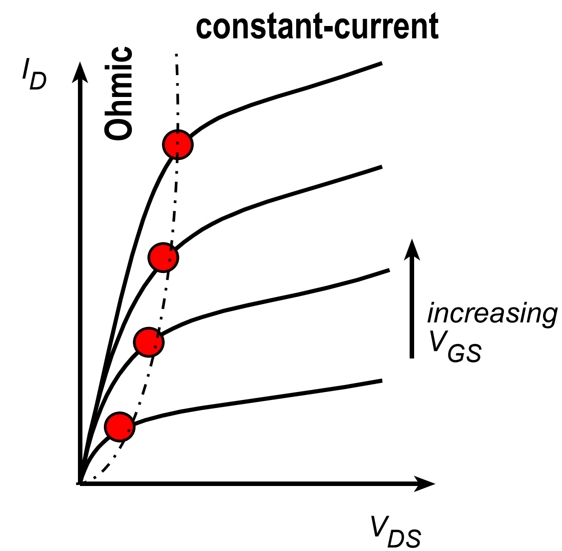
T_{ox} = equivalent oxide thickness - about 1 nm = 10^{-9} m

V_{th} threshold voltage --- usually 0.2 - 0.4 V for modern N-FETs

λ gives slope of output characteristics: $1/\lambda$ typically 3 - 20 V

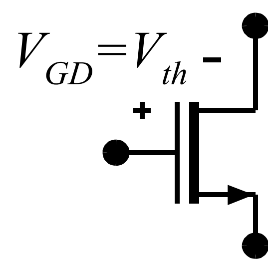
Knee Voltage: Mobility-Limited Case

The knee voltage defines the boundary between the Ohmic and constant - current regions

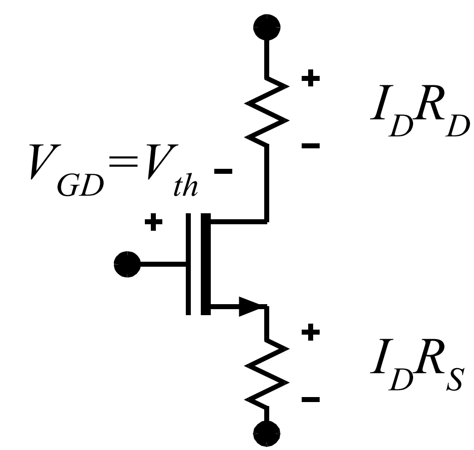


In the mobility - limited regime, the knee in curve occurs when

$$V_{dg} = V_{ds} - V_{gs} = -V_{th}$$

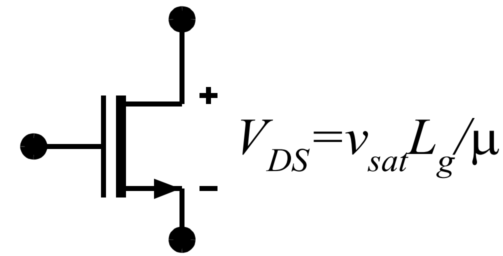


The Knee Voltage is further increased by voltage drops across the parasitic source & drain resistances.

