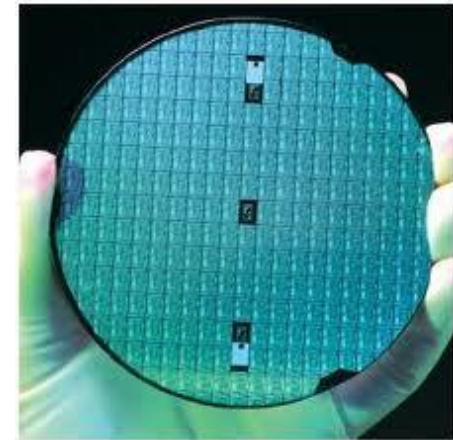
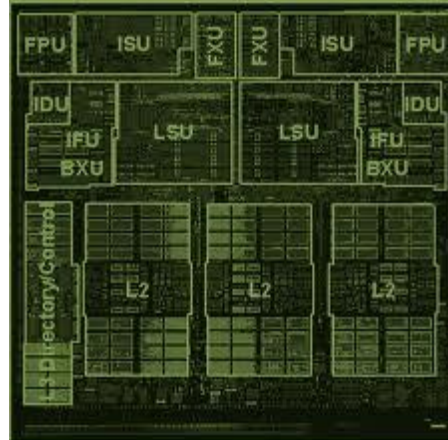
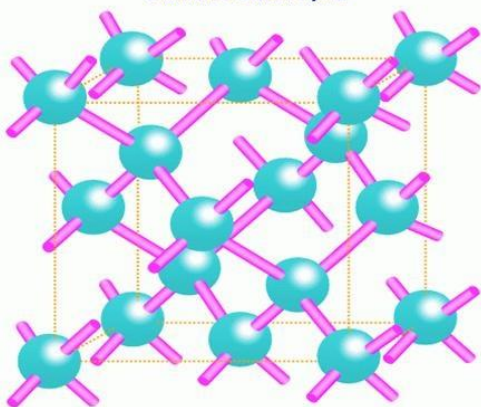


Structure of silicon crystal



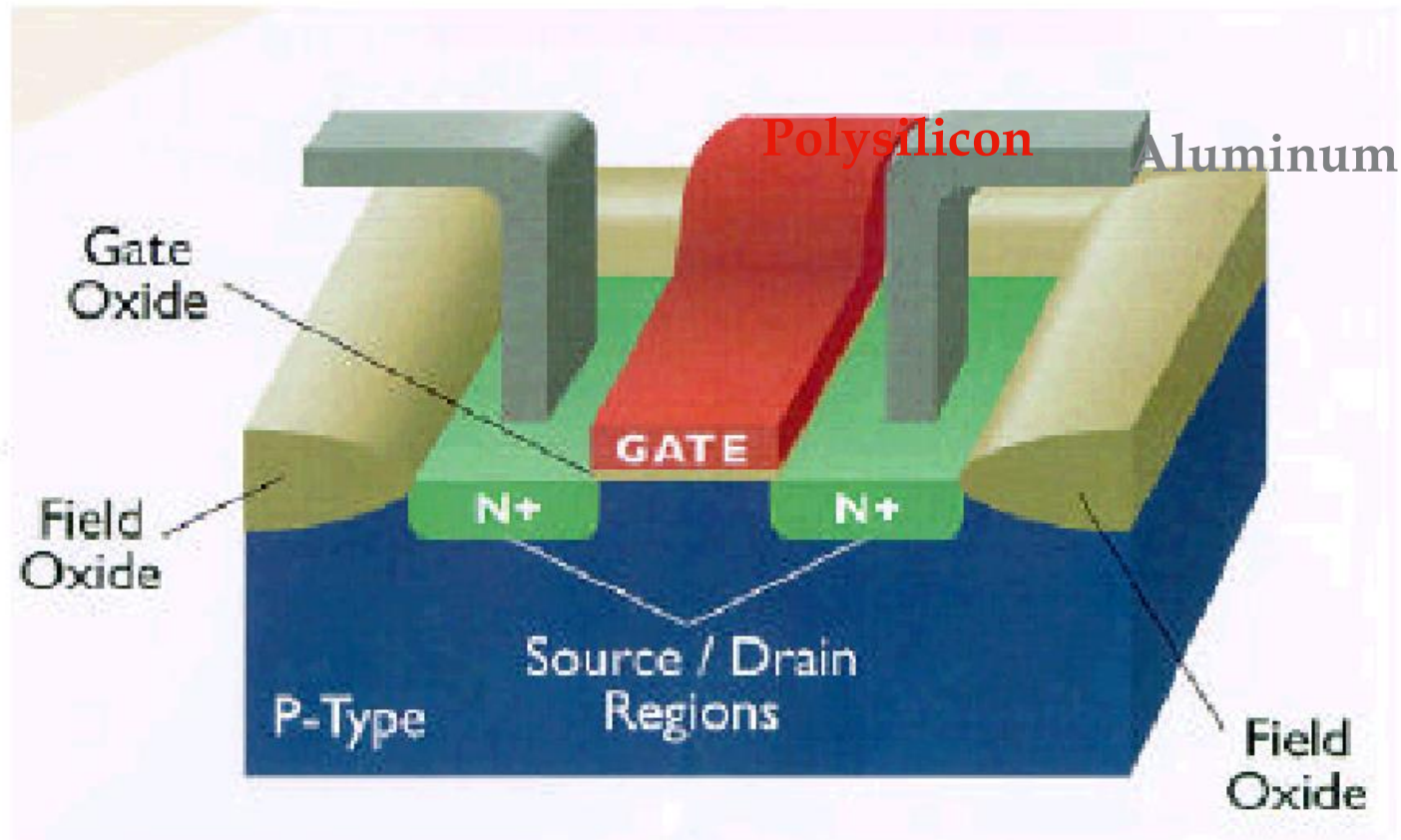
ECE 122A

VLSI Principles

Lecture 7

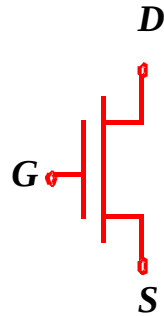
Prof. Kaustav Banerjee
Electrical and Computer Engineering
University of California, Santa Barbara
E-mail: kaustav@ece.ucsb.edu

The MOS Transistor

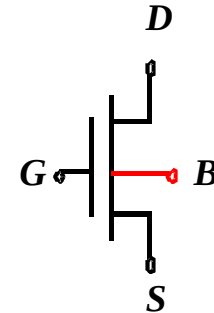
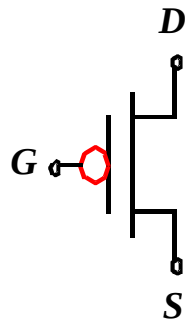


MOS Transistors - Types and Symbols

NMOS



PMOS



**NMOS with
Body Contact**

For NMOS: Body tied to Gnd

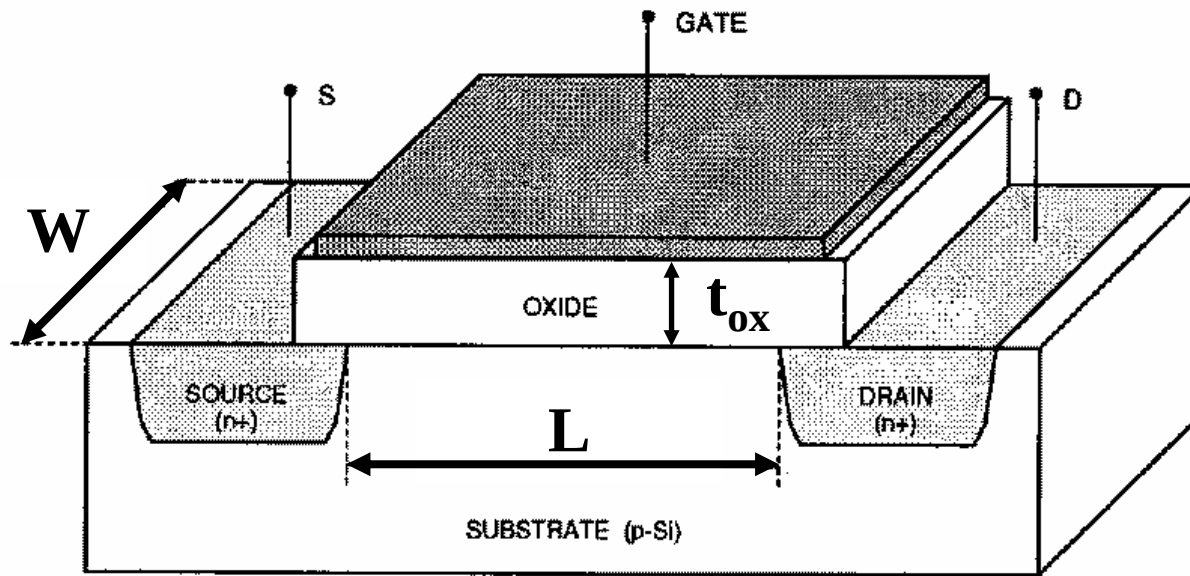
For PMOS: Body tied to Vdd

Why?

MOS Transistor

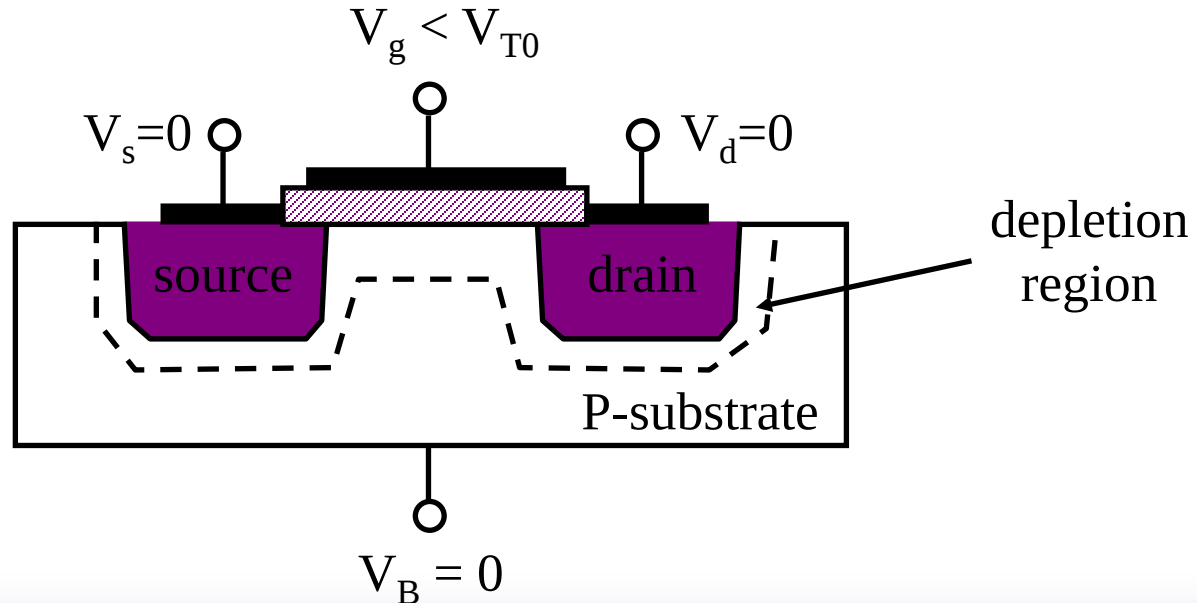
□ Important transistor physical characteristics

