

Lecture 4: Device Theory

Digital CMOS VLSI Design

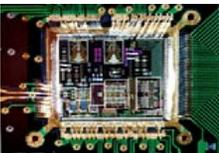
Instructor: Saraju P. Mohanty, Ph. D.

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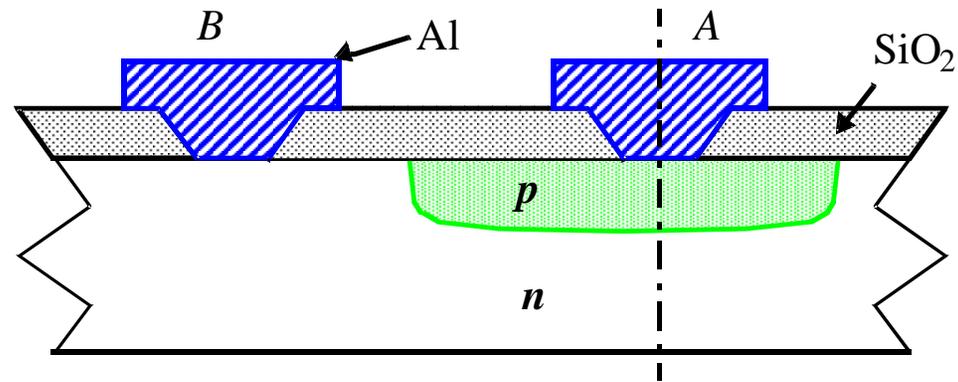


Outline of the Lecture

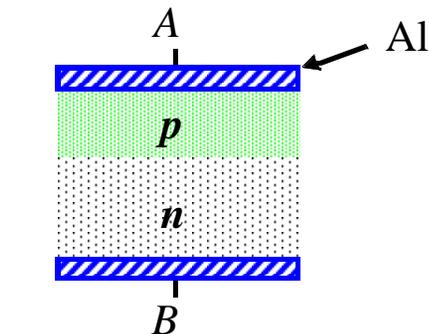
- Present intuitive understanding of device operation
- Introduction of basic device equations
- Introduction of models for manual analysis
- Introduction of models for SPICE simulation
- Analysis of secondary effects



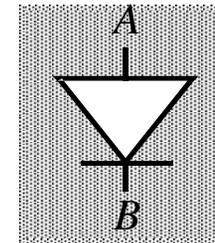
The Diode



Cross-section of pn -junction in an IC process

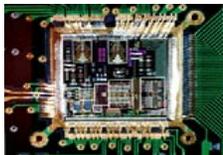


One-dimensional representation

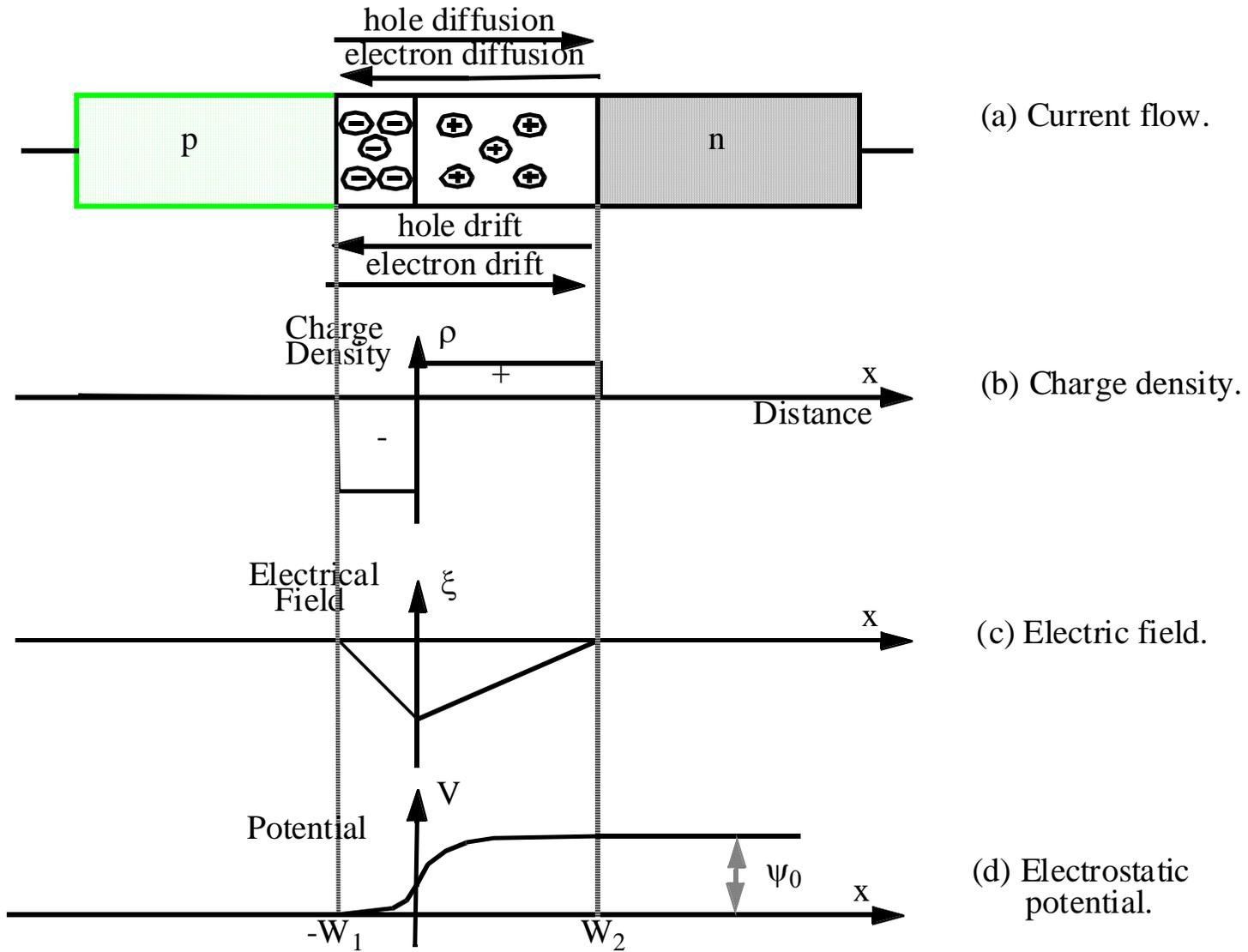


diode symbol

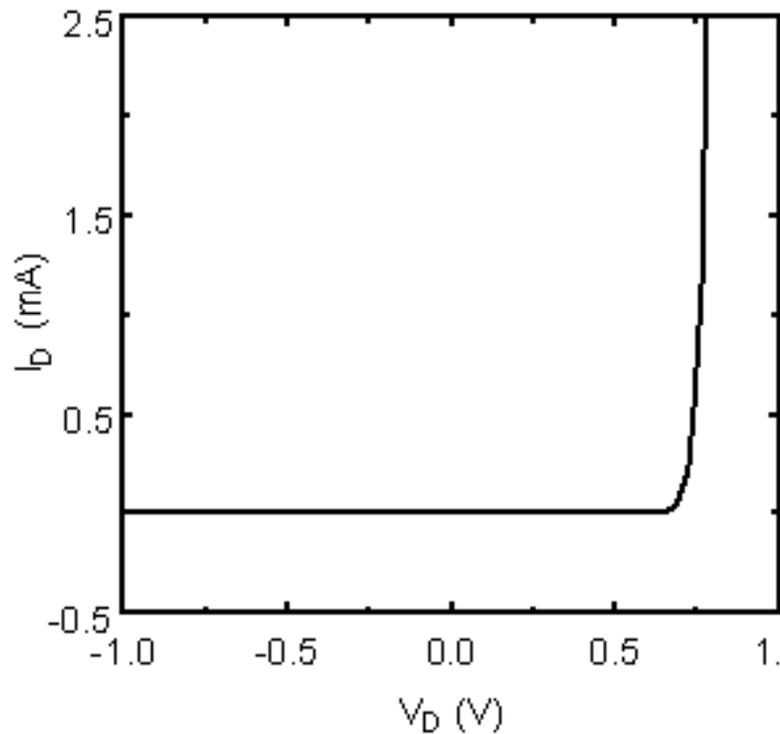
Mostly occurring as parasitic element in Digital ICs



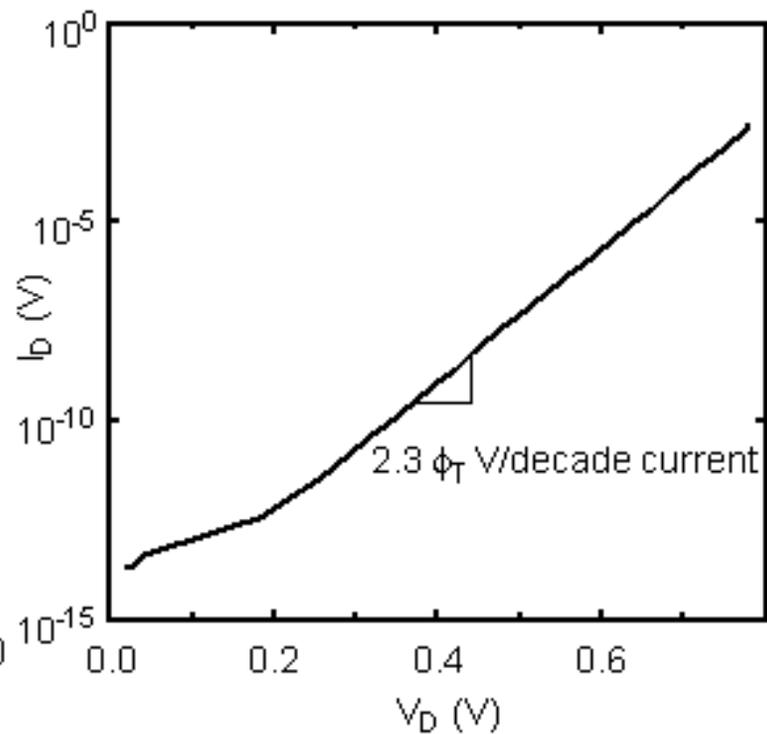
Depletion Region



Diode Current

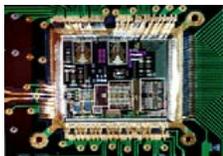


(a) On a linear scale.

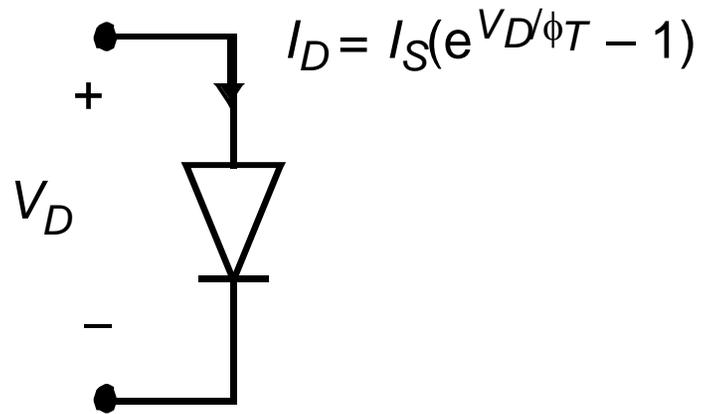


(b) On a logarithmic scale (forward bias).

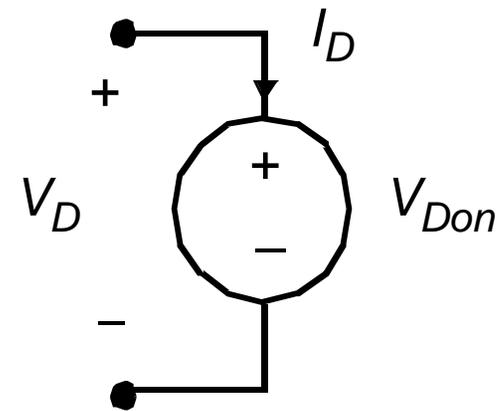
$$I_D = I_S \left(e^{V_D / \phi_T} - 1 \right)$$