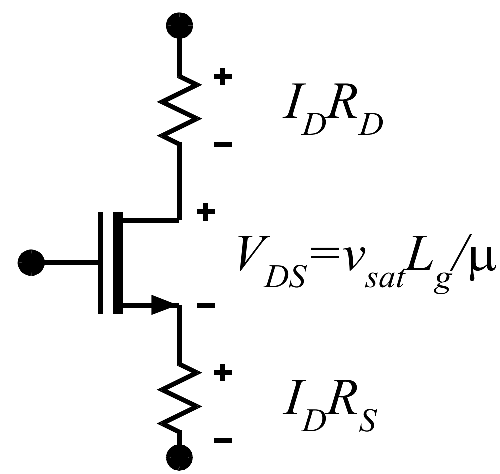


Knee Voltage: Velocity-Limited Case

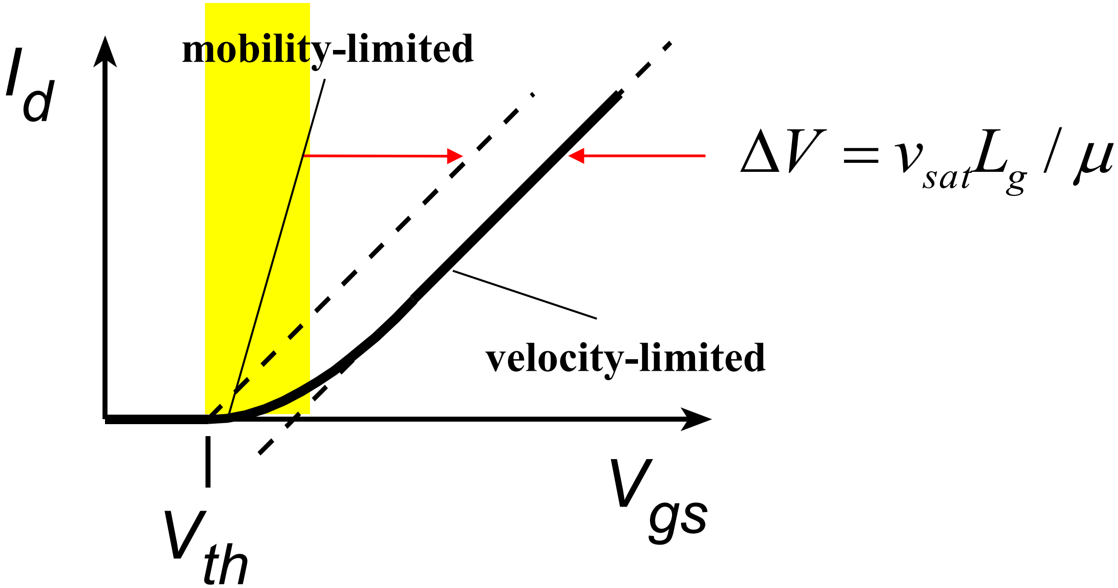
In the velocity - limited regime, the knee in curve occurs when $V_{ds} = v_{sat} L_g / \mu$