- Channel length L
- Channel width W



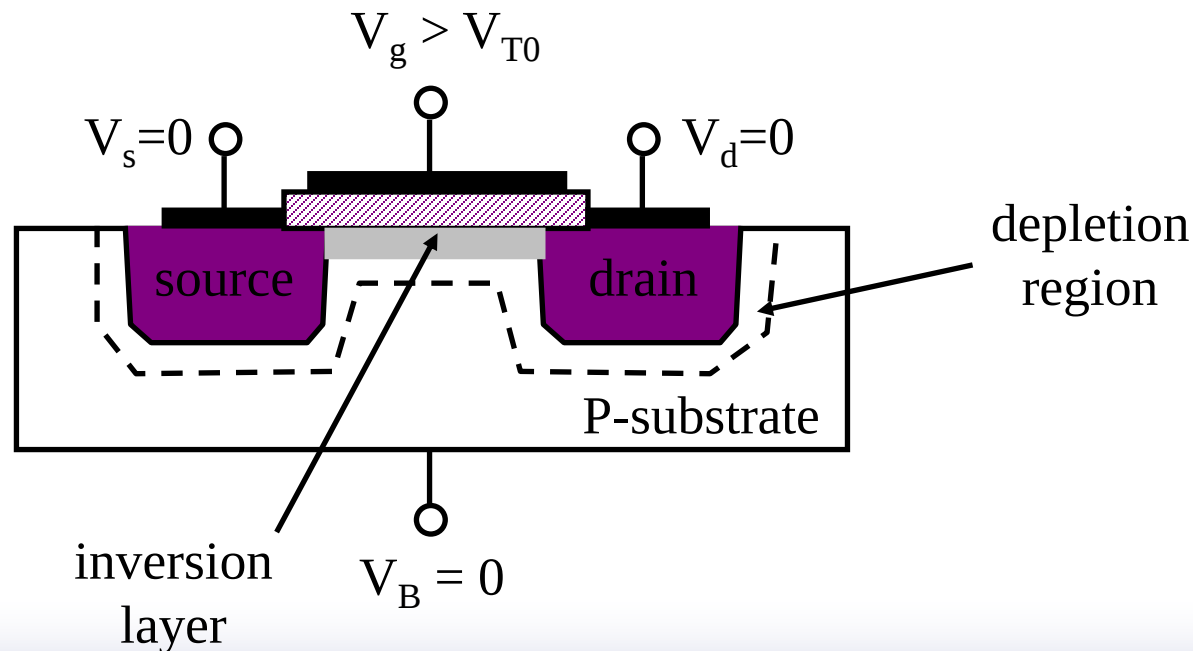
MOS Transistor Operation

- ❑ Simple case: $V_D = V_S = V_B = 0$
 - Operates as MOS capacitor
- ❑ When $V_{GS} < V_{T0}$ (but positive), depletion region forms
 - No carriers in channel to connect S and D
- ❑ V_{T0} is known as the *threshold voltage*

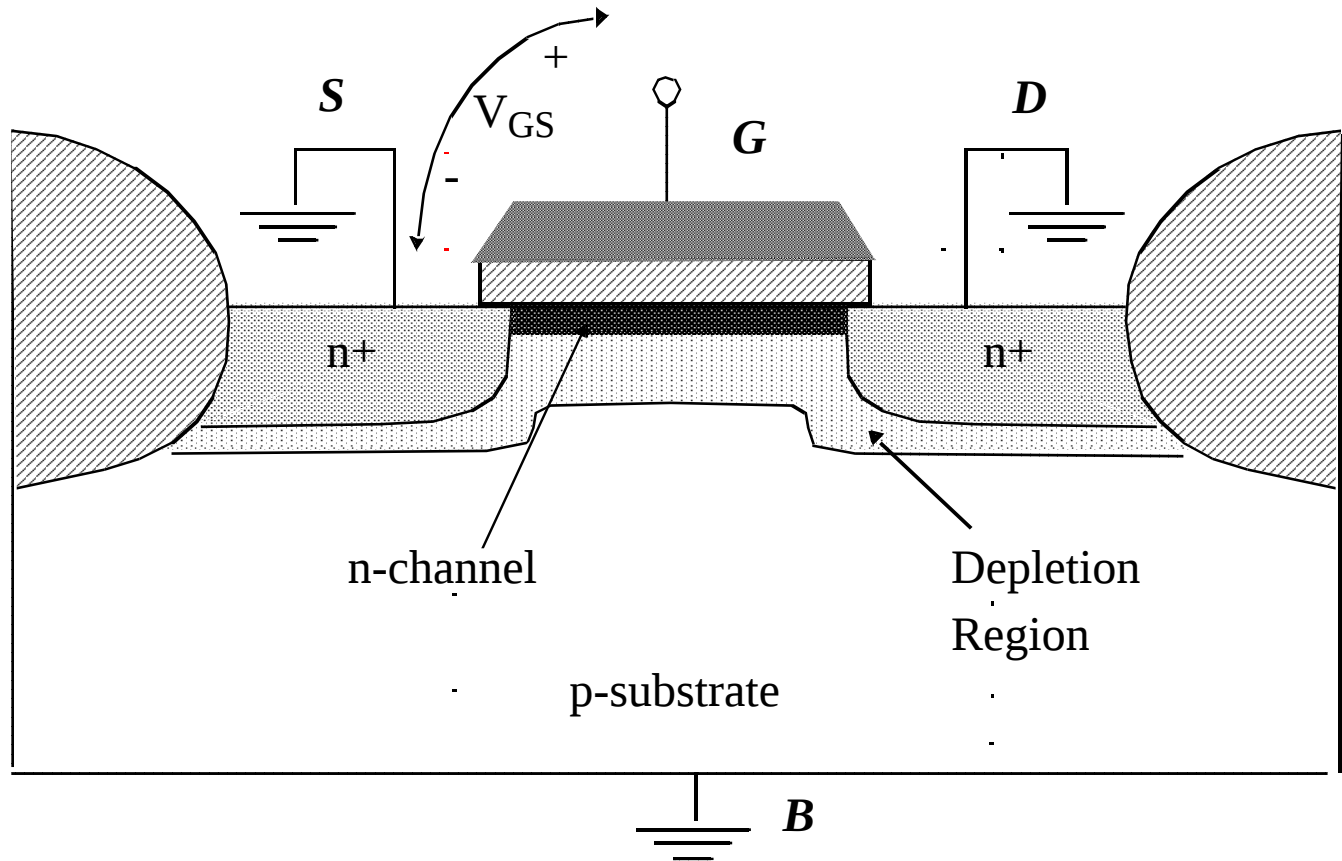


MOS Transistor Operation

- When $V_{GS} > V_{T0}$, inversion layer forms
- Source and drain connected by conducting n-type layer (for NMOS)



Threshold Voltage (V_{T0}): Concept



Note: gate is insulated from the substrate...hence no dc current flows through the oxide...channel is capacitively coupled to the gate through the electric-field in the oxide....that's how it gets the name MOS-FET (field effect transistor)

Physical Parameters that Affect V_{T0}

- ❑ Threshold voltage (V_{T0}): voltage between gate and source required for inversion
 - NMOS Transistor is “off” when $V_{GS} < V_{T0}$
- ❑ Components:
 - Work function difference between gate and channel (Flat-band voltage)
 - Gate voltage to change surface potential
 - Gate voltage to offset depletion region charge
 - Gate voltage to offset fixed charges in gate oxide and in silicon-oxide interface

Threshold voltage (1)

- Work function difference $q\Phi_{GC}$ between gate and channel
 - Represents built-in potential of MOS system
 - For metal gate: $\Phi_{GC} = \Phi_M(\text{metal-gate}) - \Phi_F(\text{substrate}) = \Phi_{ms}$
 - For poly gate: $\Phi_{GC} = \phi_F(\text{poly-Si-gate}) - \phi_F(\text{substrate})$

$$V_{T0} = \Phi_{GC} + \dots$$

Threshold voltage (2)

- First component accounts for built-in voltage drop
- Now apply additional gate voltage to achieve inversion: change surface potential by $-2\phi_F$ (note that ϕ_F is negative for p-type substrate)

$$V_{T0} = \Phi_{GC} - 2\phi_F + \dots$$

Threshold voltage (3)

- Offset depletion region charge, due to fixed acceptor ions
- Calculate charge at inversion ($\phi_S = -\phi_F$)

- From before: $Q = -\sqrt{2qN_A\epsilon_{Si}|\phi_S - \phi_F|}$

- So: $Q_{B0} = -\sqrt{2qN_A\epsilon_{Si}|-2\phi_F|}$

Depletion charge is negative....why? (acceptor ions after accepting electrons are -ve)

- For non-zero substrate bias ($V_{SB} \neq 0$):

$$Q_B = -\sqrt{2qN_A\epsilon_{Si}|-2\phi_F + V_{SB}|}$$

- Due to larger depletion region

Threshold voltage (3, cont.)

- To offset this charge, need voltage $-Q_B/C_{ox}$
- C_{ox} = gate capacitance per unit area
 - $C_{ox} = \epsilon_{ox}/t_{ox}$
 - t_{ox} = thickness of gate oxide (normally in Å)

$$V_{T0} = \Phi_{GC} - 2\phi_F - \frac{Q_B}{C_{ox}} + \dots$$

Threshold voltage (4)

- Finally, correct for non-ideal fixed charges
 - Fixed positive charged ions at boundary between oxide and substrate. Density = N_{ox}
 - Due to impurities, lattice imperfections at interface
 - Positive charge density $Q_{ox} = qN_{ox}$
 - Correct with gate voltage = $-Q_{ox}/C_{ox}$
- Final threshold voltage formula (for NMOS):

$$V_{T0} = \Phi_{GC} - 2\phi_F - \frac{Q_{B0}}{C_{ox}} - \frac{Q_{ox}}{C_{ox}}$$

Threshold voltage, summary

- If $V_{SB} = 0$ (no substrate bias):

$$V_{T0} = \Phi_{GC} - 2\phi_F - \frac{Q_{B0}}{C_{ox}} - \frac{Q_{ox}}{C_{ox}}$$

- If $V_{SB} \neq 0$ (non-zero substrate bias)

$$V_T = V_{T0} + \gamma \left(\sqrt{|-2\phi_F + V_{SB}|} - \sqrt{|2\phi_F|} \right) \quad \text{For uniform body doping....}$$