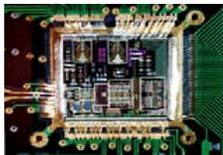
Diode Models for Manual Analysis



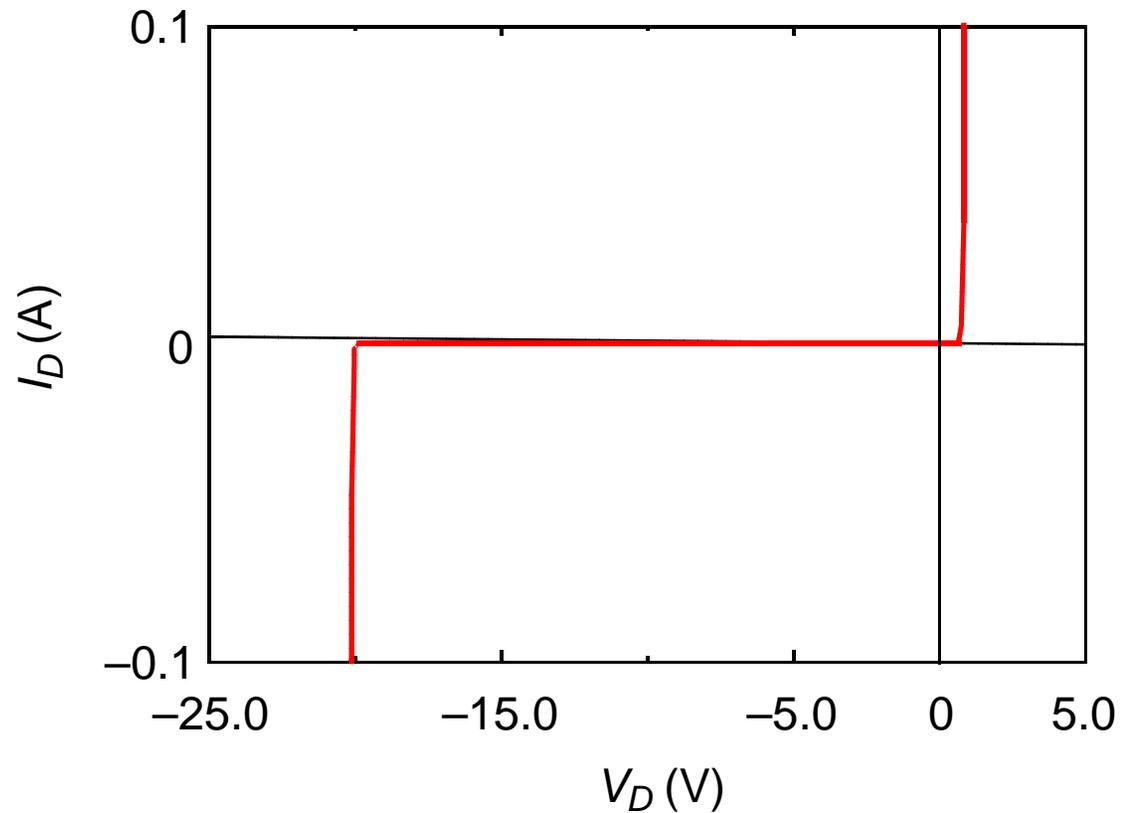
(a) Ideal diode model



(b) First-order diode model



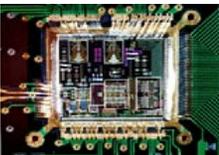
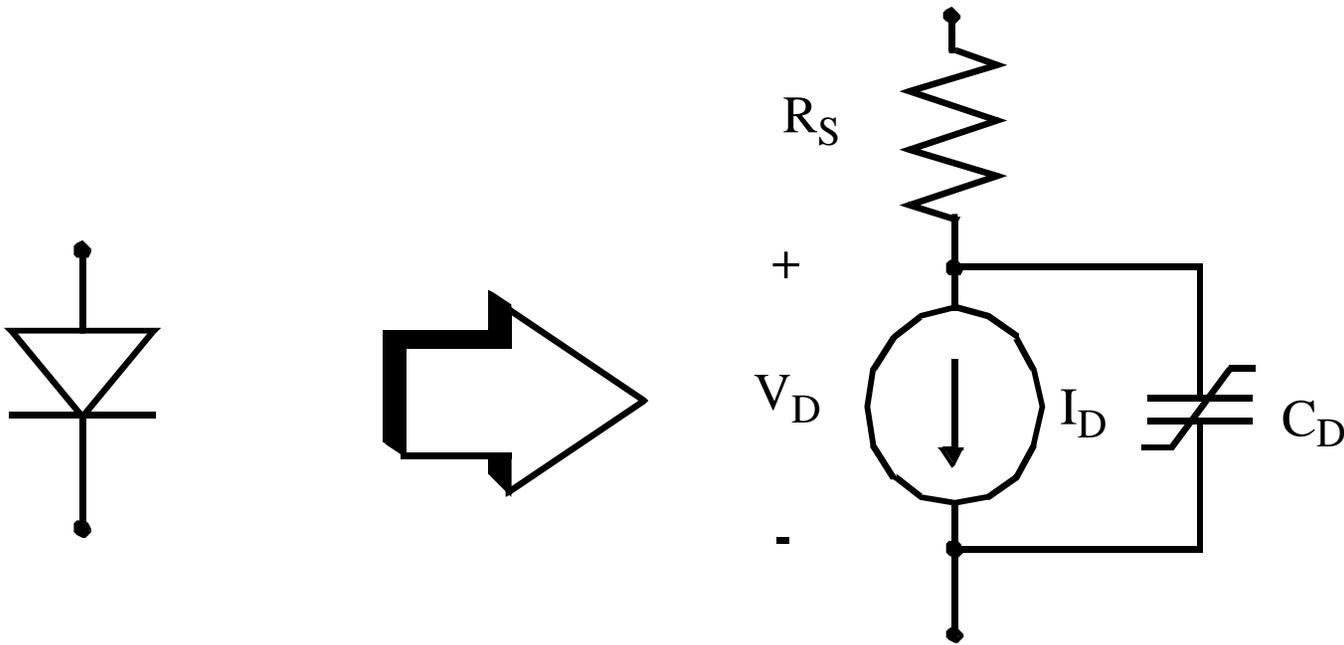
Diode: Secondary Effects



Avalanche Breakdown

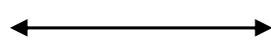


Diode : SPICE Model

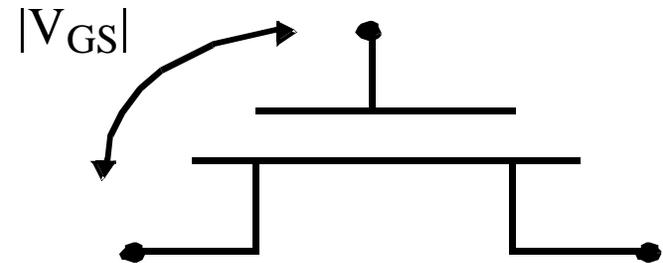
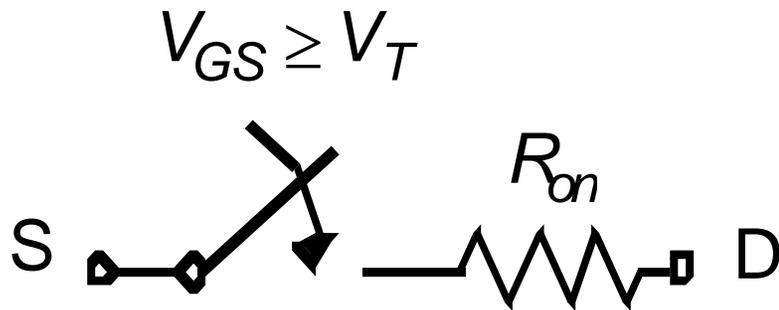


What is a Transistor?

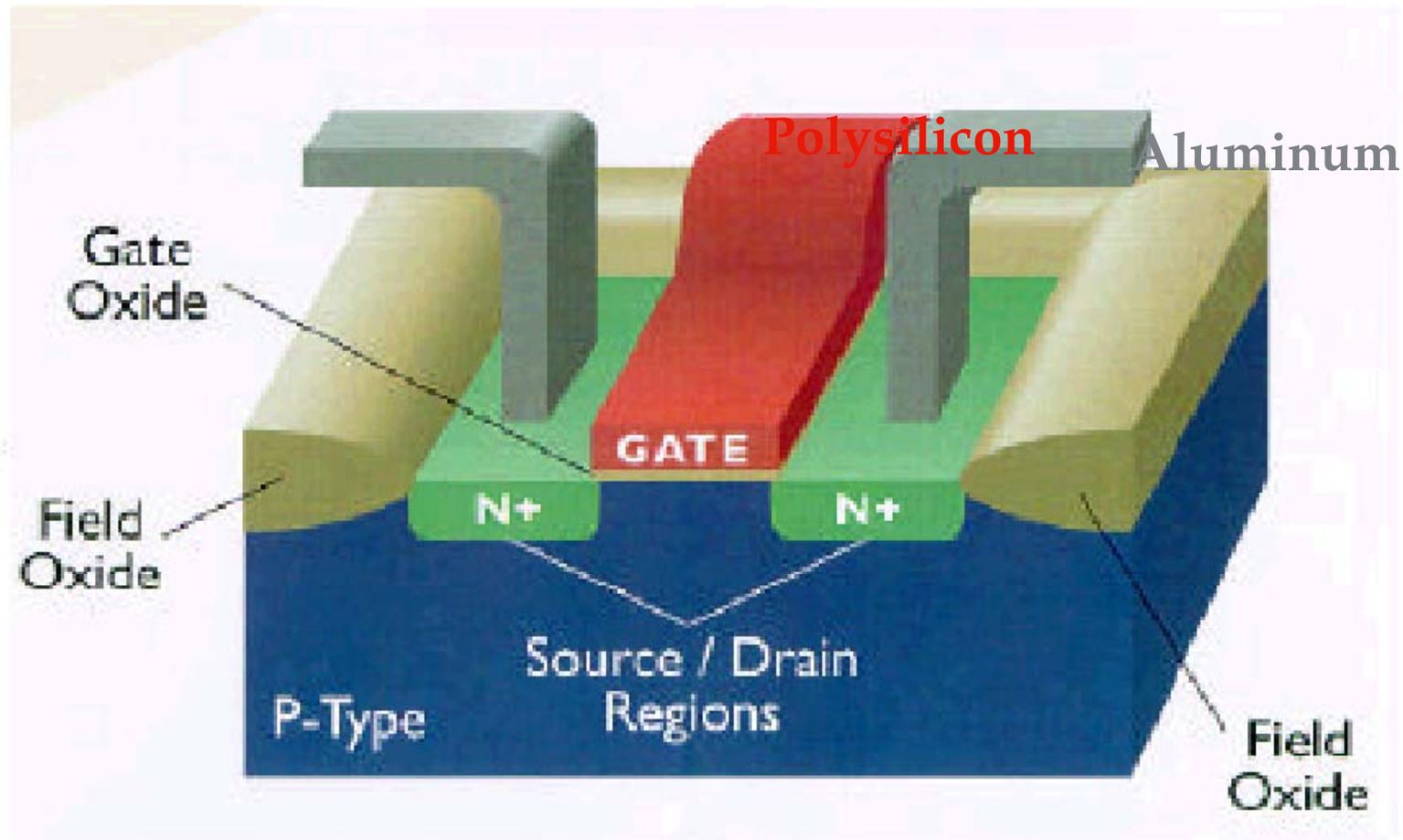
A Switch!



An MOS Transistor

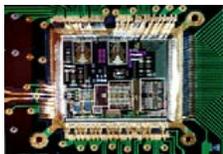
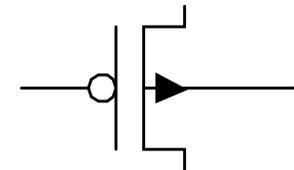
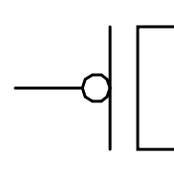
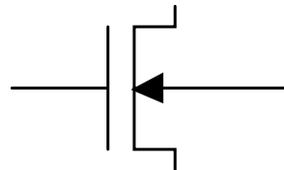
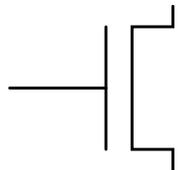


The MOS Transistor



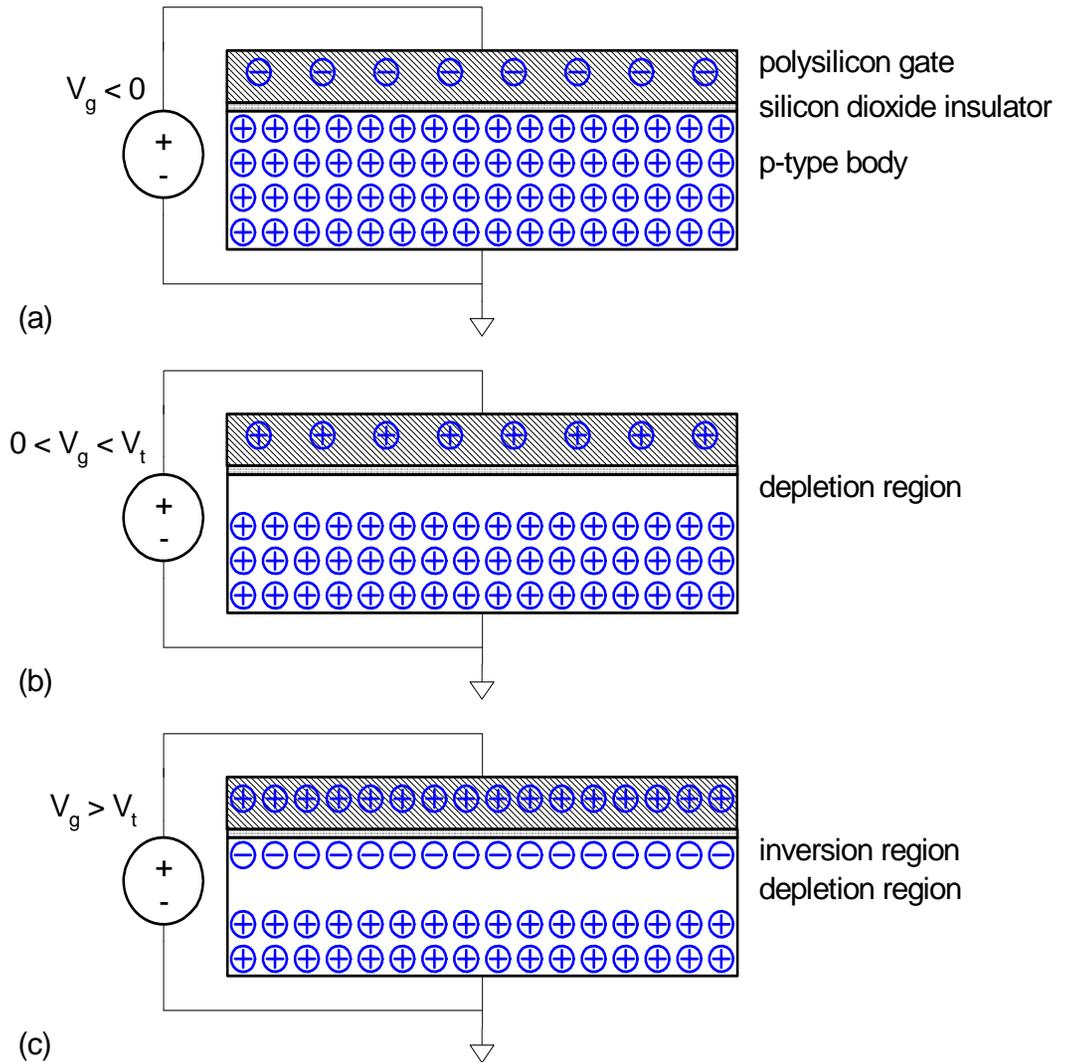
Some Facts about MOS Transistor

- MOS is a majority carrier device in which the current in a conducting channel between source and drain is controlled by voltage applied to the gate.
- Majority carriers: NMOS-electron and PMOS-hole
- When ON, the MOS transistor passes a finite amount of current in channel.
 - Depends on terminal voltages
 - Derive current-voltage (I-V) relationships
- Transistor's gate, source, drain have capacitance
- Different symbols for NMOS/PMOS:

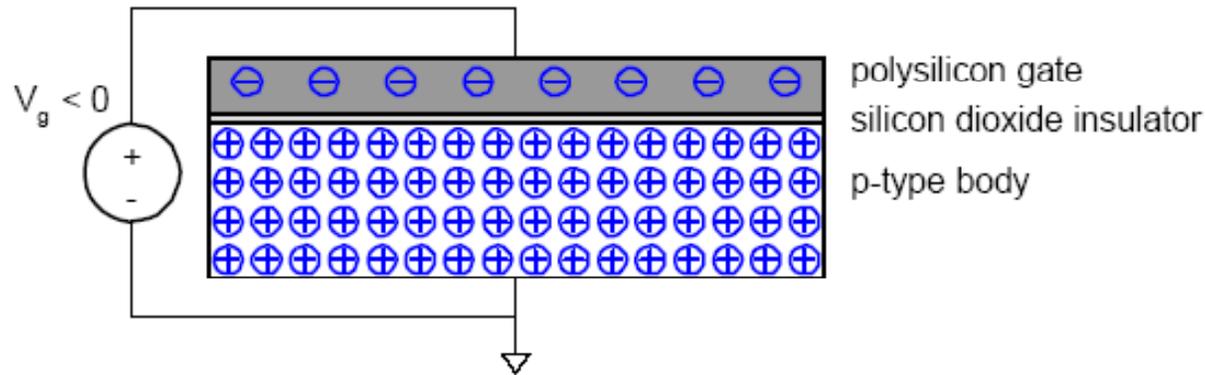


MOS Modes of Operation

- Gate and body form MOS capacitor
- Three operating modes
 - Accumulation
 - Depletion
 - Inversion



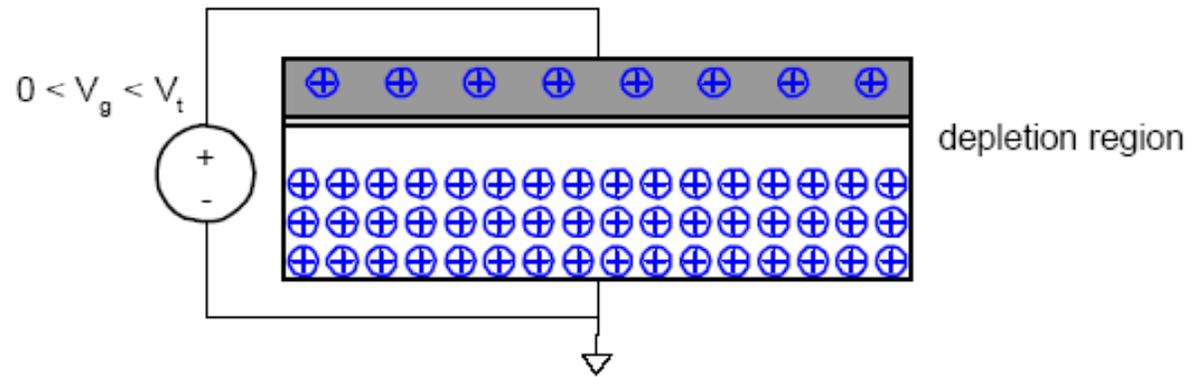
MOS Modes of Operation : Accumulation



- When a negative voltage is applied to gate, there is negative charge on the gate.
- The mobile positive carriers are attracted to the region below the gate.