Again, the Knee Voltage is further increased by voltage drops across the parasitic source & drain resistances.



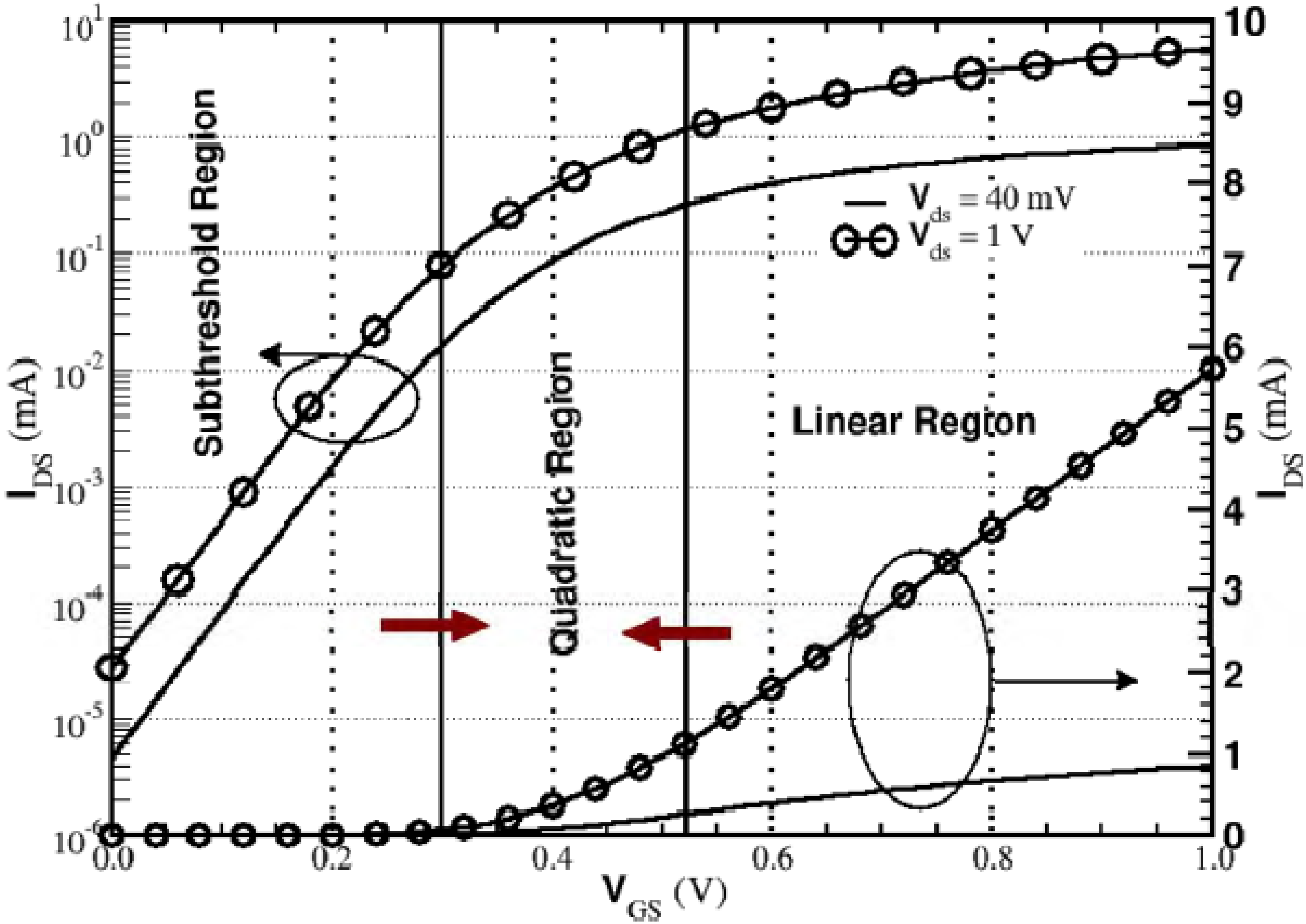
Which Model to use When ?