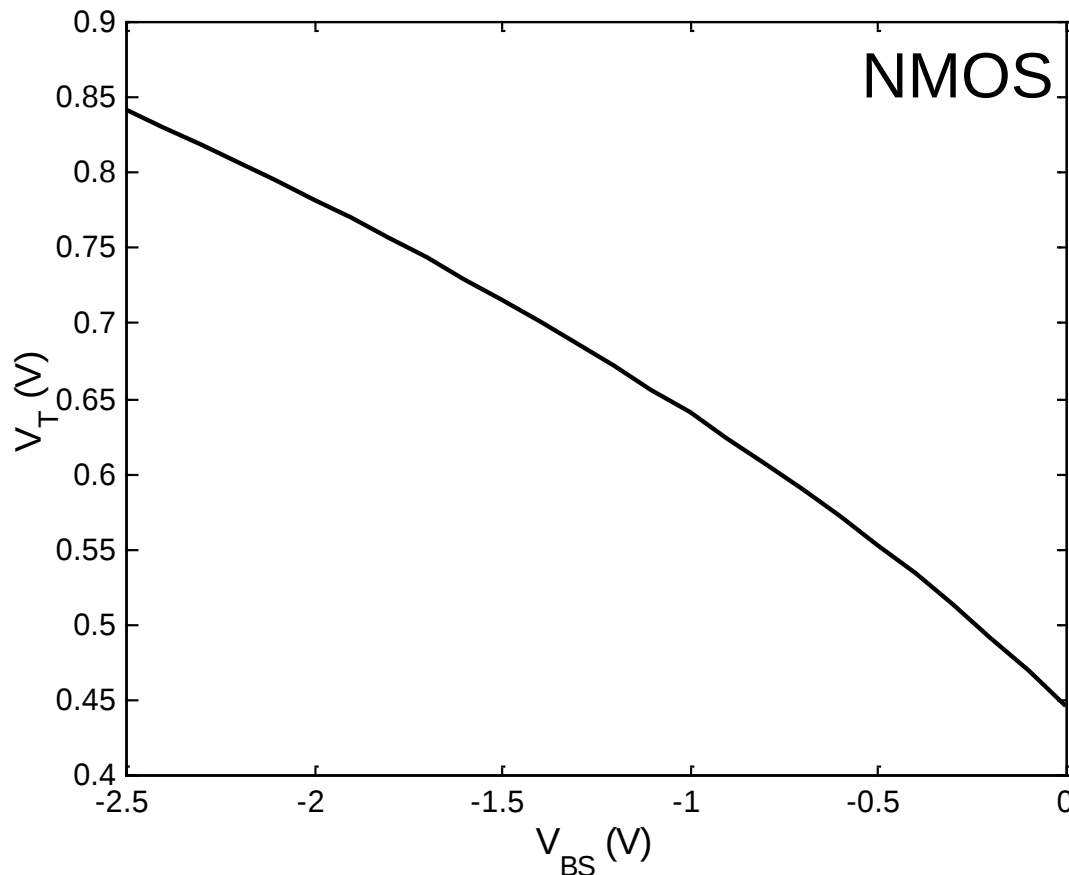
- Body effect (substrate-bias) coefficient:

$$\gamma = \frac{\sqrt{2qN_A\epsilon_{Si}}}{C_{ox}} \quad \begin{array}{l} + \text{ for NMOS} \\ - \text{ for PMOS} \end{array}$$

For modern FETs with retrograde doping, V_T varies ~linearly with V_{SB}

- Threshold voltage increases as V_{SB} increases!
(easy to explain with a band diagram....)

The Body Effect



Draw a band diagram to convince yourself...

Threshold Voltage (NMOS vs. PMOS)

	NMOS	PMOS
Substrate Fermi potential	$\phi_F < 0$	$\phi_F > 0$
Depletion charge density	$Q_B < 0$	$Q_B > 0$
Substrate bias coefficient	$\gamma > 0$	$\gamma < 0$
Substrate bias voltage	$V_{SB} > 0$	$V_{SB} < 0$
Threshold voltage (enhancement devices)	$V_{T0} > 0$	$V_{T0} < 0$

Remember: You need not memorize this table but rather should be able to fill it in based on the band diagrams...

Threshold Voltage Adjustment

- Threshold voltage can be changed by doping the channel region with donor or acceptor ions
- For NMOS:
 - V_T increased by adding acceptor ions (p-type)
 - V_T decreased by adding donor ions (n-type)
 - Opposite for PMOS
- Approximate change in V_{T0} :
 - Density of implanted ions = N_I [cm^{-2}]
 - Assume all implanted impurities are ionized

$$\Delta V_{T0} = \frac{qN_I}{C_{ox}}$$

Example: V_{T0} Adjustment

□ Consider an NMOS device:

- P-type substrate: $N_A = 2 \times 10^{16} \text{ cm}^{-3}$
- Polysilicon gate: $\Phi_{GC} = -0.92\text{V}$
- $t_{ox} = 600 \text{ \AA}$ ($1\text{\AA} = 1 \times 10^{-8} \text{ cm}$)
- $N_{ox} = 2 \times 10^{10} \text{ cm}^{-2}$
- $\epsilon_{Si} = 11.7 \epsilon_0$, $\epsilon_{ox} = 3.97 \epsilon_0$

□ (a) Find V_{T0}

□ (b) Find amount and type of channel implant to get $V_{T0} = 0.4 \text{ V}$

MOS Capacitor (Review)

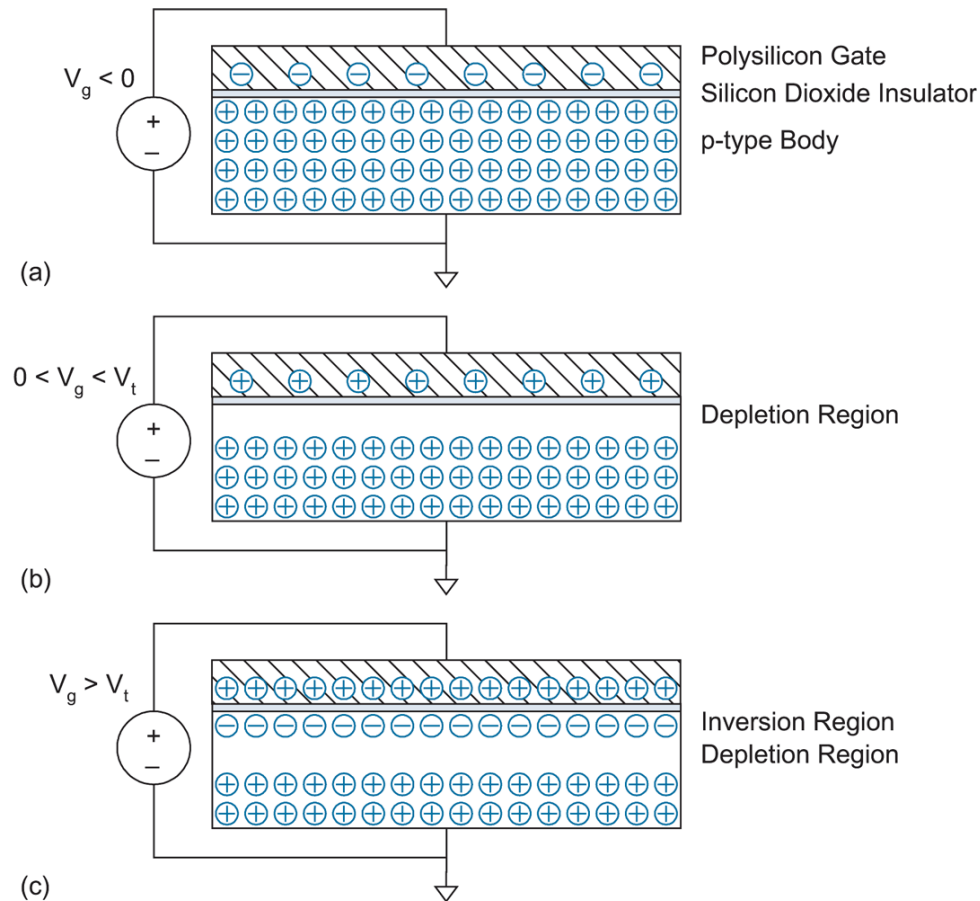
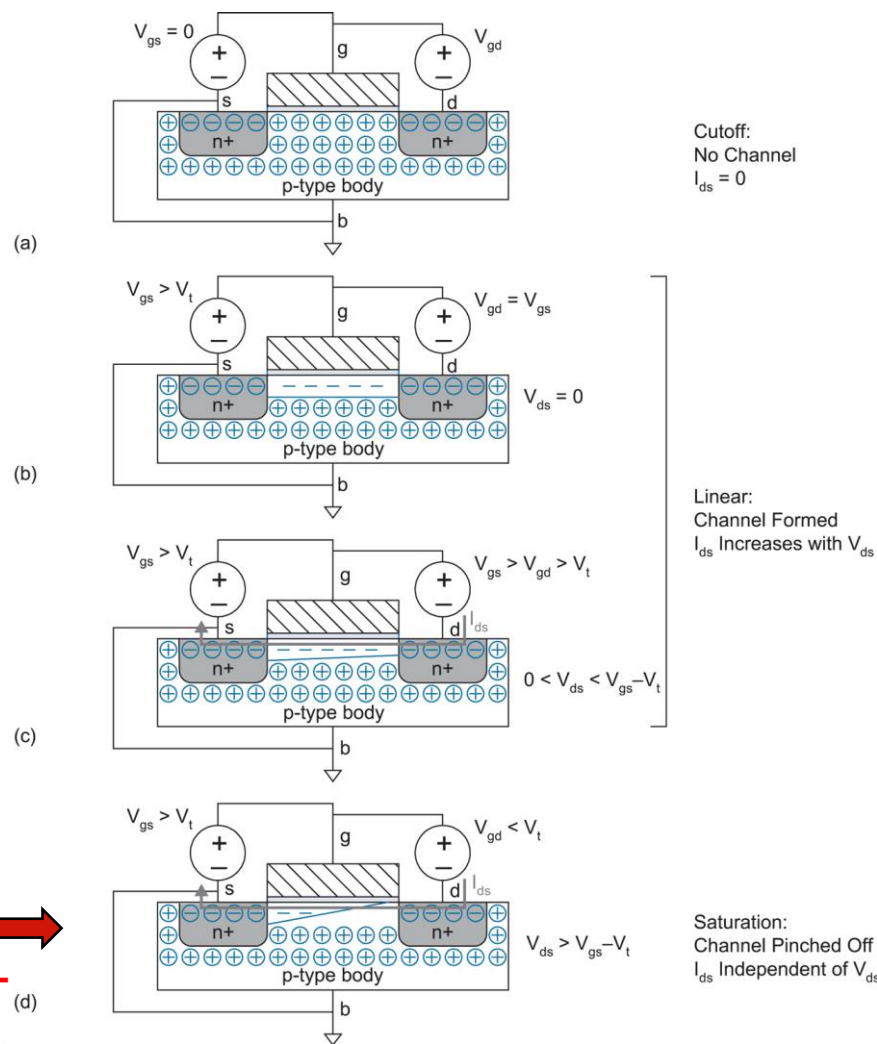


FIG 2.2 MOS structure demonstrating (a) accumulation, (b) depletion, and (c) inversion

MOSFET Operation (NMOS)

Easy to understand
with a band diagram
across S-Ch-D.....



Remember, both
drift and diffusion
currents play a
role...