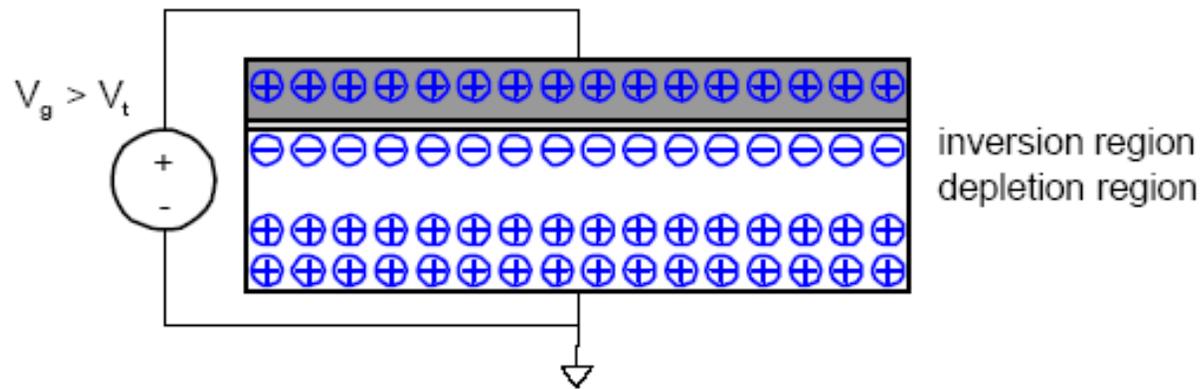
MOS Modes of Operation : Depletion



- A low positive voltage at the gate results in some positive charge on the gate.
- The holes in the body i.e. mobile positive carriers are repelled from the region below the gate; thus forming a depletion region.



MOS Modes of Operation : Inversion



- A higher positive potential (more than threshold voltage) attracts more positive charge to the gate.
- The holes in the body are repelled further and small number of electrons in the body are attracted to the region below the gate.
- This conductive electrons form inversion layer.



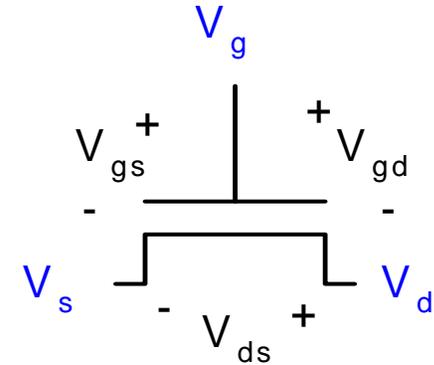
MOS regions of operation

- Operations depends on V_g , V_d , V_s

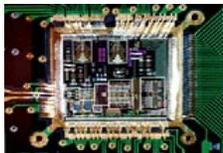
$$-V_{gs} = V_g - V_s$$

$$-V_{gd} = V_g - V_d$$

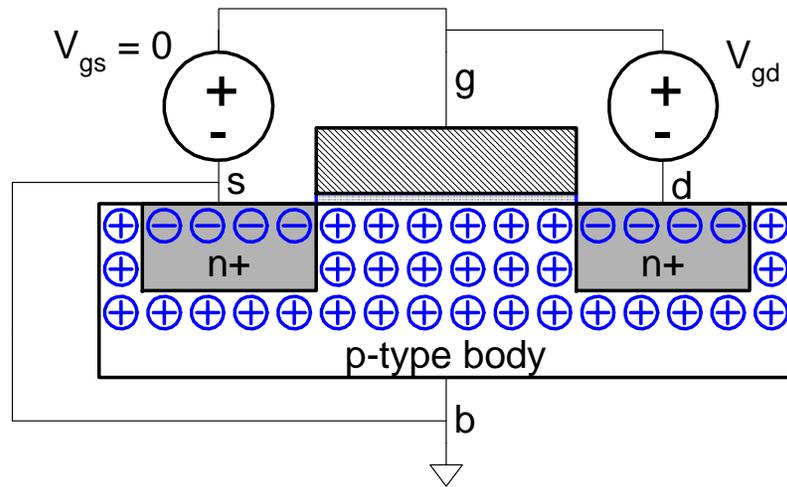
$$-V_{ds} = V_d - V_s = V_{gs} - V_{gd}$$



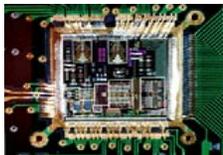
- Source and drain are symmetric diffusion terminals
 - By convention, source is terminal at lower voltage
 - Hence $V_{ds} \geq 0$
- NMOS body is grounded.
- Three regions of operation
 - Cutoff
 - Linear
 - Saturation



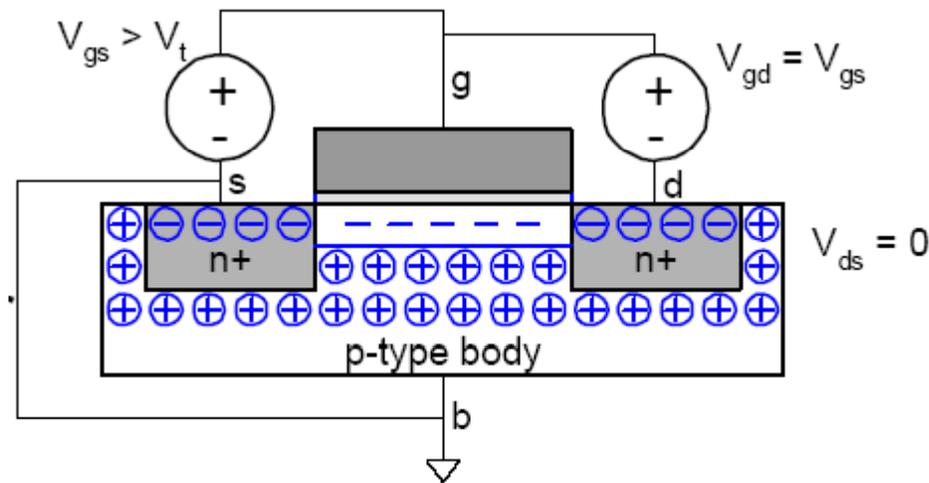
NMOS regions of operation : Cutoff



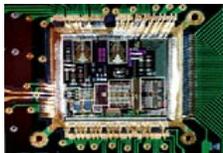
- Gate to source voltage (V_{gs}) is less than threshold voltage (V_T)
- Source and drain have free electrons.
- Body has free holes, but no free electrons.
- No channel
- $I_{ds} = 0$



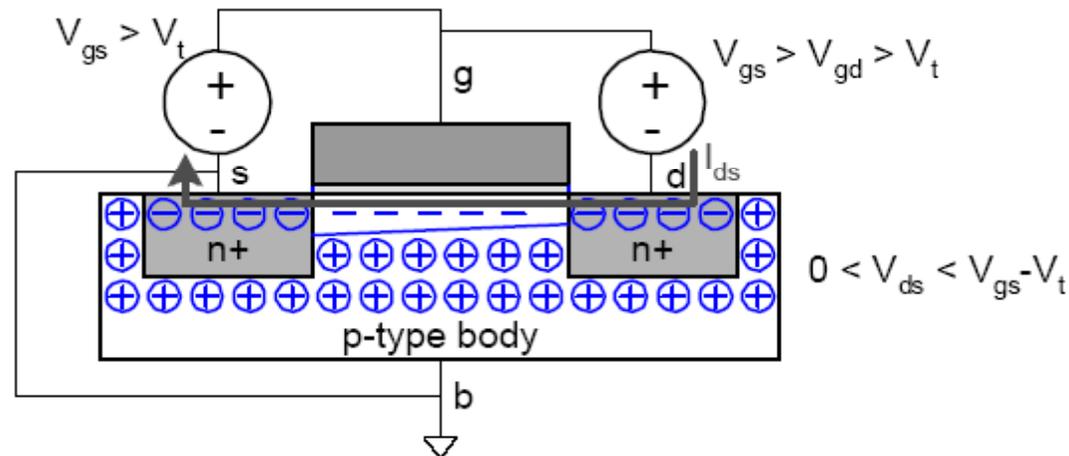
NMOS regions of operation : Linear



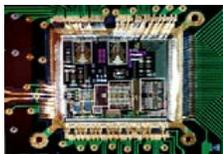
- When, $V_{gs} > V_T$, $V_{gd} = V_{gs}$ and $V_{ds} = 0$
- Inversion region of electrons form a channel
- Since $V_{ds} = 0$, there is no electric field to push current from drain to source.
- Number of carriers and conductivity can increase with the gate voltage, and I_{ds} can increase with V_{ds}



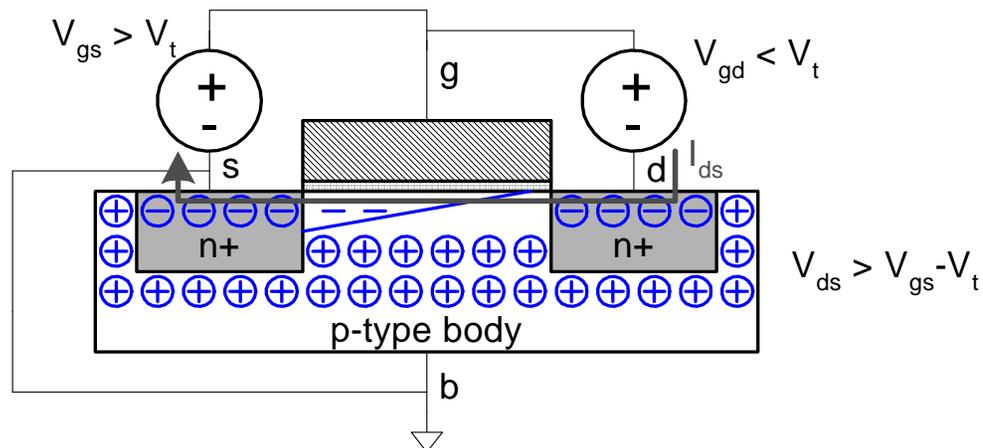
NMOS regions of operation : Linear ...



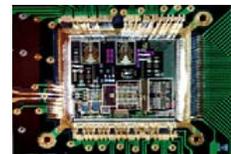
- When $V_{gs} > V_T$, $V_{gs} > V_{gd} > V_T$, and $0 < V_{ds} < V_{gs} - V_T$
- Since $V_{ds} > 0$, there is electric field to push current from drain to source.
- Current flows from d to s (i.e. e^- from s to d)
- Drain-to-source current I_{ds} increases with V_{ds}
- Linear mode of operation is also known as resistive and nonsaturated or unsaturated.



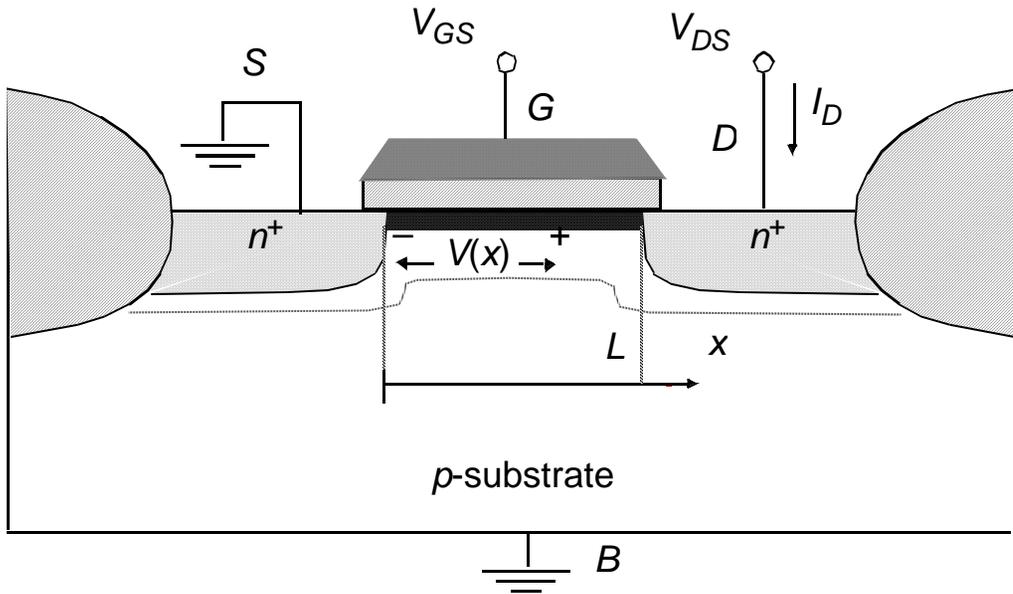
NMOS regions of operation : Saturation



- When $V_{gs} > V_T$, $V_{gd} < V_T$, and $V_{ds} > V_{gs} - V_T$
- Channel is not inverted near drain and becomes pinched off
- There is still conduction due to drifting motion of the electron
- I_{ds} independent of V_{ds} and depends on V_{gs} only.
- We say current saturates as current does not change much
- Similar to current source

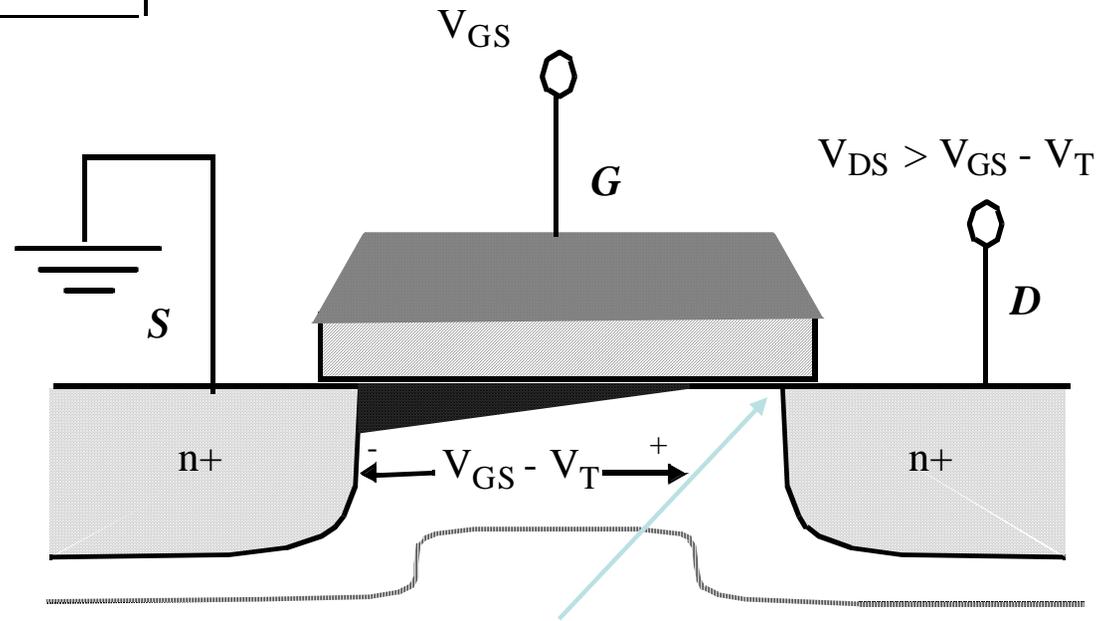


Transistor : Pinch-off Condition



(Linear Region)