$$\text{If } V_{gs} - V_{th} < \Delta V \quad \text{where } \Delta V = v_{sat} L_g / \mu \text{, use the constant - mobility model}$$

$$\text{If } V_{gs} - V_{th} > \Delta V \quad \text{, use the constant - velocity model}$$

Linear vs. Square-Law Characteristics: 90 nm



Sorin Voinigescu, CSICS RF & High Speed CMOS, Nov. 12, 2006

Which Model to use When ?

for 90 nm CMOS, ΔV is about 0.2 - 0.3 V

For 45 nm CMOS, ΔV is about 0.15 V

short gate length devices obey the velocity model.

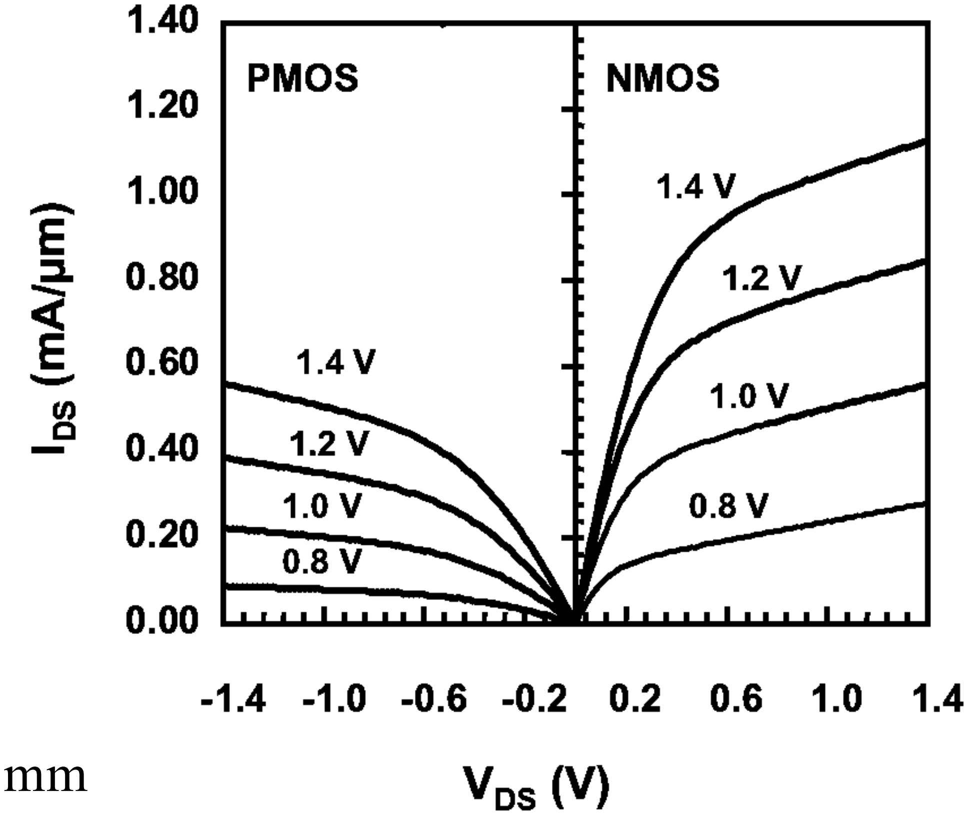
- but -

short gate length devices have very low breakdown voltage.

- so -

analog circuit design is very hard with short-gate-length devices.

90 nm MOSFET DC Characteristics



N - channel

$$g_m / W_g = c_{ox} v_{sat} = 1.4 \text{ mS/μm} = 1.4 \text{ S/mm}$$

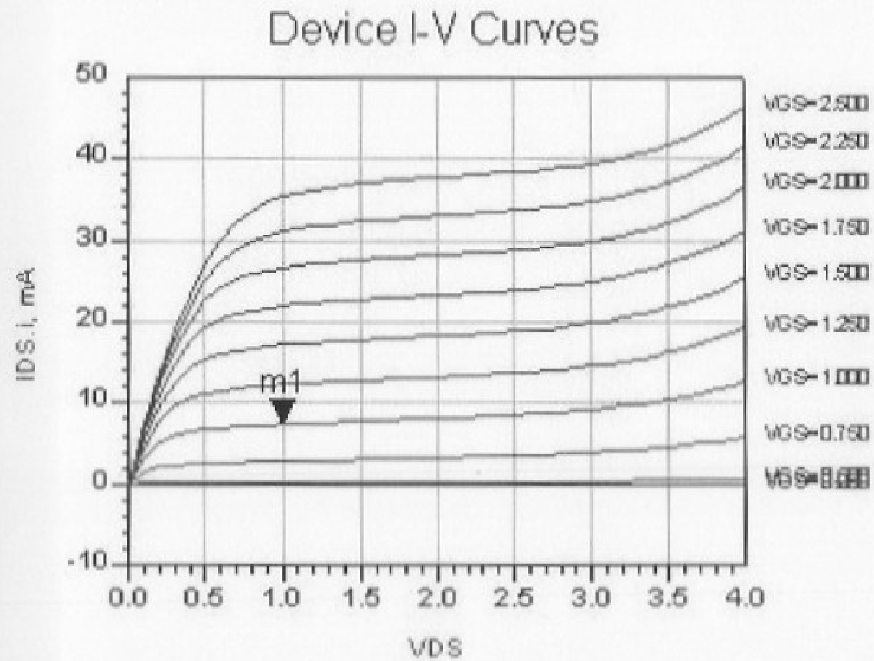
$$V_{th} = 0.6 \text{ V} \quad 1/\lambda \sim 3\text{V}$$