**Pinch-off: conduction
still takes place from
Source to Drain due to
drift of electrons under
the influence of the +ve
drain voltage**

$V_{GS} - V(x) < V_t$
**Conduction
dominated by DRIFT**

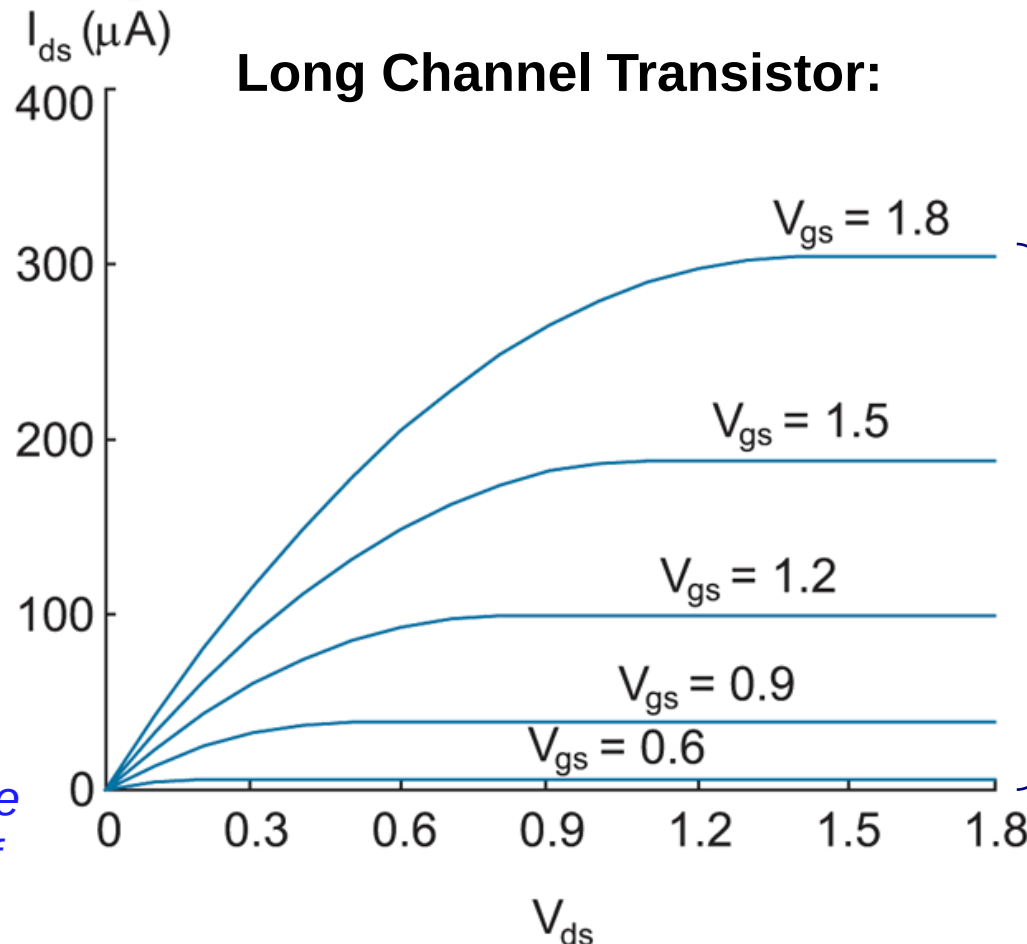


FIG 2.3 nMOS transistor demonstrating cutoff, linear, and saturation regions of operation

NMOS Output Characteristics

Recall that the surface channel vanishes at the drain end of the channel....when current saturates...known as “pinch-off”

Any voltage $V_{DS} > V_{D,sat}$ is dropped across the high-field pinch-off region...where inversion charge = 0



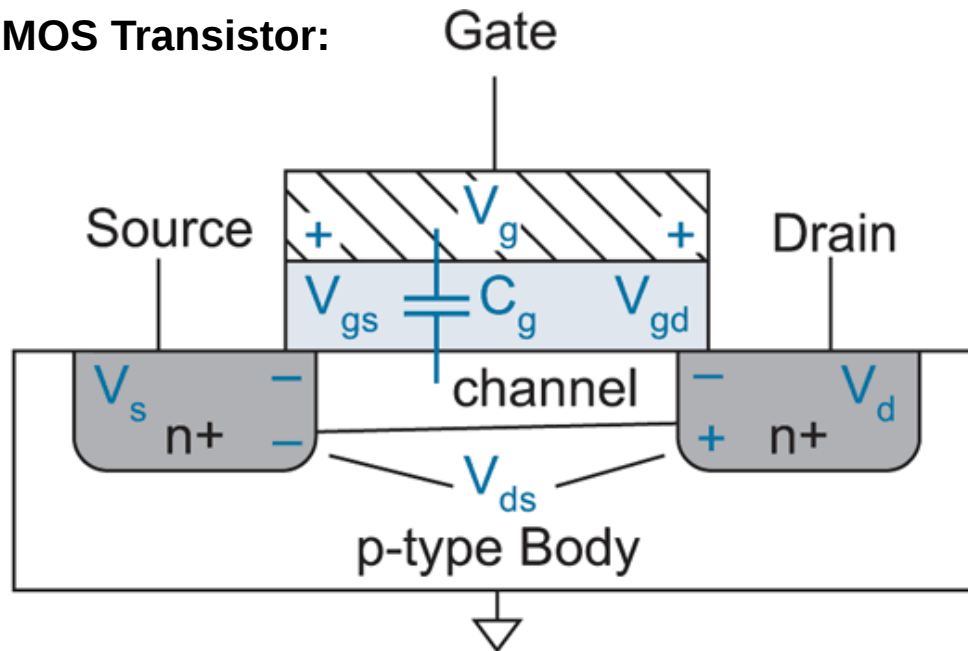
Quadratic Relationship

The saturation voltage $V_{D,sat}$ can be estimated by equating dI_{ds}/dV_{ds} to zero

FIG 2.7 I-V characteristics of ideal nMOS transistor

Channel Mobile Charge

NMOS Transistor:



*Note: i) The inversion layer thickness is assumed to be zero: all charges are assumed to be located at the Si surface....like a sheet of charge....
ii) Hence, there is no potential drop or band bending across the inversion layer....*

$$V_{ds} = V_{gs} - V_{gd} \quad \text{Use Kirchoff's voltage law: } -V_{gs} + V_{ds} + V_{gd} = 0$$

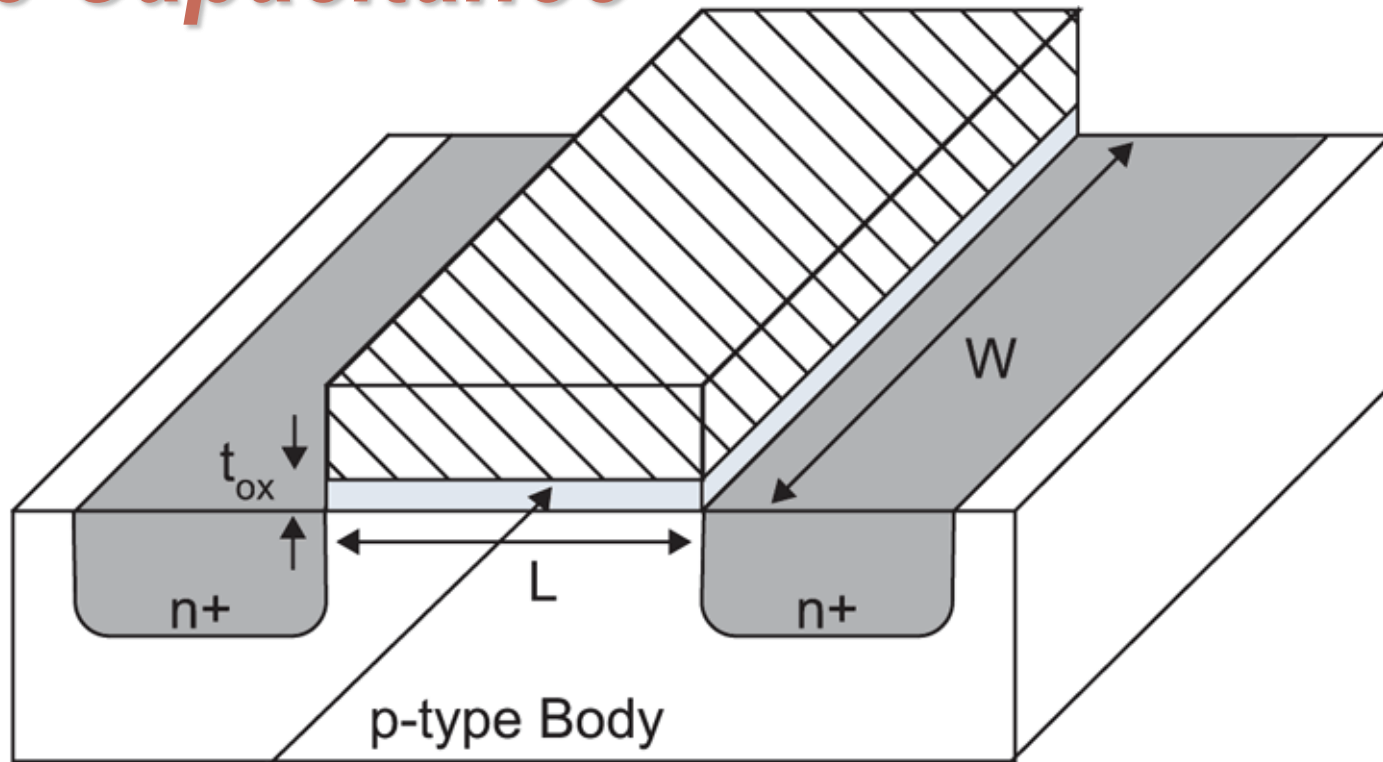
Average gate to channel potential:

$$V_{gc} = (V_{gs} + V_{gd})/2 = V_{gs} - V_{ds}/2$$

$$Q_{channel} = C_g (V_{gc} - V_t)$$

FIG 2.5 Average gate to channel voltage

Gate Capacitance



SiO₂ Gate Oxide
(Good insulator, $\epsilon_{ox} = 3.9\epsilon_0$)

$$C_g = C_{ox} = \epsilon_{ox} WL/t_{ox}$$

FIG 2.6 Transistor dimensions

Transistor Currents (NMOS)

Cutoff Region: $I_{ds} = 0$, $V_{gs} < V_t$

Linear Region: $V_{gs} > V_t$, $V_{ds} < V_{gs} - V_t$

$$I_{ds} = W Q_{channel} \cdot \text{carrier velocity}(v)$$

$$I_{ds} = \mu C_{ox} W/L (V_{gs} - V_t - V_{ds}/2) V_{ds}$$

Since V_{ds} is small, $V_{ds}/2$ can be neglected...and I_{ds} is linearly proportional to V_{ds}like a resistor

$$Q_{channel} = C_g (V_{gc} - V_t)$$

$$V_{gc} = V_{gs} - V_{ds}/2$$

$$v = \mu E$$

$$E_{lateral} = V_{ds}/L$$

$$\beta = \mu C_{ox} W/L$$

Saturation Region: $V_{gs} > V_t$, $V_{ds} > V_{gs} - V_t$

Note: as V_{ds} increases, average $Q_{channel}$ decreases...since V_{gc} decreases

$$dI_{ds}/dV_{ds} = 0 \text{ at } V_{ds} = V_{dsat} = V_{gs} - V_t$$

Substituting V_{ds} with V_{dsat} above: $I_{ds} = \beta/2 (V_{gs} - V_t)^2$

Note: for PMOS $V_{tp} = V_{tn}$, $\mu_p < \mu_n$, hence $(W/L)_{PMOS} \sim 2 (W/L)_{NMOS}$