MOS transistor and its bias conditions



(Saturation Region)

Pinch-off

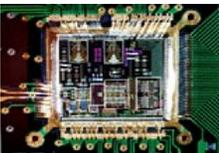
Digital CMOS VLSI Design



I-V Characteristics

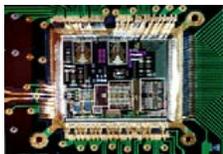
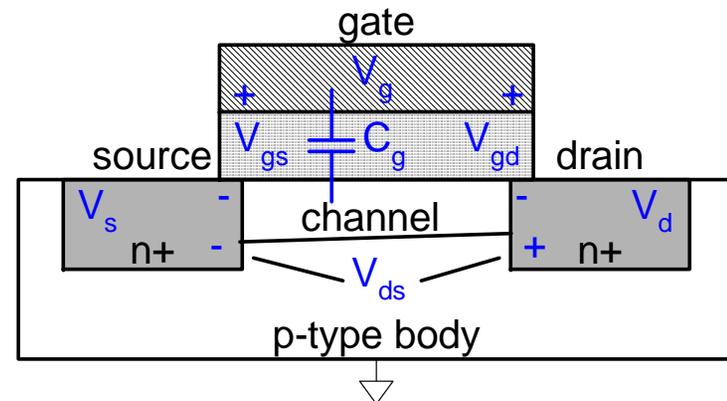
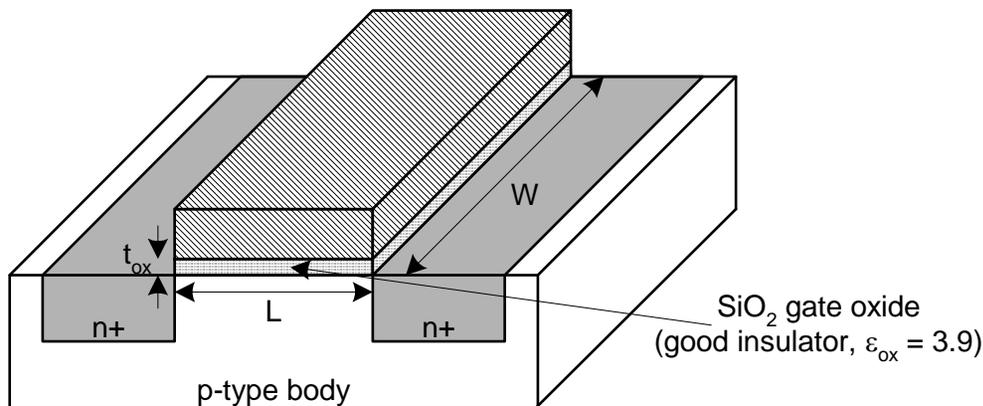
- Three regions of operation:
 - Cut-off
 - Linear
 - Saturation

- In Linear region, I_{ds} depends on
 - How much charge is in the channel?
 - How fast is the charge moving?



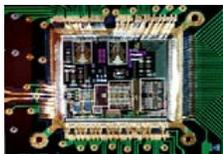
I-V Characteristics : Channel Charge

- MOS structure looks like parallel plate capacitor while operating in inversion
 - Gate – oxide – channel
- The charge in channel, $Q_{\text{channel}} = CV$
- $C = C_g = \epsilon_{\text{ox}} WL/t_{\text{ox}} = C_{\text{ox}} WL$ (where, $C_{\text{ox}} = \epsilon_{\text{ox}}/t_{\text{ox}}$)
- $V = V_{\text{gc}} - V_T = (V_{\text{gs}} - V_{\text{ds}}/2) - V_T$
- Average gate to channel voltage $V_{\text{gc}} = (V_{\text{gs}} - V_{\text{ds}}/2)$



I-V Characteristics : Carrier velocity

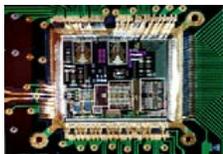
- Charge is carried by e- (for NMOS)
- Carrier velocity v proportional to lateral electric field between source and drain
 - $v = \mu E$ (where, μ called mobility)
- Electric field between source-drain,
 - $E = V_{ds}/L$
- Time for carrier to cross channel:
 - $t = L / v$



I-V Characteristics : Linear

- Now we know
 - How much charge Q_{channel} is in the channel
 - How much time t each carrier takes to cross
- The current between source-to-drain is the total amount charge in the channel divided by the time to cross channel.

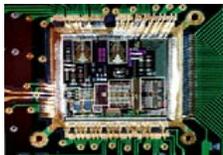
$$\begin{aligned} I_{ds} &= \frac{Q_{\text{channel}}}{t} \\ &= \mu C_{\text{ox}} \frac{W}{L} \left(V_{gs} - V_t - \frac{V_{ds}}{2} \right) V_{ds} & \beta &= \mu C_{\text{ox}} \frac{W}{L} \\ &= \beta \left(V_{gs} - V_t - \frac{V_{ds}}{2} \right) V_{ds} \end{aligned}$$



I-V Characteristics : Saturation

- If $V_{gd} < V_t$, channel pinches off near drain
- The drain voltage at which current is no longer affected by it is known as drain saturation voltage.
 - When $V_{ds} > V_{dsat} = V_{gs} - V_t$
- Now drain voltage no longer increases current

$$\begin{aligned} I_{ds} &= \beta \left(V_{gs} - V_t - \frac{V_{dsat}}{2} \right) V_{dsat} \\ &= \frac{\beta}{2} (V_{gs} - V_t)^2 \end{aligned}$$



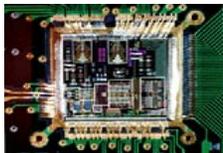
I-V Characteristics : Summary

- *Shockley* 1st order transistor models

$$I_{ds} = \begin{cases} 0 & V_{gs} < V_t & \text{cutoff} \\ \beta \left(V_{gs} - V_t - \frac{V_{ds}}{2} \right) V_{ds} & V_{ds} < V_{dsat} & \text{linear} \\ \frac{\beta}{2} (V_{gs} - V_t)^2 & V_{ds} > V_{dsat} & \text{saturation} \end{cases}$$

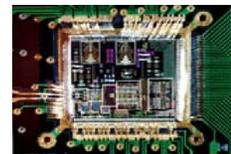
- The current at which transistor is fully ON I_{dsat} :

$$I_{dsat} = \beta/2 (V_{DD} - V_t)^2$$

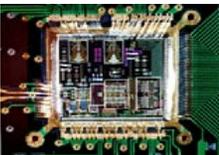
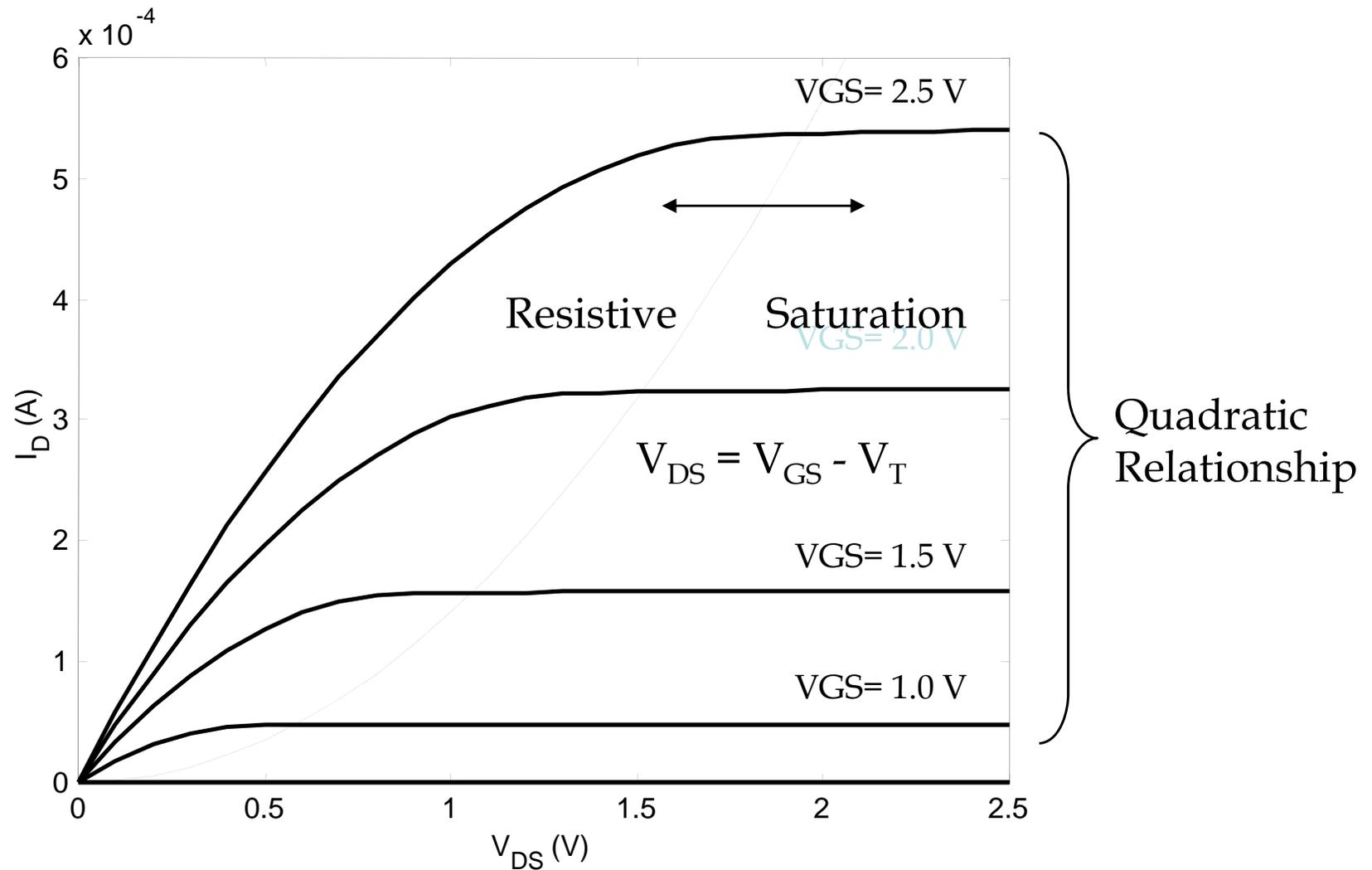


MOSFET Operating Regions : Summary

- Strong Inversion $V_{GS} > V_T$
 - Linear (Resistive) $V_{DS} < V_{DSAT}$
 - Saturated (Constant Current) $V_{DS} \geq V_{DSAT}$
- Weak Inversion (Sub-Threshold) $V_{GS} \leq V_T$
 - Exponential in V_{GS} with linear V_{DS} dependence

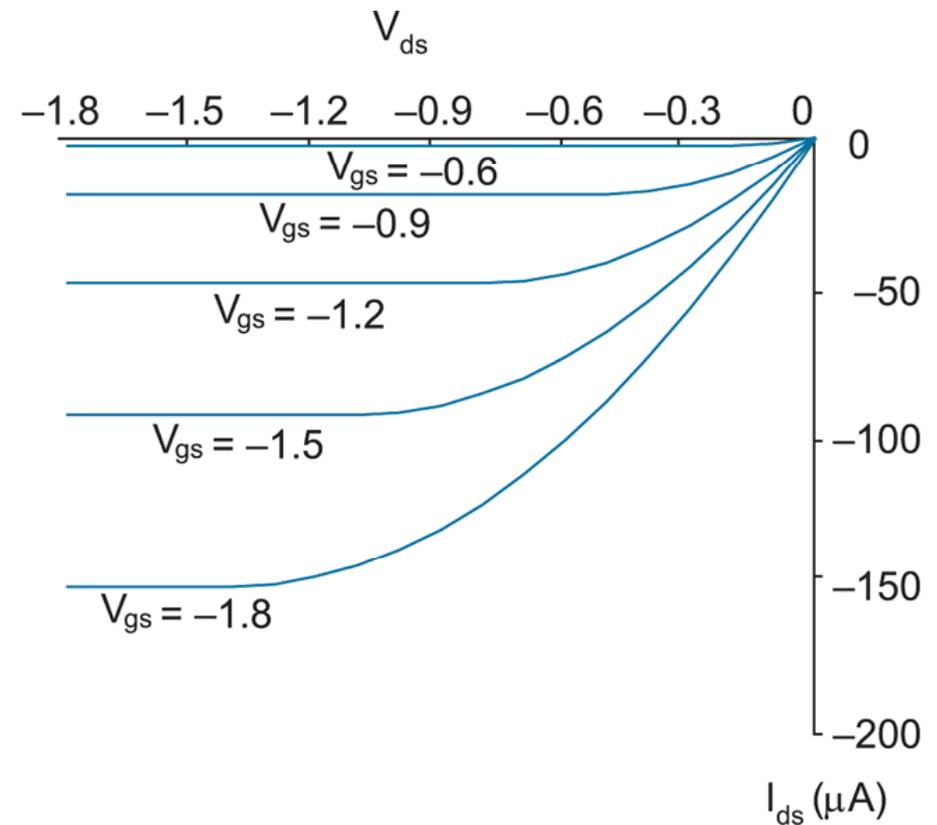


Current-Voltage Relations



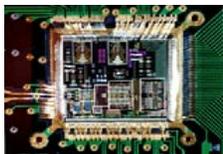
I-V Characteristics : PMOS

- All dopings and voltages are inverted for PMOS
- Mobility μ_p is determined by holes
 - Typically 2-3x lower than that of electrons μ_n
- Thus PMOS must be wider to provide same current
 - Typically, $\mu_n / \mu_p = 2$