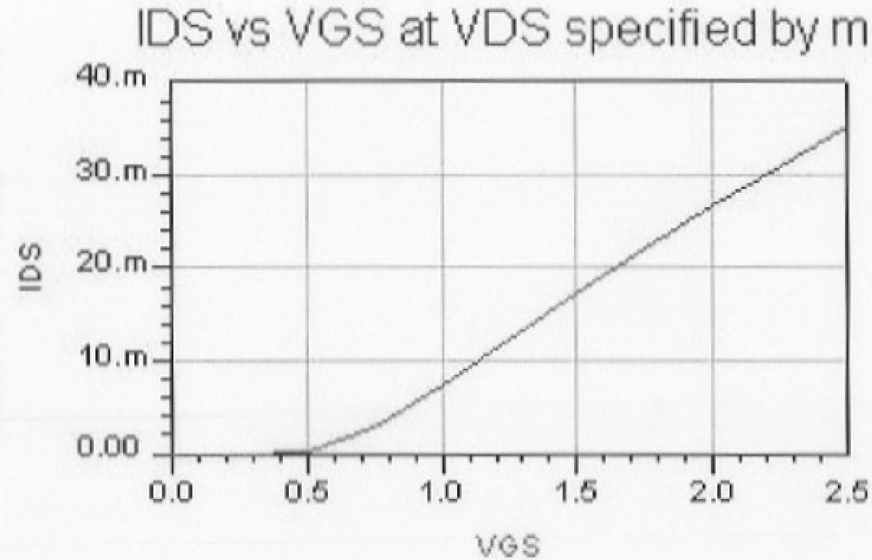
P - channel

$$g_m / W_g = c_{ox} v_{sat} = 0.7 \text{ mS/μm} = 0.7 \text{ S/mm}$$

$$|V_{th}| = 0.6 \text{ V} \quad 1/\lambda \sim 3\text{V}$$

180 nm MOSFET DC Characteristics





$$g_m / W_g = c_{ox} v_{sat} = 35\text{mA} / (2\text{V} \cdot 80\,\mu\text{m})$$

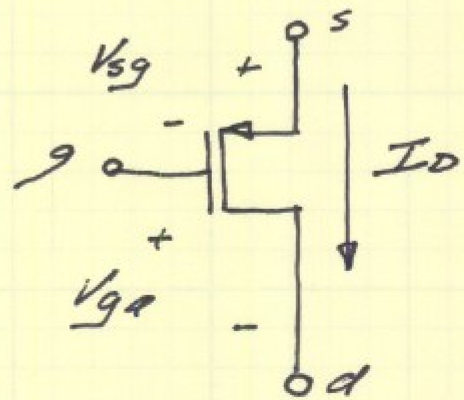
$$= 0.22\text{mS} / \mu\text{m} = 0.22\,\text{S} / \text{mm}$$

This is lower than typical of a 180 nm device

$$V_{th} = 0.5\,\text{V}$$

P-Channel MOSFET

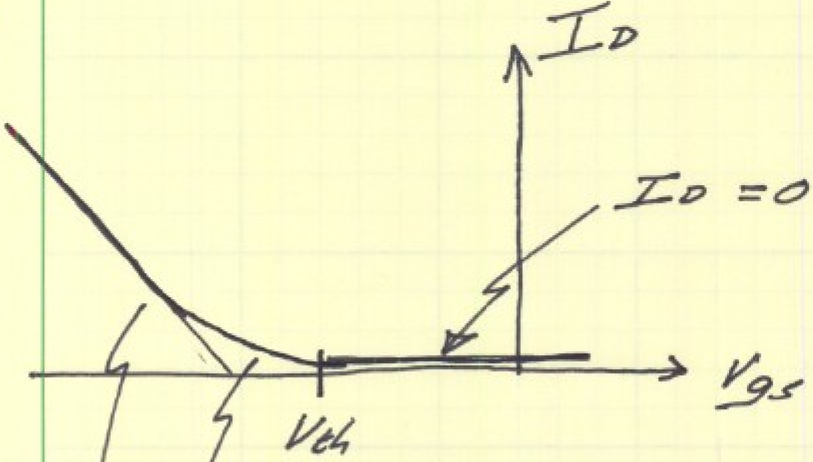
p-channel MOSFET



To turn the device on

the gate must be more negative than the source, by an amount exceeding the threshold voltage V_{th}

P-Channel MOSFET



$$I_D = (\mu C_{ox} W_g / L_g)\left(-(V_{gs} - V_{th})\right)^2 (1 + \lambda V_{DS})$$

$$I_D = v_{sat} C_{ox} W_g \left(-(V_{gs} - V_{th} - \Delta V)\right)(1 + \lambda V_{DS})$$

P-Channel MOSFET

The device is in the constant current region if V_{ds} above the knee voltage.

Example: constant mobility model:

knee @ $V_{DG} < -V_{th}$

example: suppose the threshold voltage is -1V. Then the P-MOSFET is in the constant-current region if the drain is <u>at</u> <u>most</u> 1V more positive than the gate.