PMOS Transistor

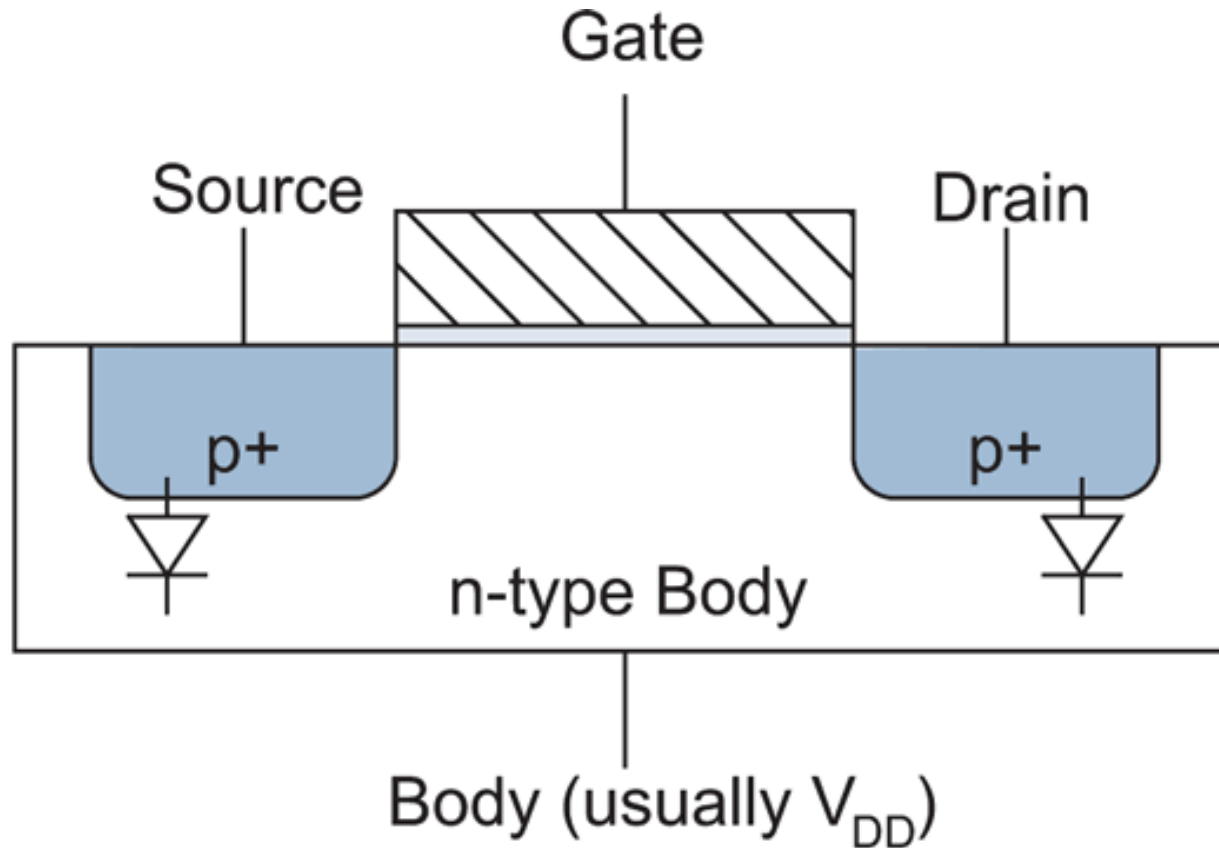


FIG 2.4 pMOS transistor

PMOS Output Characteristics

Long Channel Transistor:

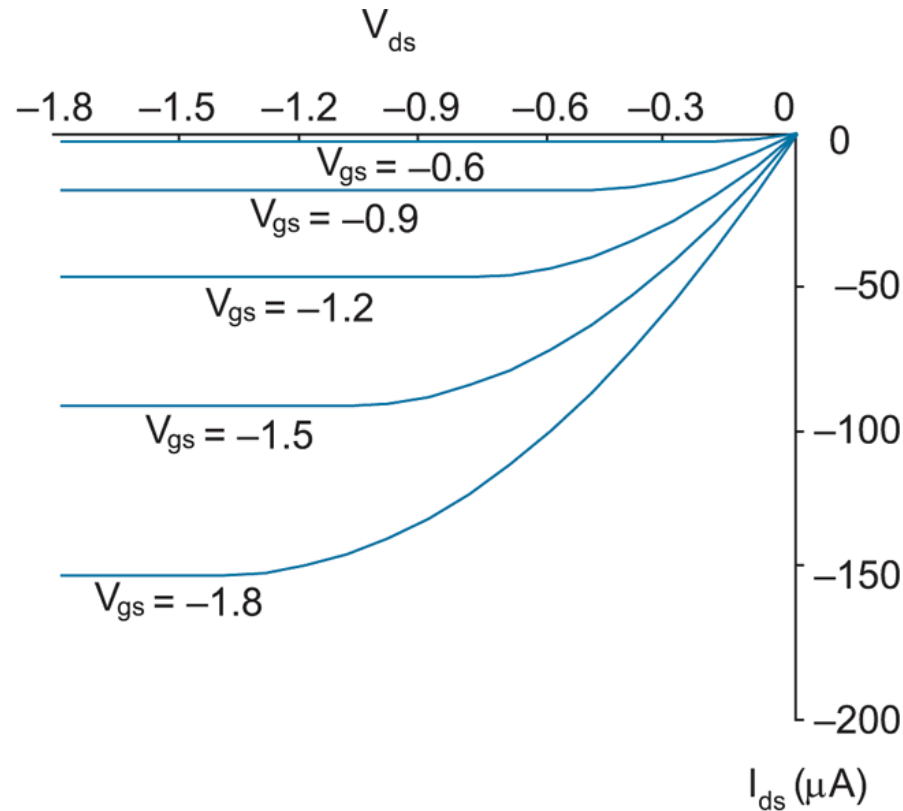


FIG 2.8 I-V characteristics of ideal pMOS transistor

Channel Length Modulation

- In saturation, pinch-off point moves
 - As V_{DS} is increased, pinch-off point moves closer to source
 - Effective channel length becomes shorter
 - Current increases due to shorter channel

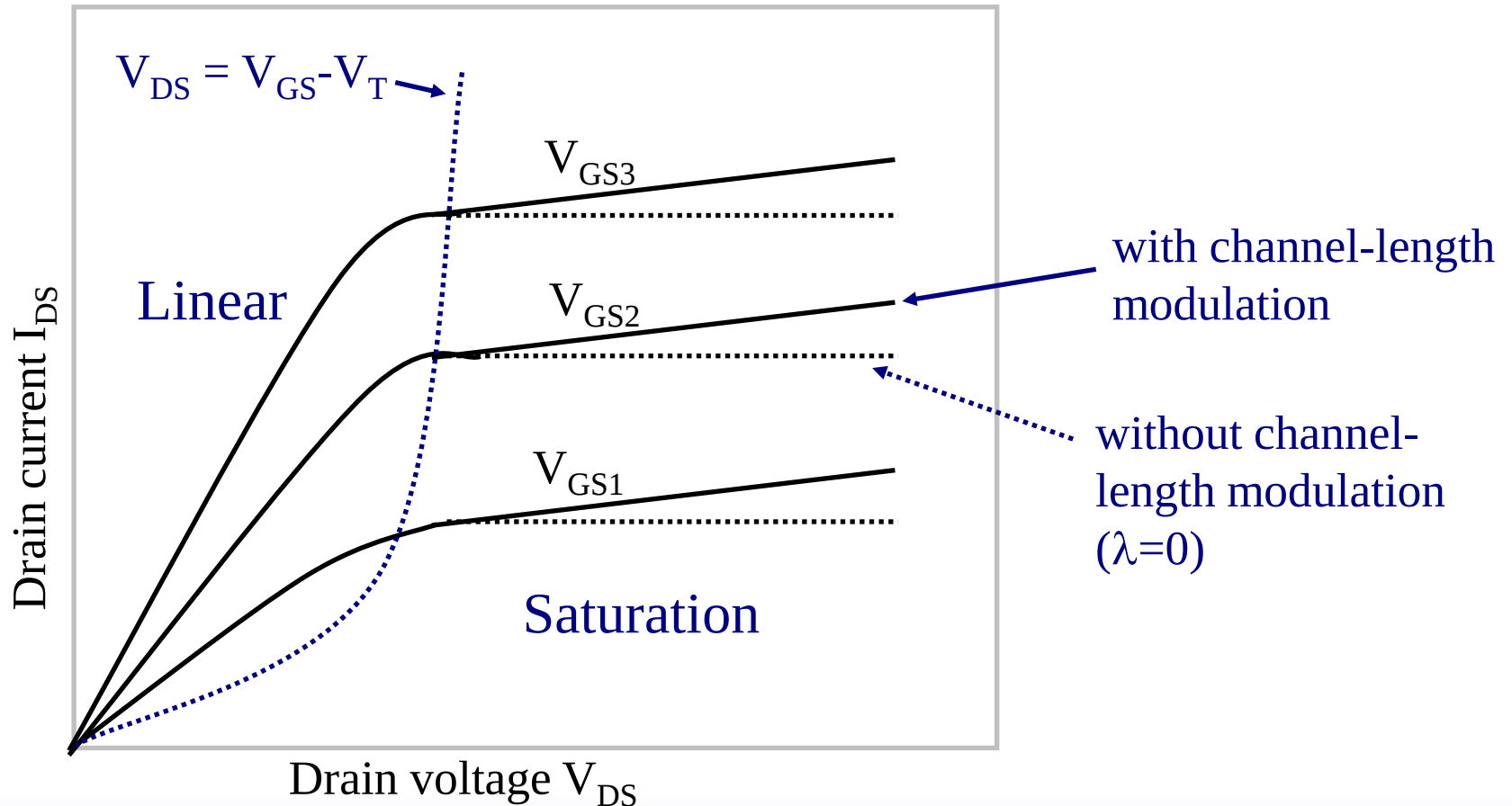
$$L' = L - \Delta L$$

$$I_D = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_{TN})^2 (1 + \lambda V_{DS})$$