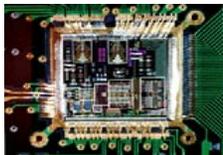
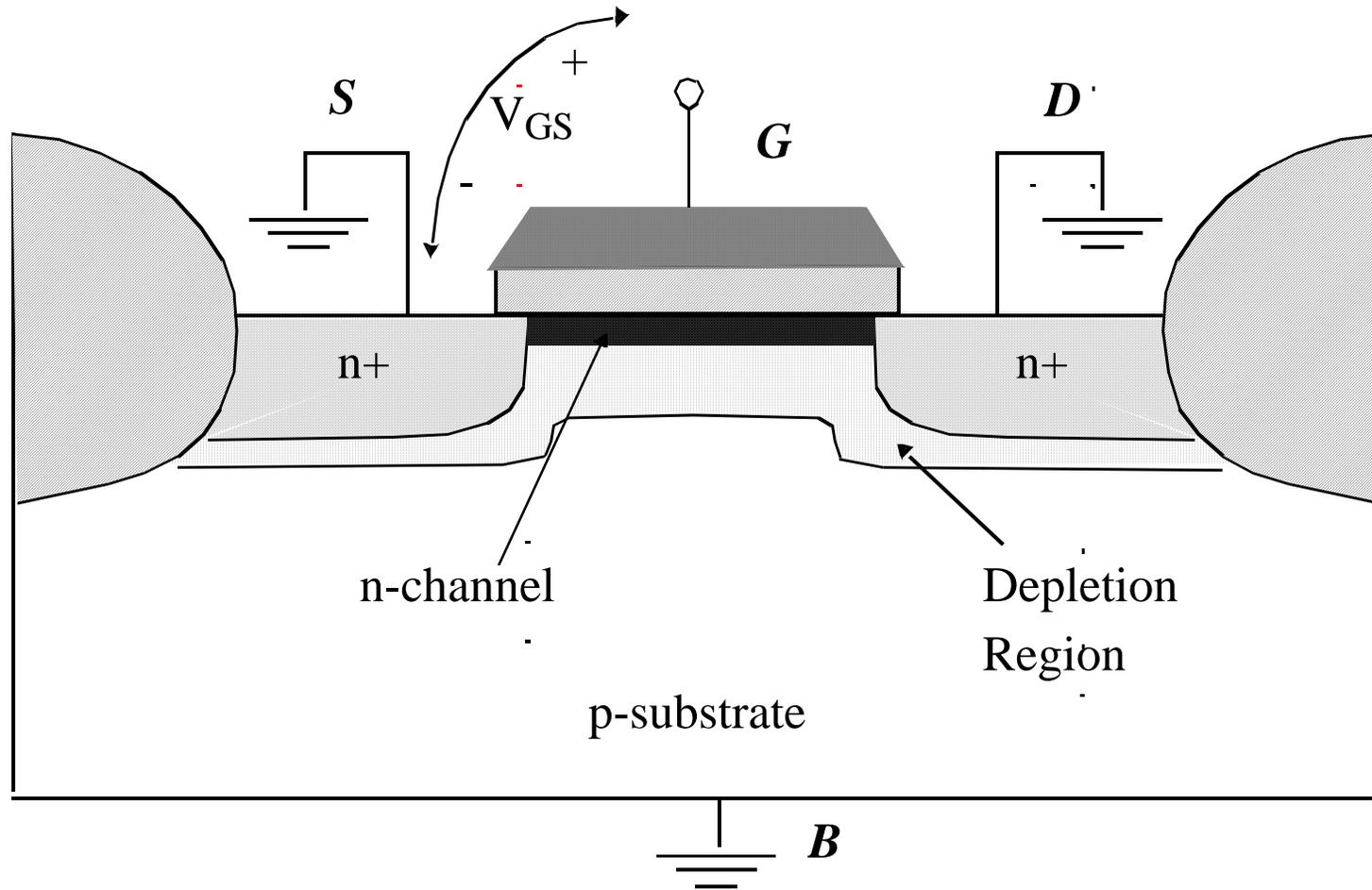


I-V characteristics of ideal pMOS transistor

Assume all variables negative!



Threshold Voltage: Concept



The Threshold Voltage

$$V_T = \phi_{mS} - 2\phi_F - \frac{Q_B}{C_{ox}} - \frac{Q_{SS}}{C_{ox}} - \frac{Q_I}{C_{ox}}$$

Workfunction Difference \uparrow \uparrow \uparrow Implants
 Depletion Layer Charge Surface Charge

$$V_T = V_{T0} + \gamma(\sqrt{|-2\phi_F + V_{SB}|} - \sqrt{|-2\phi_F|})$$

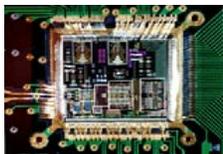
Body Effect Coefficient

with

$$V_{T0} = \phi_{mS} - 2\phi_F - \frac{Q_{B0}}{C_{ox}} - \frac{Q_{SS}}{C_{ox}} - \frac{Q_I}{C_{ox}}$$

and

$$\gamma = \frac{\sqrt{2q\epsilon_{si}N_A}}{C_{ox}}$$



Current-Voltage Relations Long-Channel Device

Linear Region: $V_{DS} \leq V_{GS} - V_T$

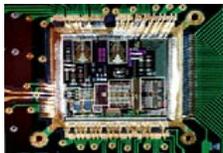
$$I_D = k'_n \frac{W}{L} \left((V_{GS} - V_T) V_{DS} - \frac{V_{DS}^2}{2} \right)$$

with

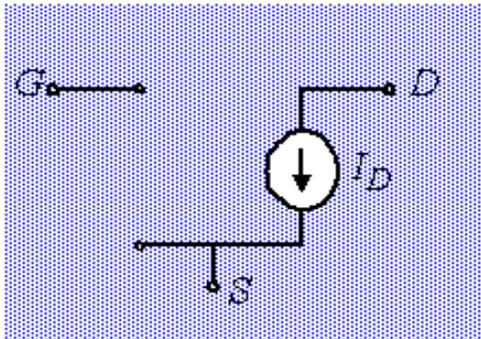
$$k'_n = \mu_n C_{ox} = \frac{\mu_n \epsilon_{ox}}{t_{ox}} \quad \text{Process Transconductance Parameter}$$

Saturation Mode: $V_{DS} \geq V_{GS} - V_T$ Channel Length Modulation

$$I_D = \frac{k'_n W}{2 L} (V_{GS} - V_T)^2 (1 + \lambda V_{DS})$$



A model for manual analysis



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

$$I_D = \frac{\kappa'_n W}{2 L} (V_{GS} - V_T)^2 (1 + \lambda V_{DS})$$

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

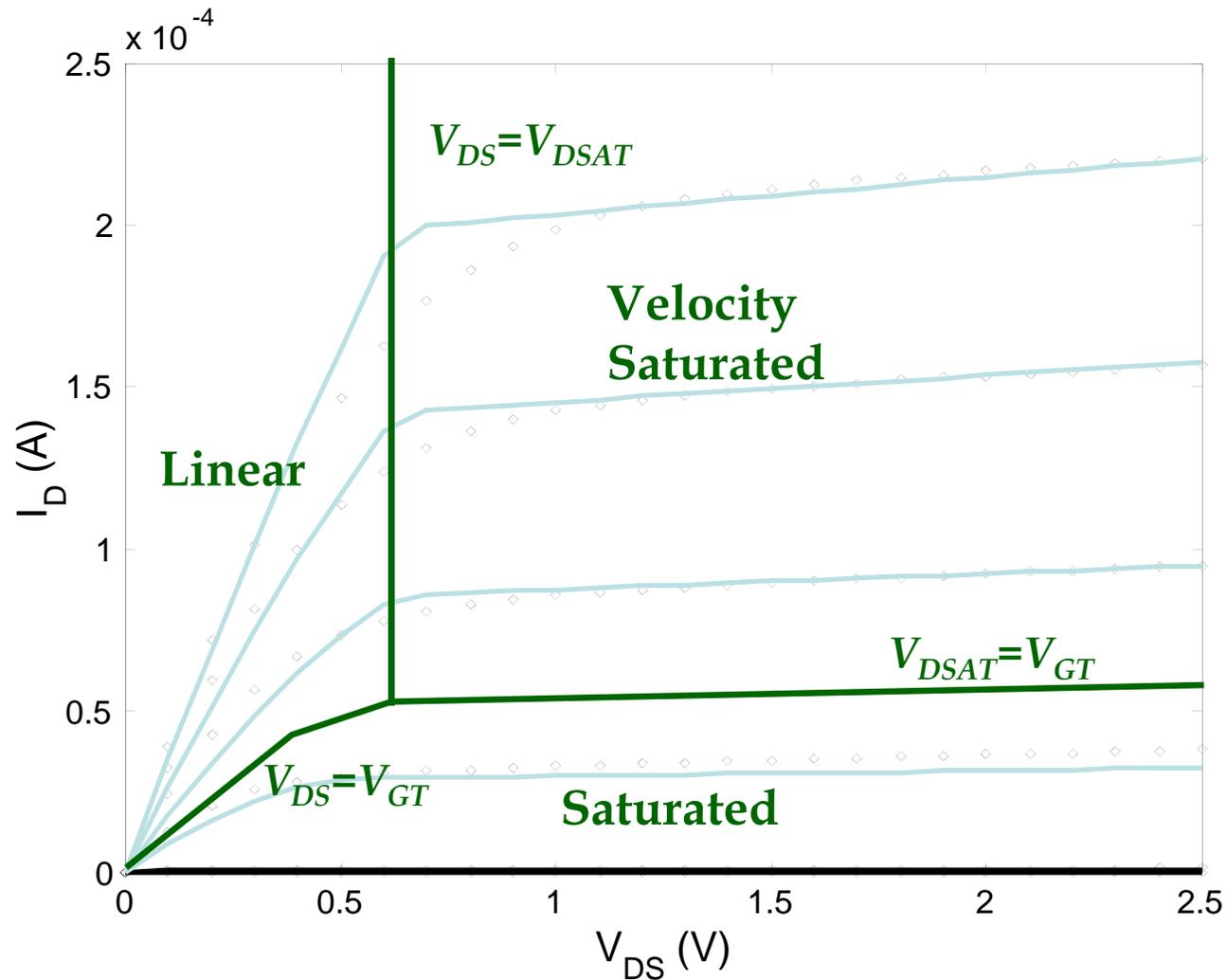
$$I_D = \kappa'_n \frac{W}{L} \left((V_{GS} - V_T) V_{DS} - \frac{V_{DS}^2}{2} \right)$$

with

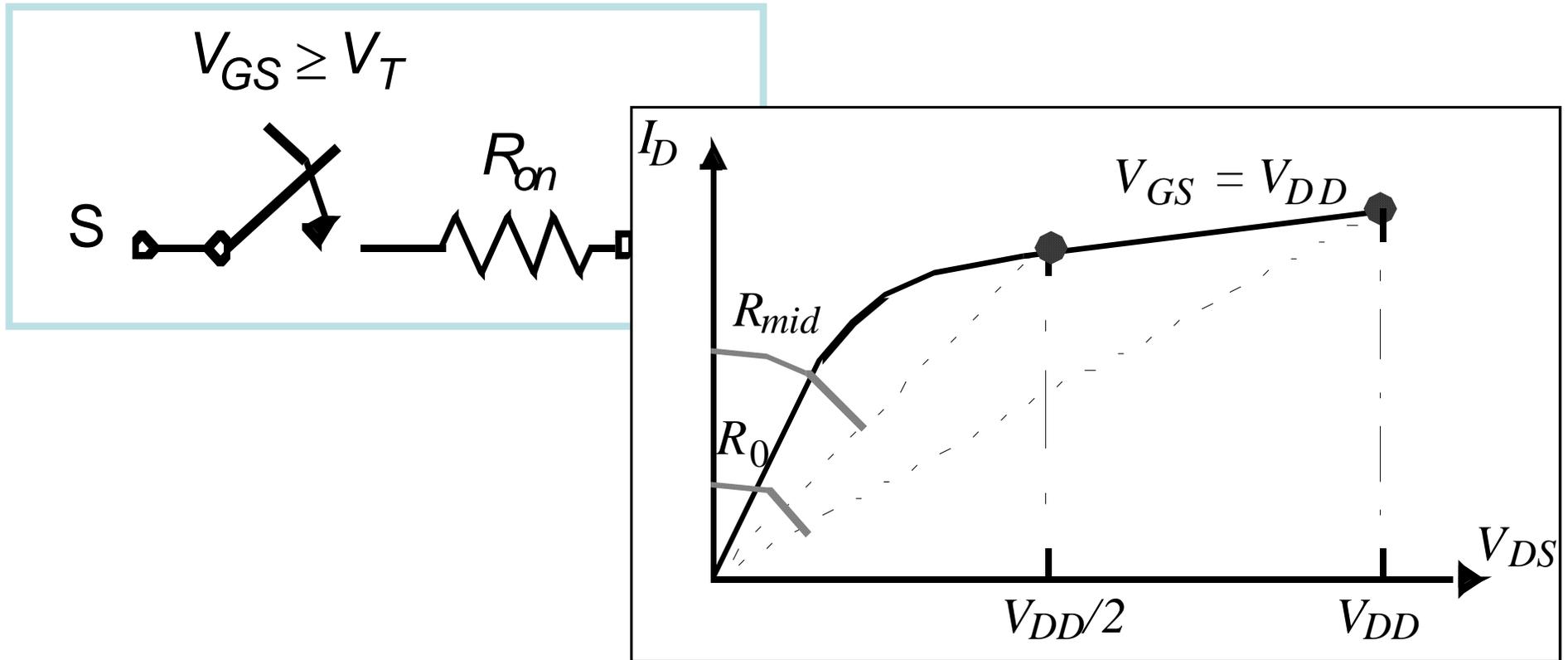
$$V_T = V_{T0} + \gamma \left(\sqrt{|-2\phi_F + V_{SB}|} - \sqrt{|-2\phi_F|} \right)$$



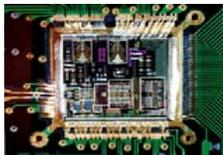
Simple Model versus SPICE



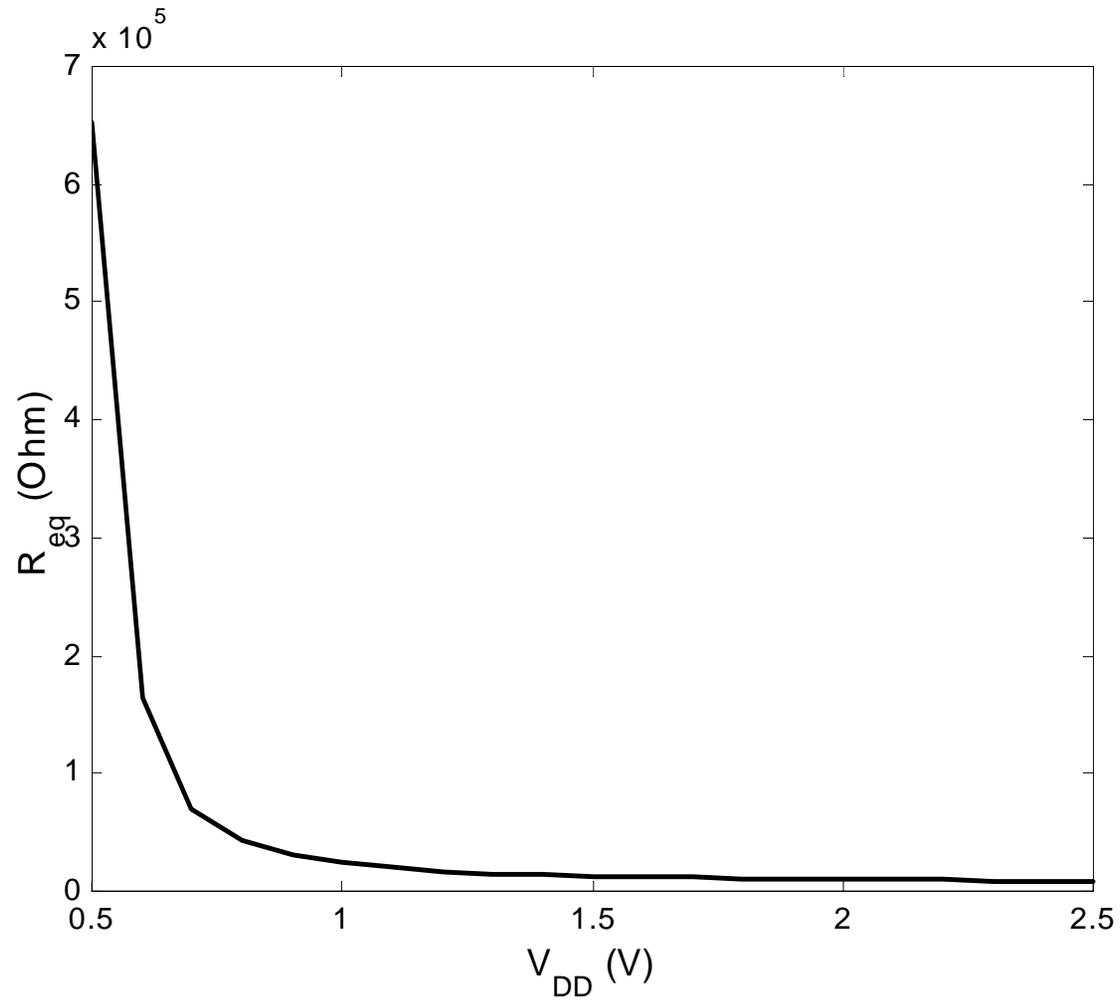
The Transistor as a Switch



$$R_{eq} = \frac{1}{2} \left(\frac{V_{DD}}{I_{DSAT}(1 + \lambda V_{DD})} + \frac{V_{DD}/2}{I_{DSAT}(1 + \lambda V_{DD}/2)} \right) \approx \frac{3}{4} \frac{V_{DD}}{I_{DSAT}} \left(1 - \frac{5}{6} \lambda V_{DD} \right)$$