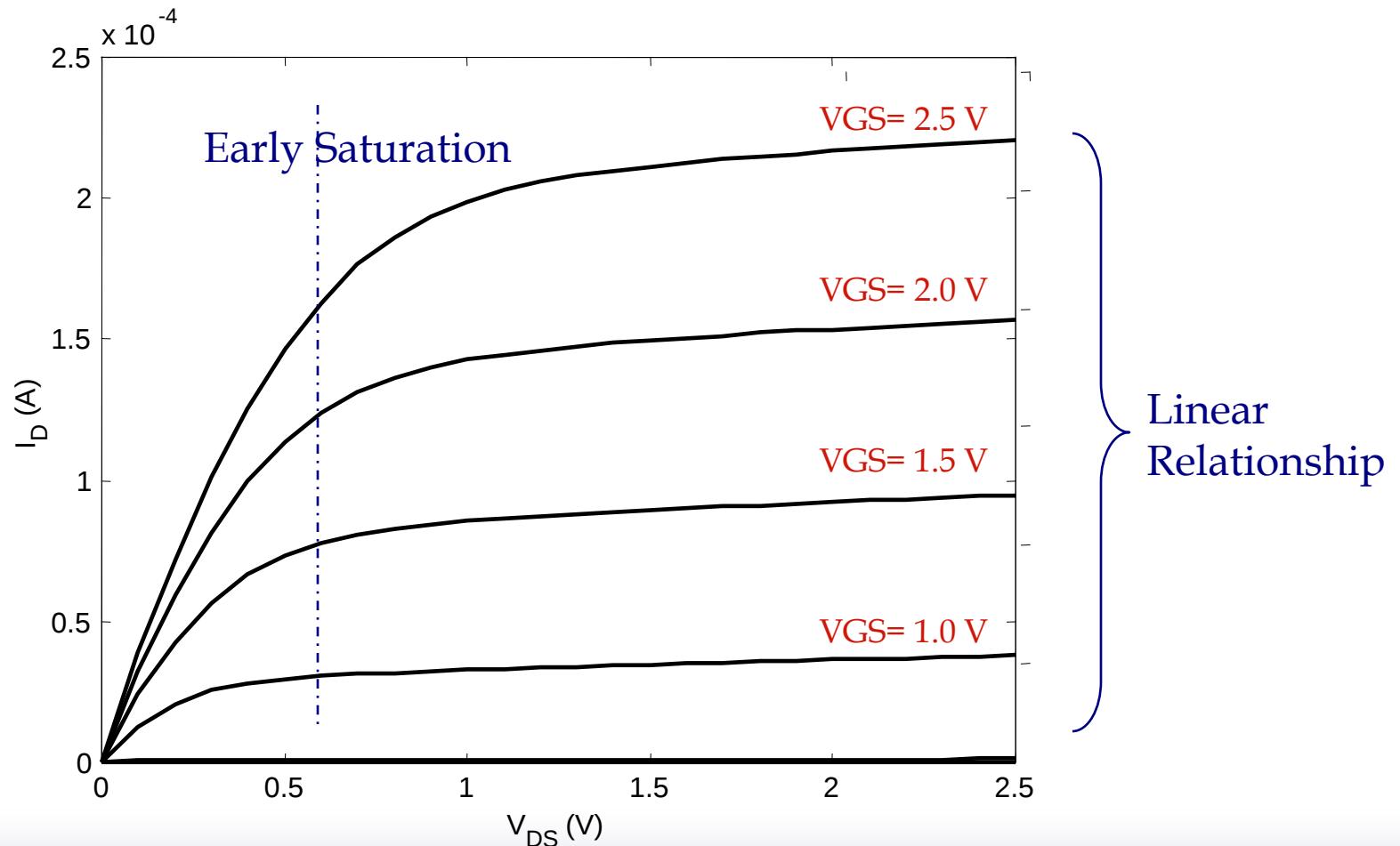
λ = channel length modulation coefficient

Summary: MOS Output I/V

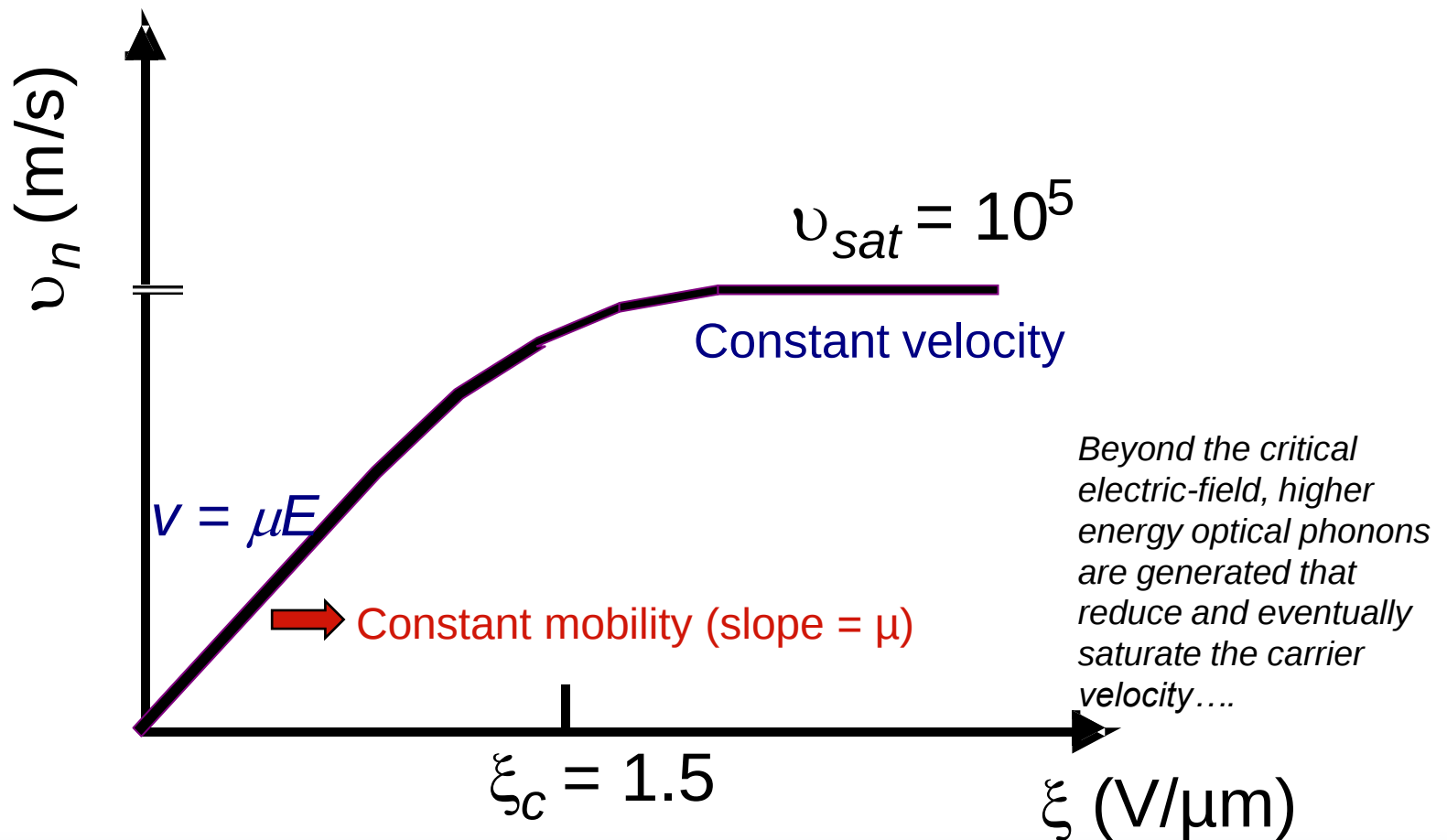
I/V curve for NMOS device:



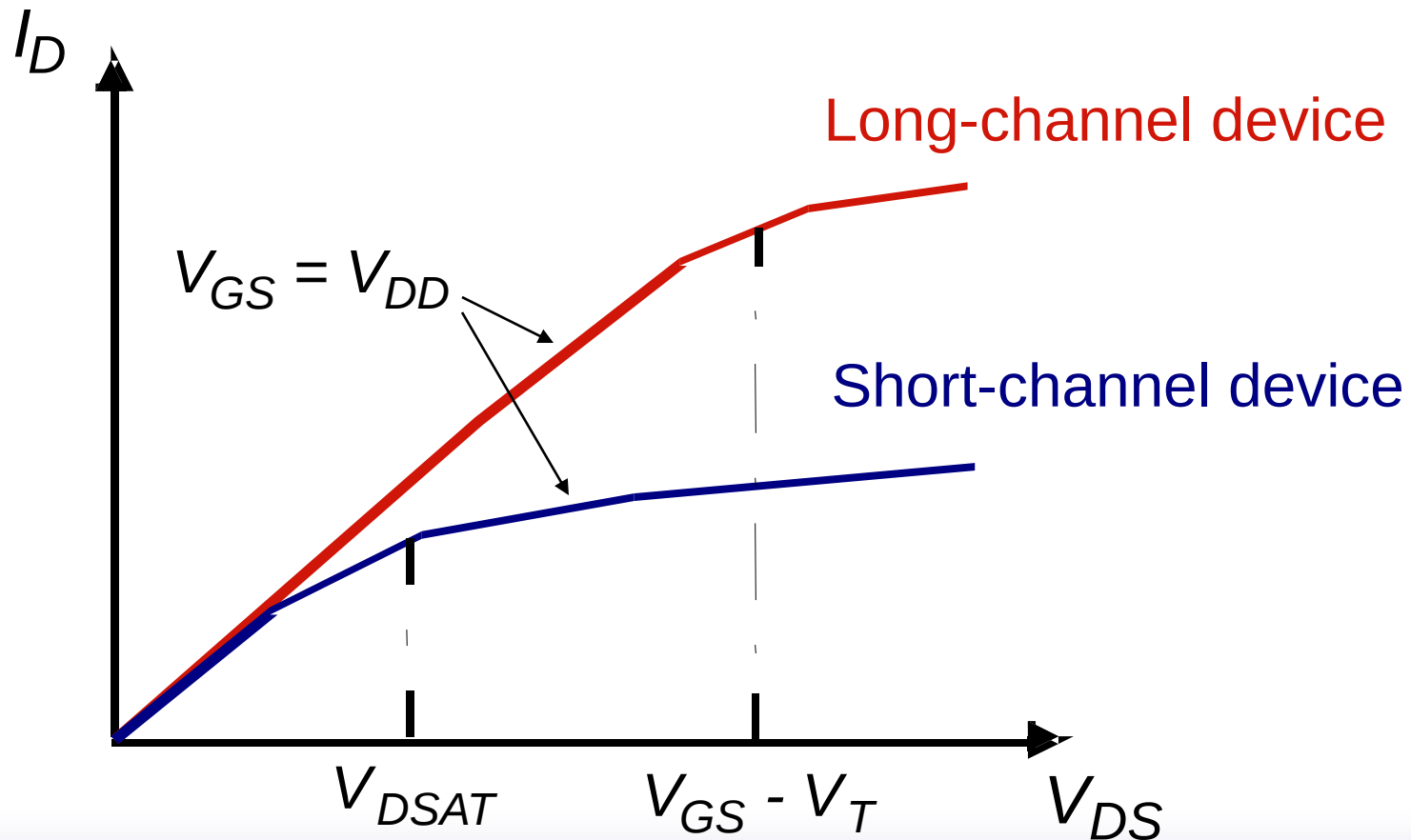
Current-Voltage Relations Short-Channel Transistors