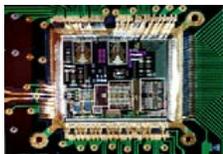


The Transistor as a Switch



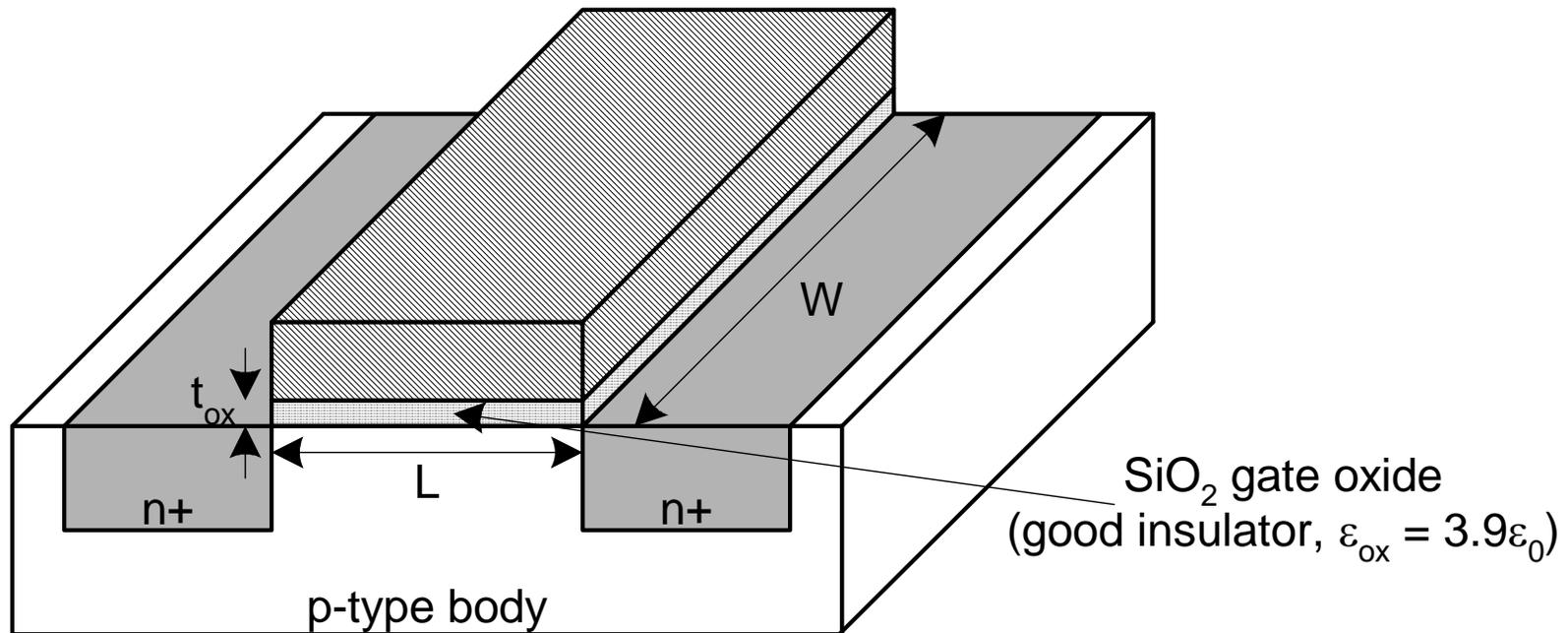
C-V Characteristics

- Any two conductors separated by an insulator have capacitance
- Gate to channel capacitor is very important
 - Creates channel charge necessary for operation
- Source and drain have capacitance to body
 - Across reverse-biased diodes
 - Called diffusion capacitance because it is associated with source/drain diffusion
- In general these capacitances are nonlinear and voltage dependent, but can be approximated as simple capacitors.

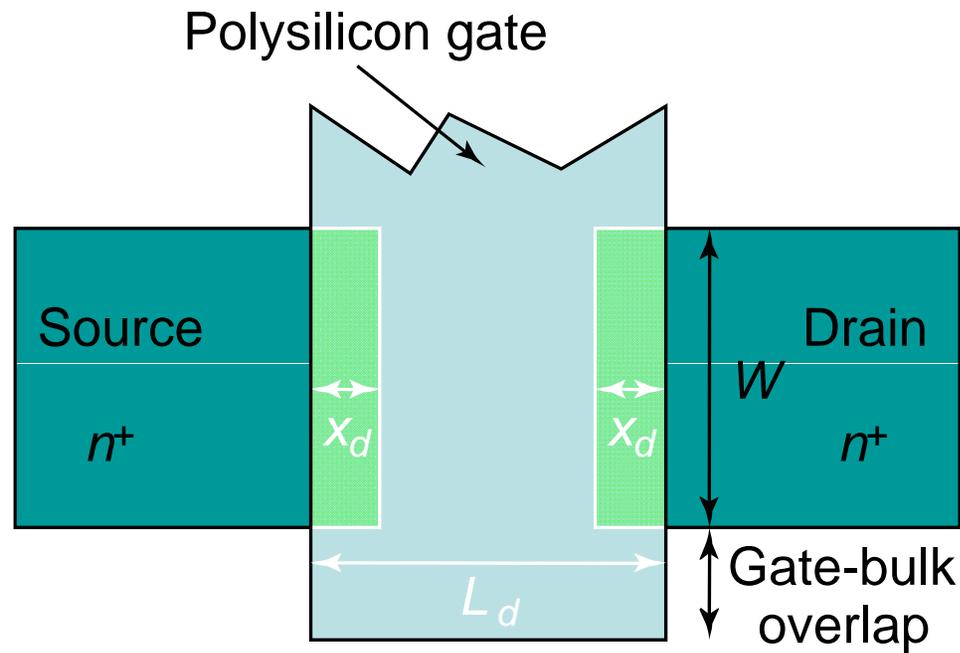


C-V Characteristics : Gate Capacitance

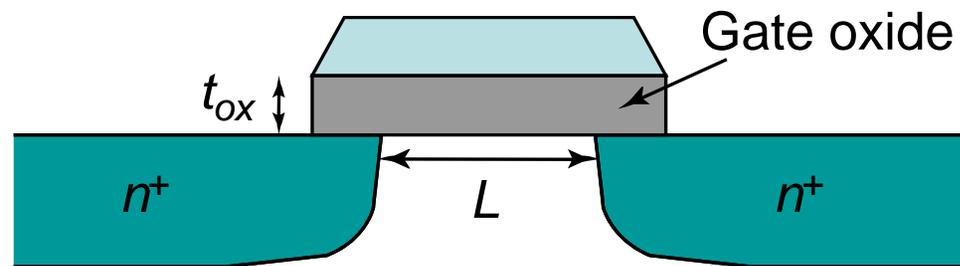
- Approximate gate capacitance as terminating at the source, thus $C_g = C_{gs}$.
- $C_{gs} = \epsilon_{ox} WL/t_{ox} = C_{ox} WL = C_{\text{permicron}} W$
- $C_{\text{permicron}}$ is typically about 2 fF/ μm



C-V Characteristics : The Gate Capacitance



Top view

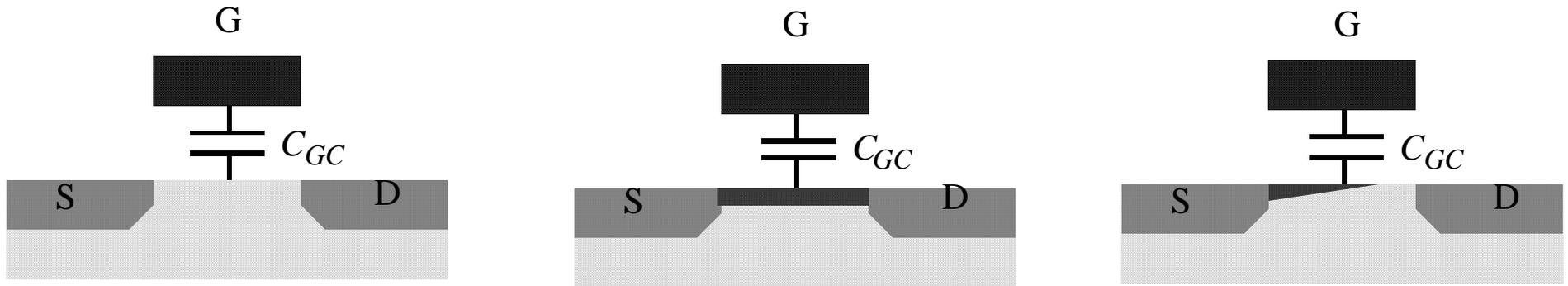


Cross section

$$C_{gate} = \frac{\epsilon_{ox}}{t_{ox}} WL$$

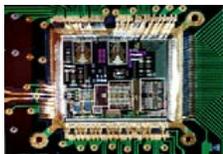


C-V Characteristics : Gate Capacitance



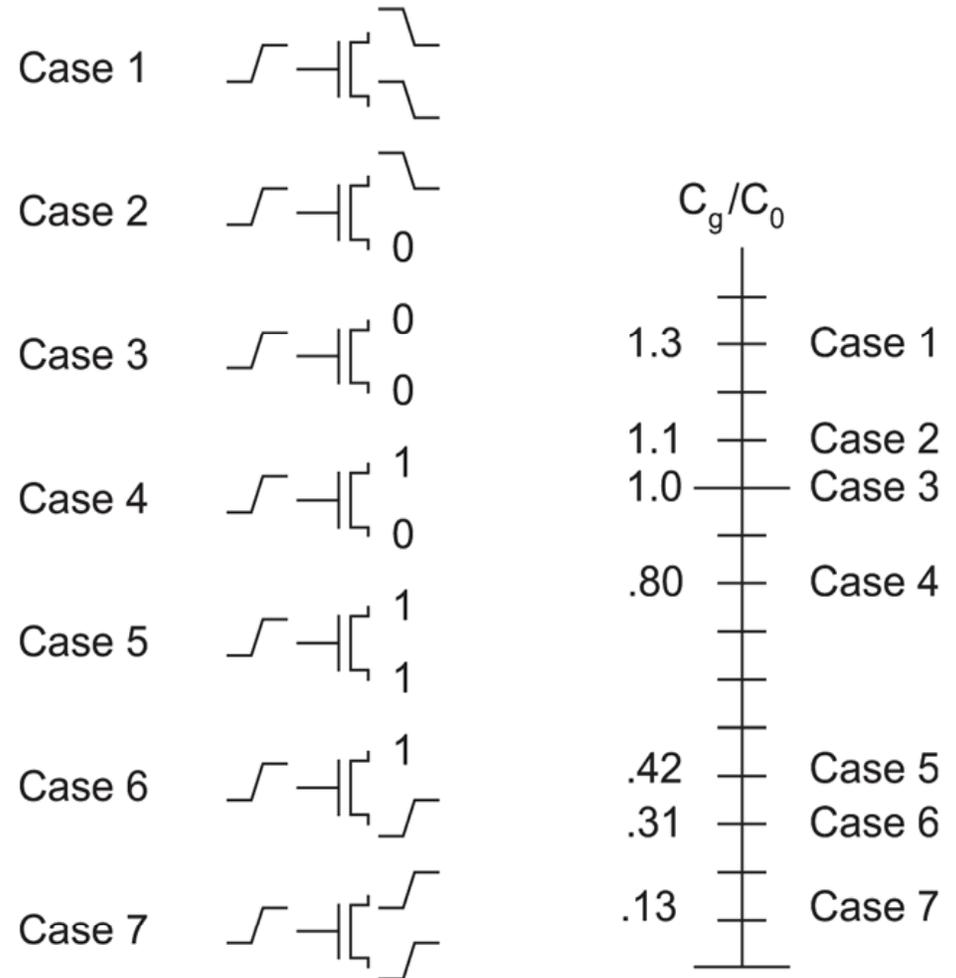
Operation Region	C_{gb}	C_{gs}	C_{gd}
Cutoff	$C_{ox}WL_{eff}$	0	0
Triode	0	$C_{ox}WL_{eff}/2$	$C_{ox}WL_{eff}/2$
Saturation	0	$(2/3)C_{ox}WL_{eff}$	0

Most important regions in digital design: saturation and cut-off

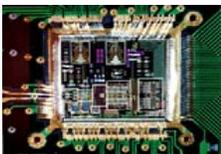


C-V Characteristics : Gate Capacitance

- The effective gate capacitance varies with switching activity of the source and drain.
- The switching activity is dependent on the input data to the device.

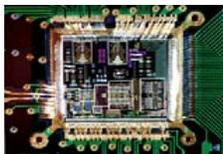
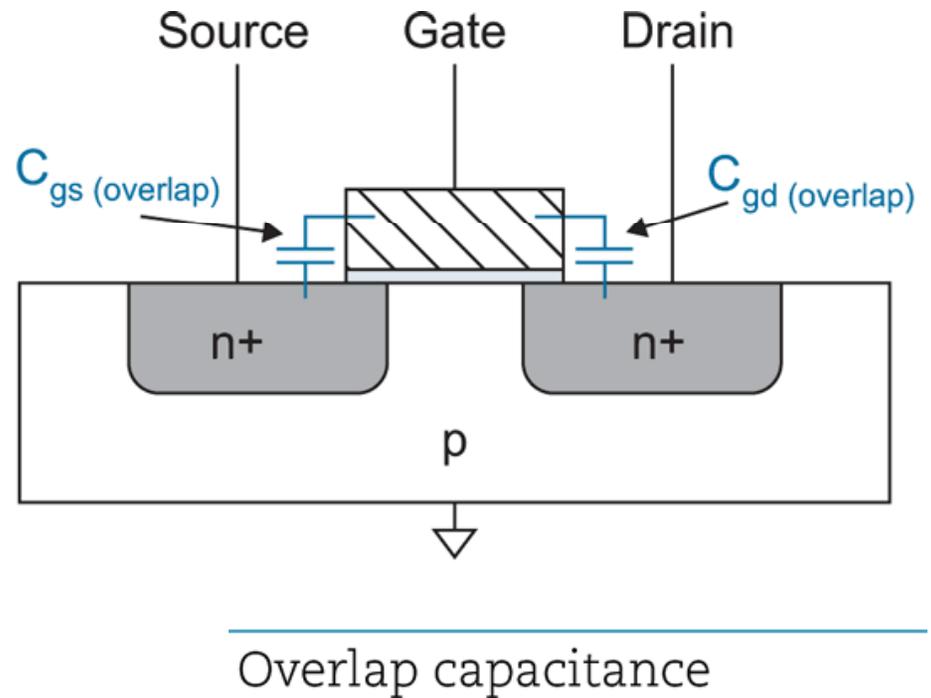


Data-dependent gate capacitance

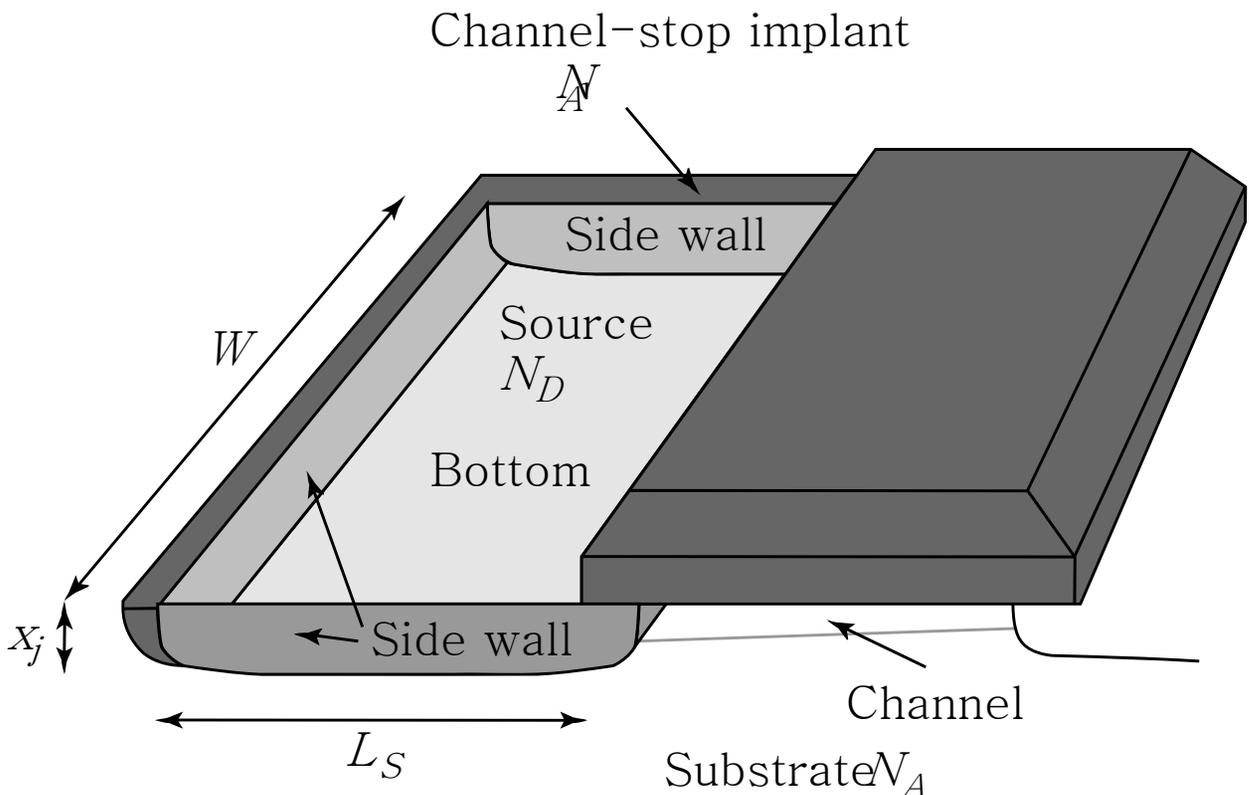


C-V Characteristics : Overlap Capacitance

- Gate overlaps the source and drain by a small amount in real device.
- These capacitances are proportional to the width of the transistor.

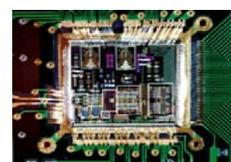


C-V Characteristics : Diffusion Capacitance

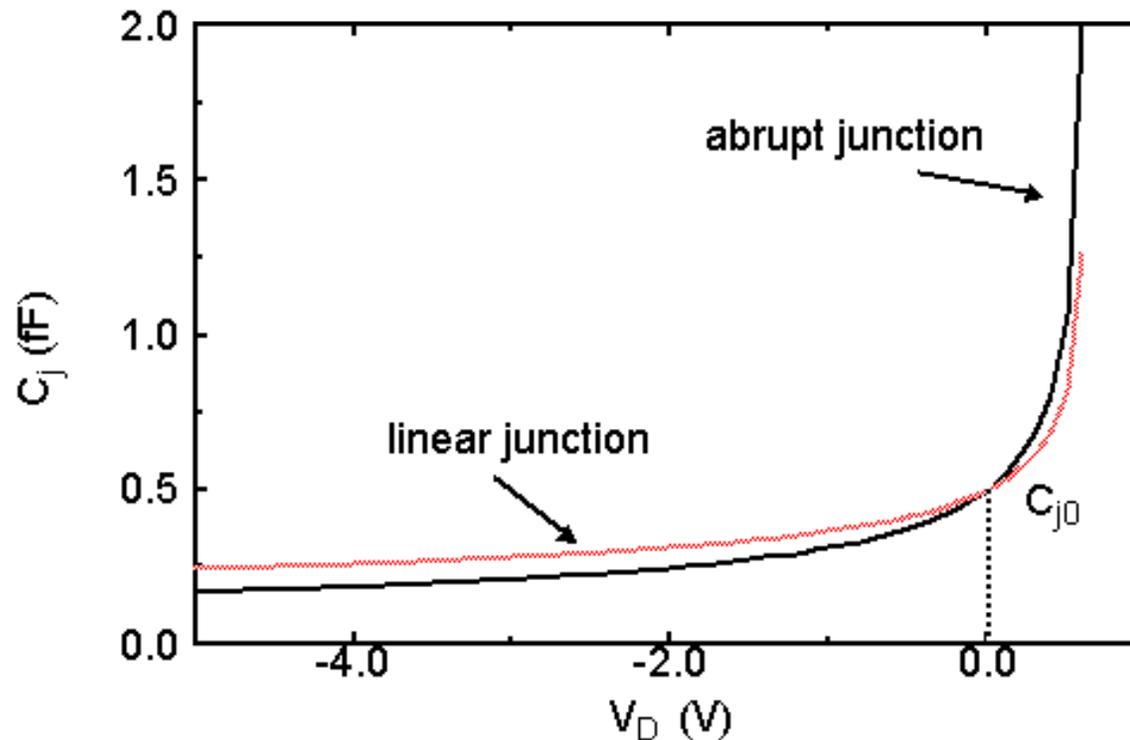


$$C_{diff} = C_{bottom} + C_{sw} = C_j \times AREA + C_{jsw} \times PERIMETER$$

$$= C_j L_S W + C_{jsw} (2L_S + W)$$



C-V Characteristics : Junction Capacitance



$$C_j = \frac{C_{j0}}{(1 - V_D / \phi_0)^m}$$

$m = 0.5$: abrupt junction
 $m = 0.33$: linear junction



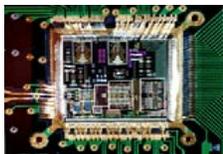
C-V Characteristics :

Linearizing the Junction Capacitance

Replace non-linear capacitance by large-signal equivalent linear capacitance which displaces equal charge over voltage swing of interest.

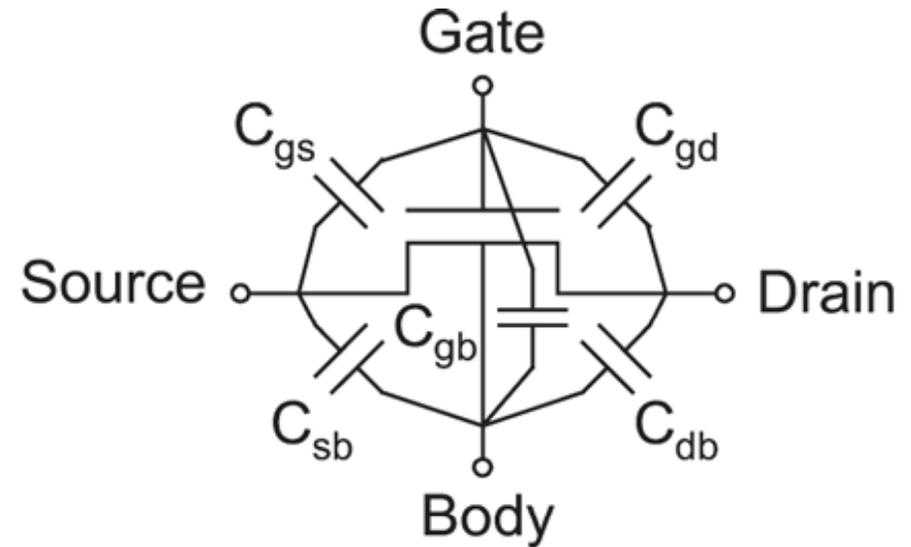
$$C_{eq} = \frac{\Delta Q_j}{\Delta V_D} = \frac{Q_j(V_{high}) - Q_j(V_{low})}{V_{high} - V_{low}} = K_{eq} C_{j0}$$

$$K_{eq} = \frac{-\phi_0^m}{(V_{high} - V_{low})(1 - m)} [(\phi_0 - V_{high})^{1-m} - (\phi_0 - V_{low})^{1-m}]$$

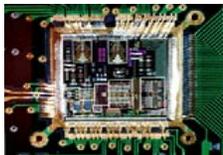


C-V Characteristics : Summary

- MOS is a four terminal device.
- Capacitance exists between each pair of terminals.
- Gate capacitance include both intrinsic and overlap components.
- The source and drain have parasitic diffusion capacitance to the body.

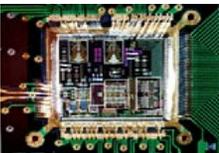


Capacitances of an MOS transistor

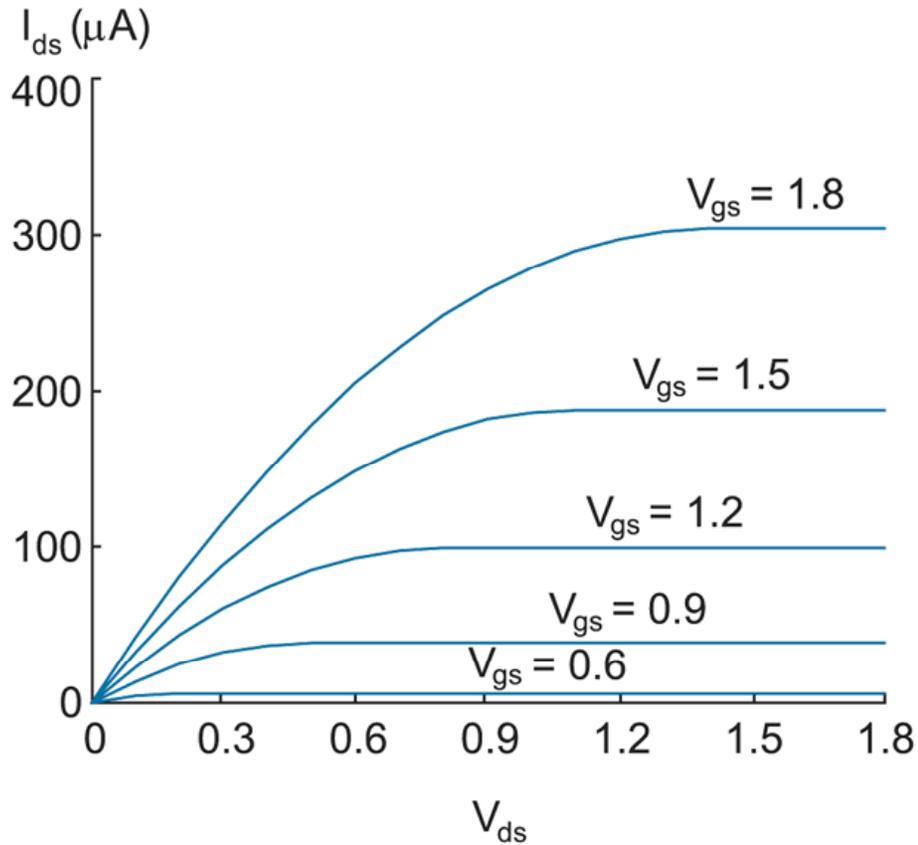


Non-ideal I-V Effects

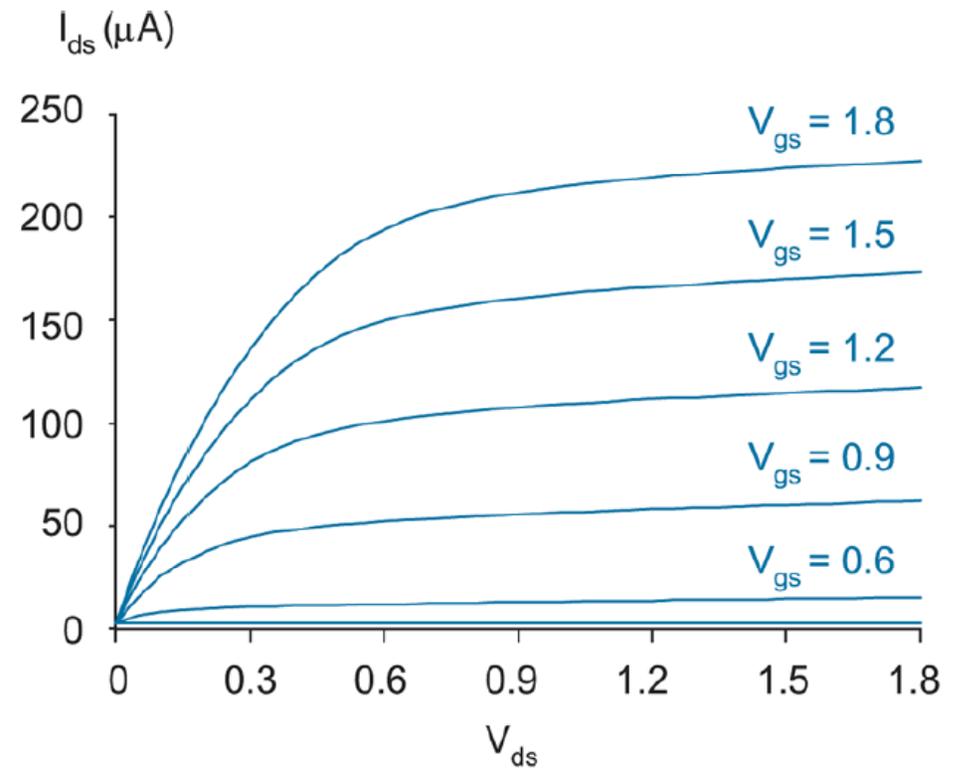
- Two effects make the saturation current increase less quadratically than expected:
 - Velocity saturation
 - Mobility degradation
- Few more effects that impact the characteristics of MOS are:
 - Channel length modulation
 - Body effect
 - Subthreshold conduction
 - Junction leakage
 - Gate leakage (tunneling)
 - Operating temperature
 - Device geometry