Velocity Saturation



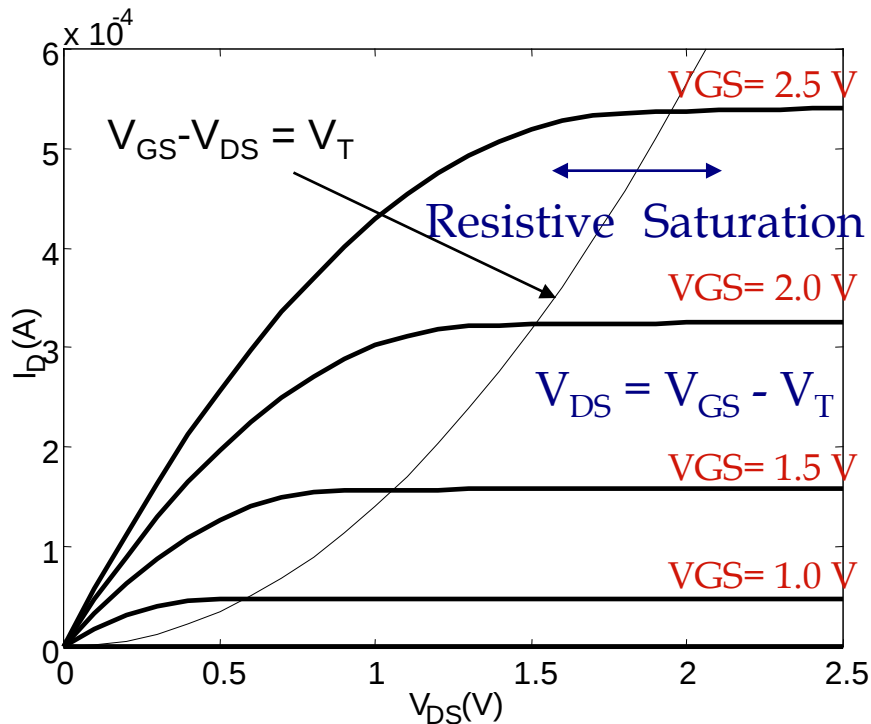
Perspective



Output Characteristics: I_D versus V_{DS}

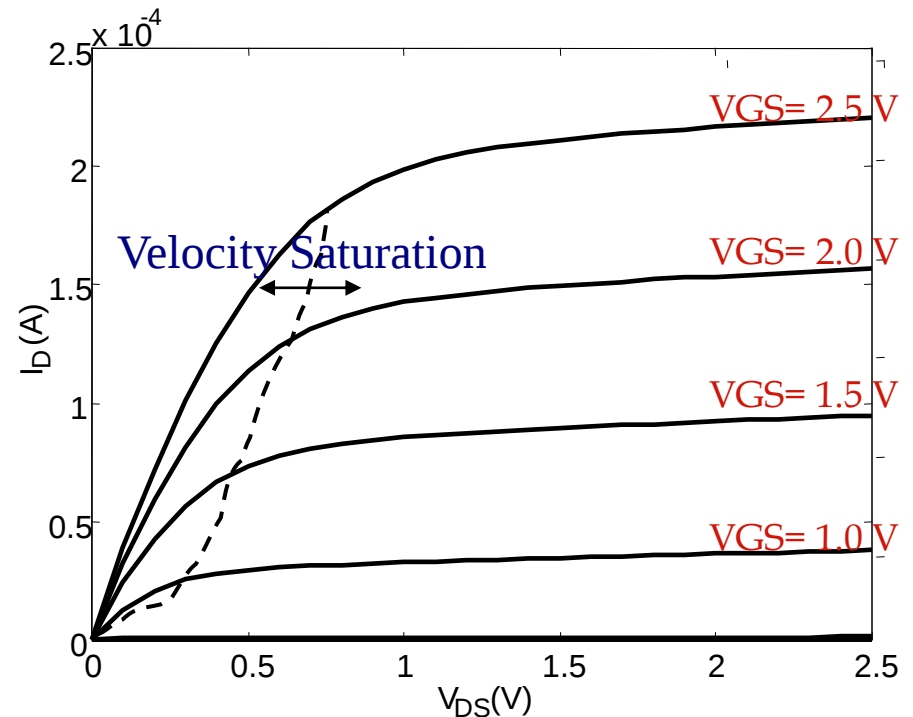
$W/L = 1.5$ for both cases....

$L = 10 \mu m$



Long Channel

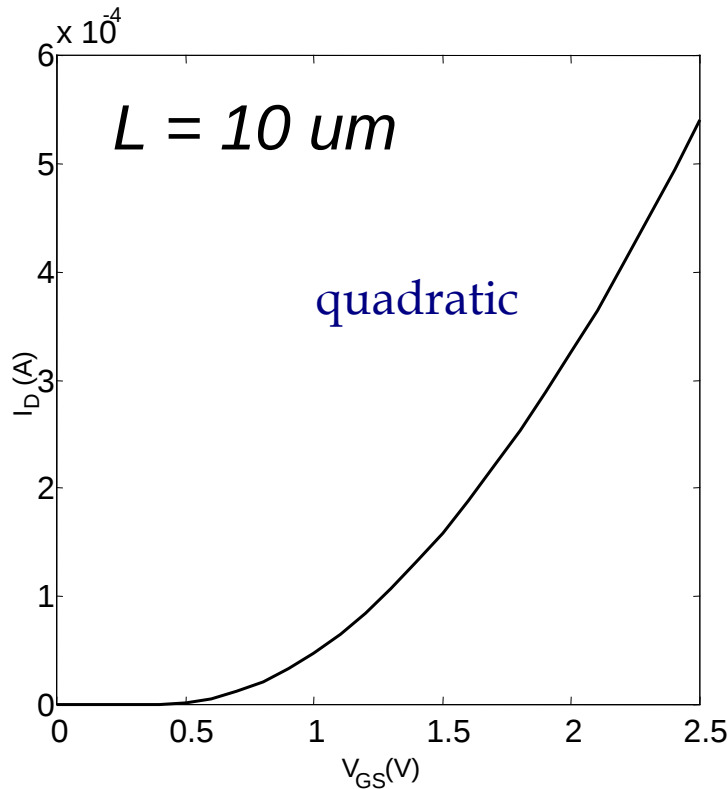
$L = 0.25 \mu m$



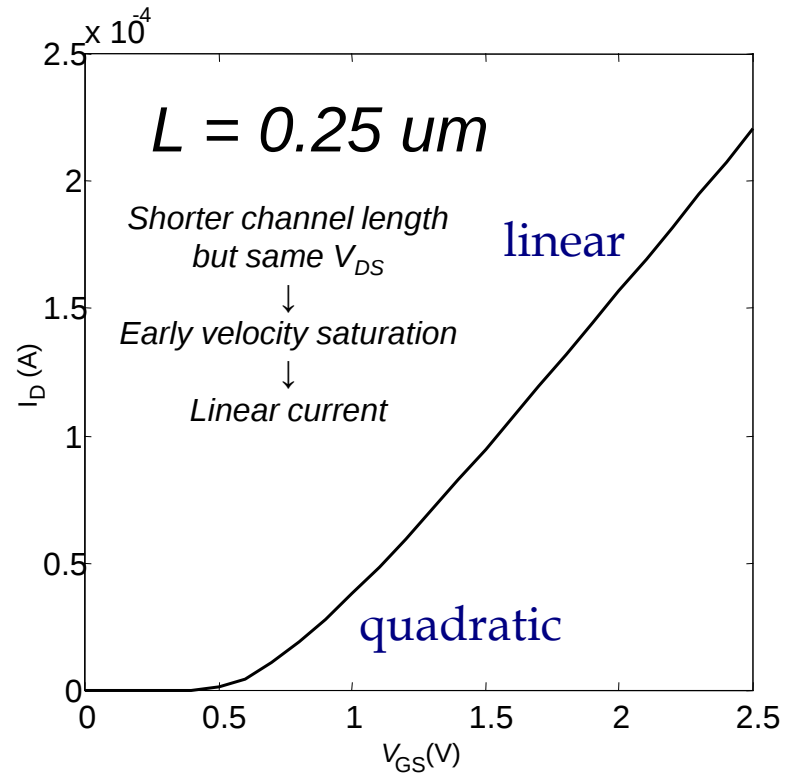
Short Channel

Input Characteristics: I_D versus V_{GS}

At small V_{GS} - current is dominated by pinch-off, hence, I_D is quadratic with V_{GS}



Long Channel



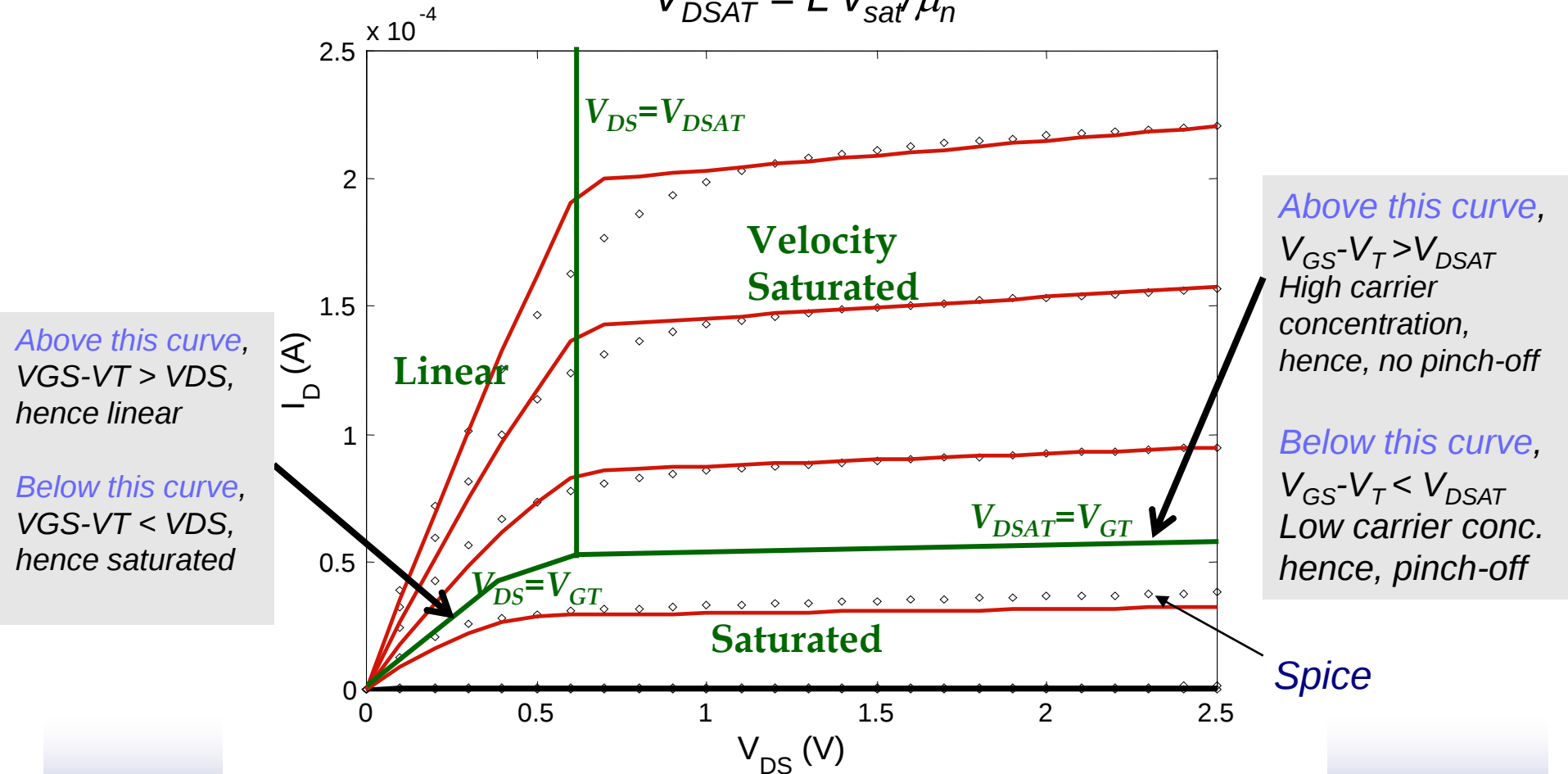
Short Channel

Note: These are Linear-Linear Plots!!

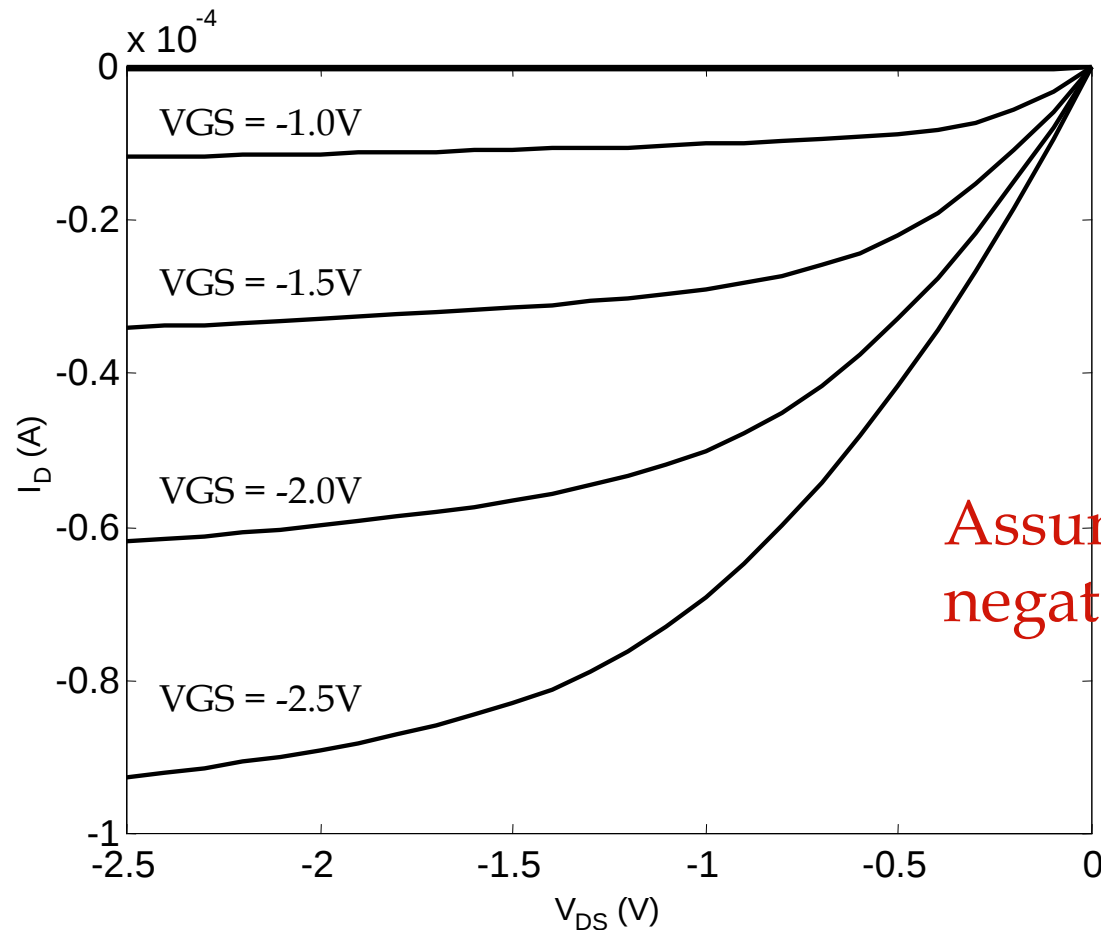
Simple Model (solid lines) versus SPICE

$$V_{GT} = V_{GS} - V_T$$

$$V_{DSAT} = L v_{sat} / \mu_n$$



A PMOS Transistor (short-channel)



Assume all variables negative!

Alpha-Power MOSFET Model

Note: Shockley method is based on the drift-diffusion transport....no velocity saturation effect

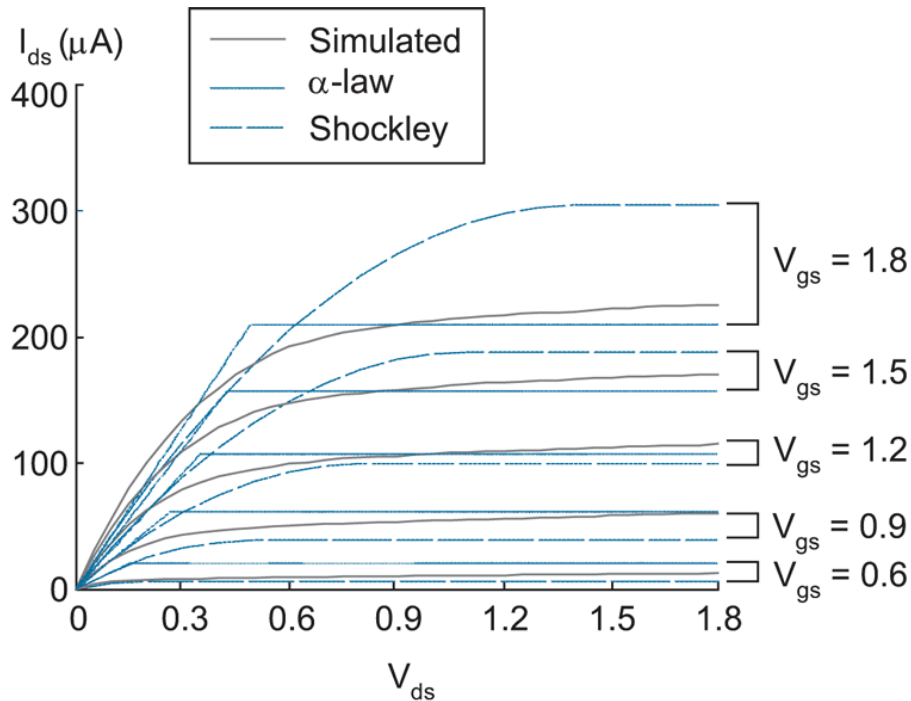


FIG 2.17 I-V characteristics for nMOS transistor with velocity saturation

Sakurai Model: $I_{ds} \propto (V_{gs} - V_t)^\alpha$

$1 < \alpha < 2$, is the velocity saturation index, determined by curve fitting.....also accounts for mobility degradation due to high vertical field (V_{gs}/t_{ox})

At low lateral E-fields, V_{ds}/L , current increases linearly with E-field

At high fields, $E = E_{sat}$

Carrier velocity saturates due to carrier scattering = $v_{sat} (= \mu E_{sat})$

$$I_{ds} = \mu C_{ox} W/L (V_{gs} - V_t)^2$$

---no velocity saturation

$$I_{ds} = C_{ox} W (V_{gs} - V_t) v_{sat}$$

---complete velocity saturation

Practical situation: carrier velocity doesn't increase linearly with field but is not completely velocity saturated....

How to Extract SS , G_m , and R_{out}

SS : Sub-threshold voltage swing

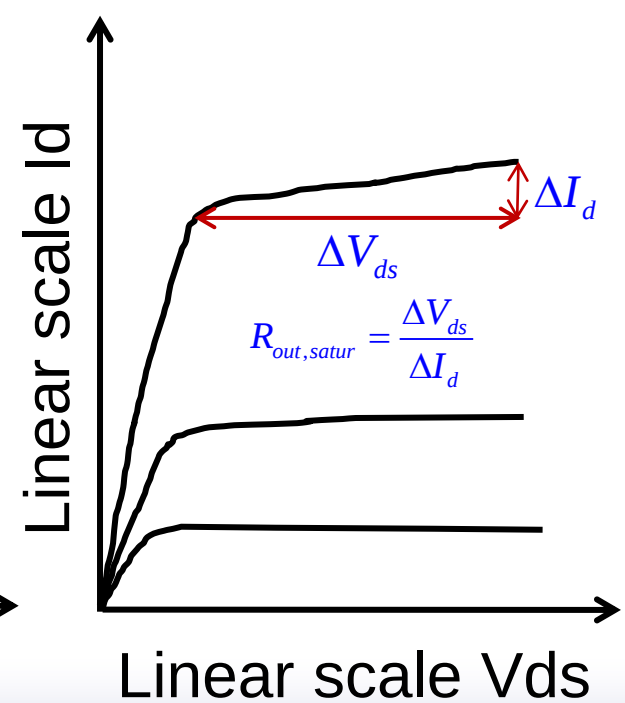
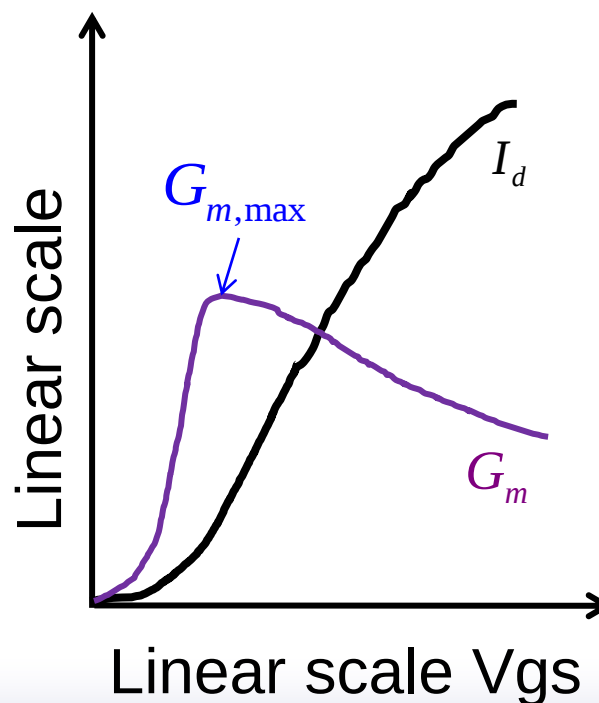
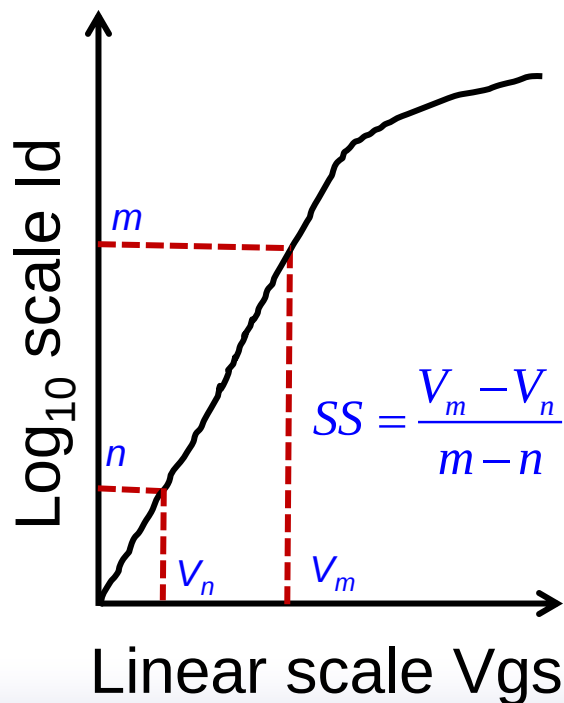
$$SS = \frac{dV_g}{d(\log_{10} I_d)}$$

G_m : Transconductance

$$G_m = \frac{dI_d}{dV_g}$$

R_{out} : output resistance

$$R_{out} = \frac{dV_{ds}}{dI_d}$$



Methods to Extract V_{th}

③ Second derivative of I_d

② Tangent method

① Constant current