Non-ideal I-V Effects : Vs Ideal



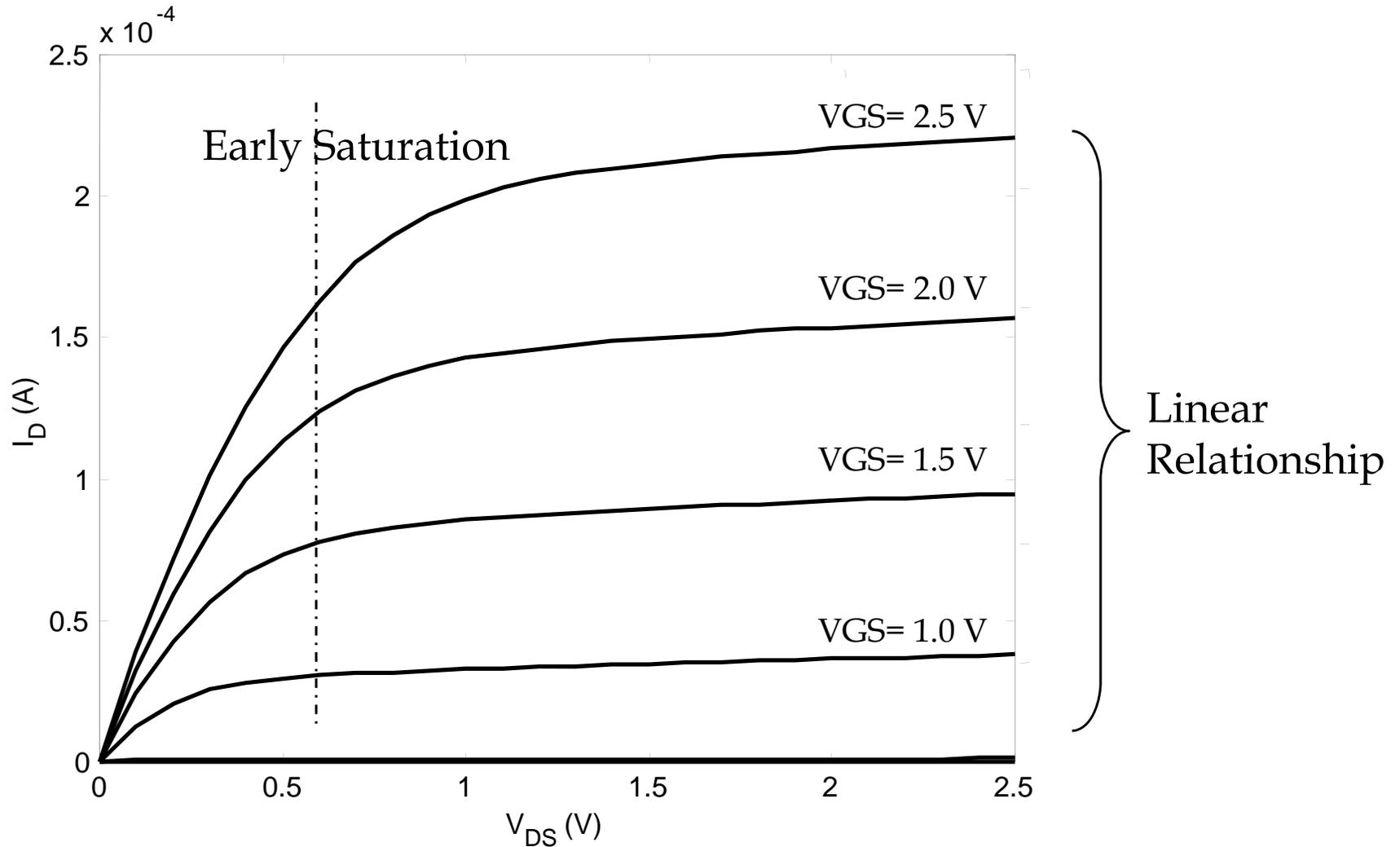
I-V Characteristic of Ideal NMOS



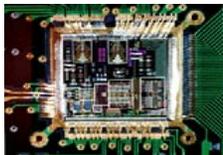
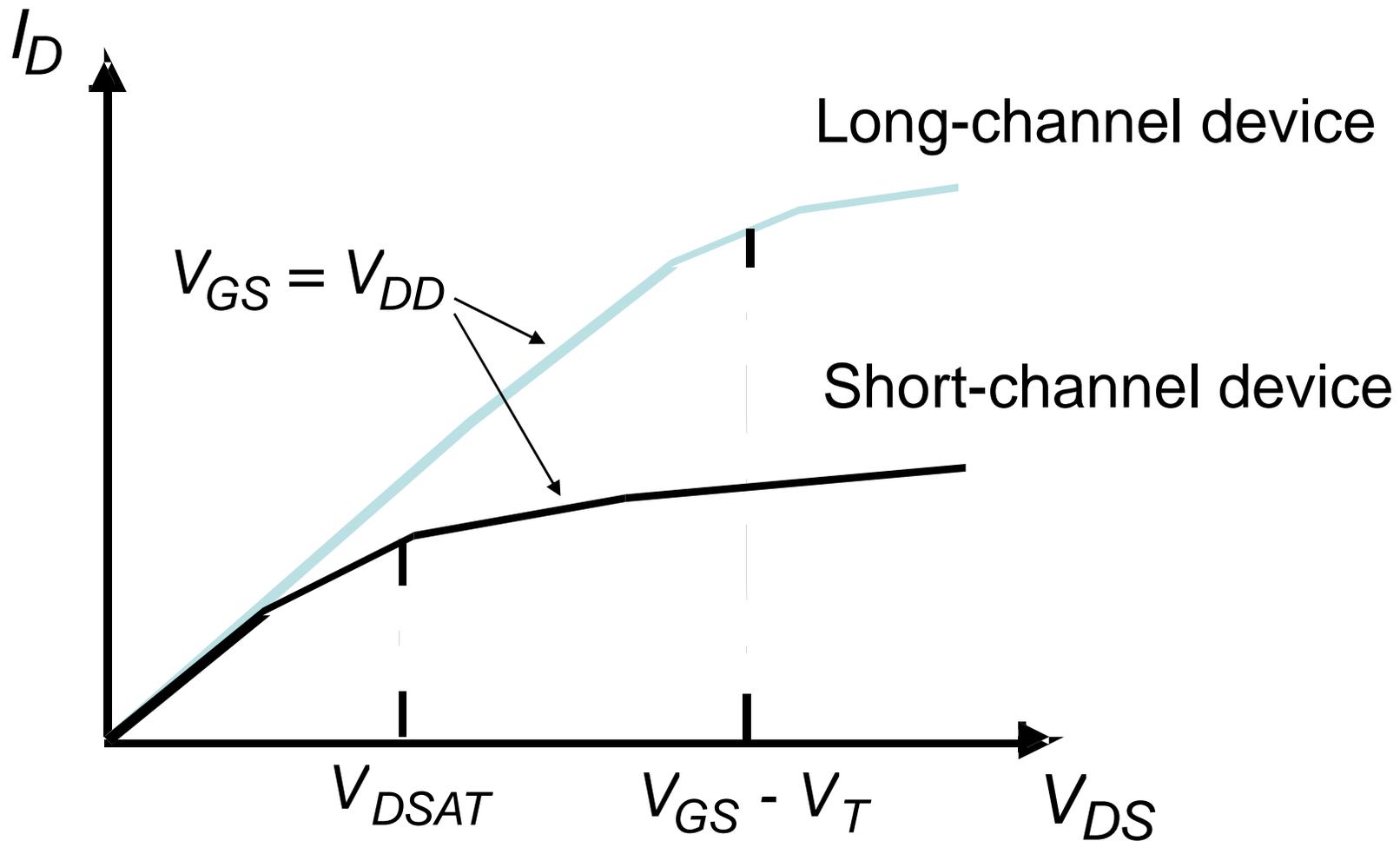
I-V Characteristic of Non-Ideal NMOS



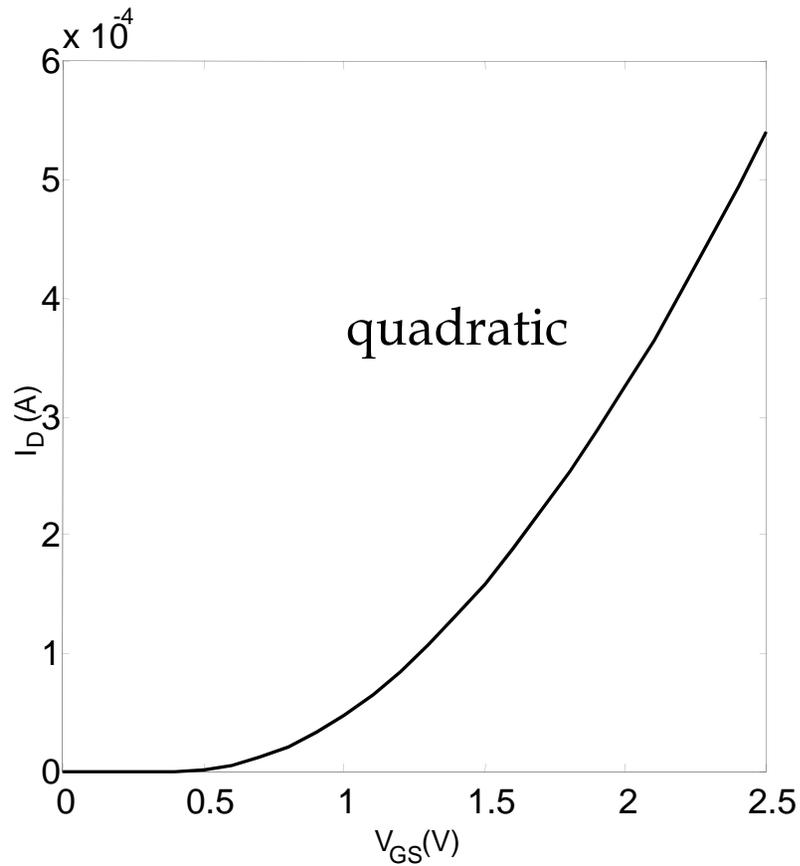
Current-Voltage Relations: The Deep-Submicron Era



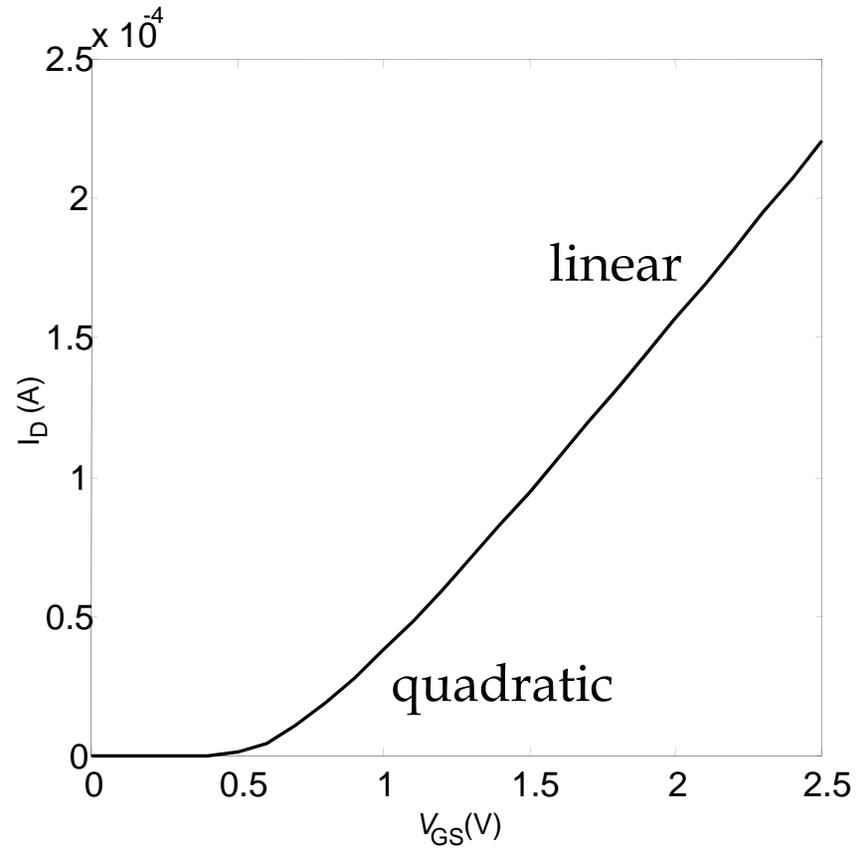
Current-Voltage Relations: Perspective



I_D versus V_{GS}



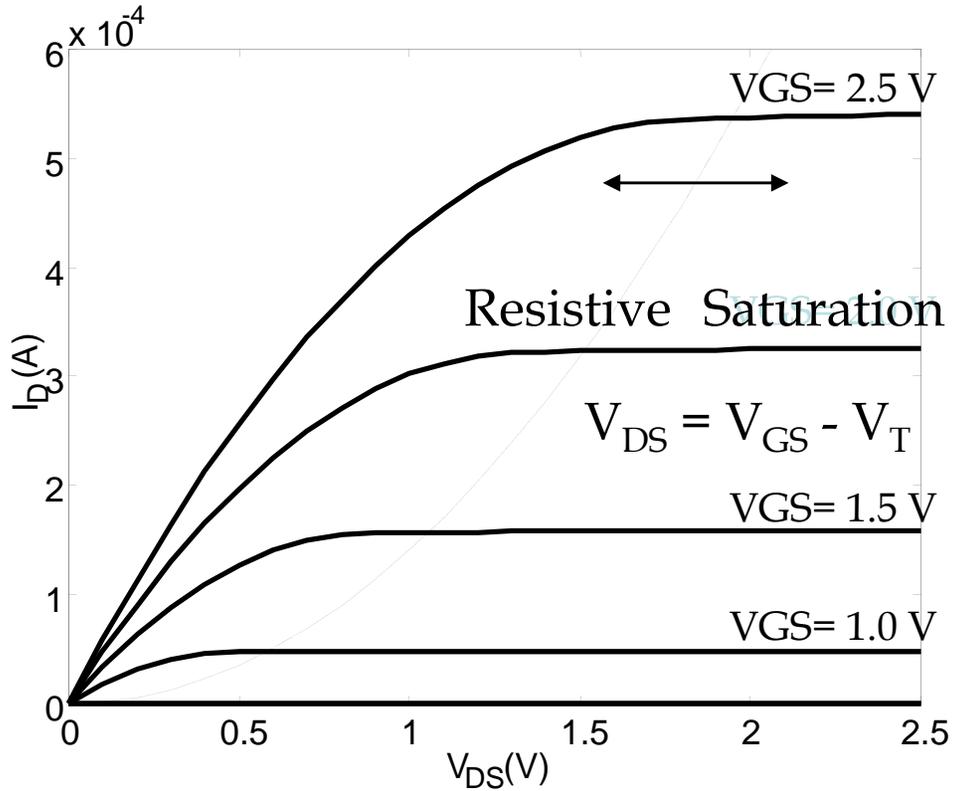
Long Channel



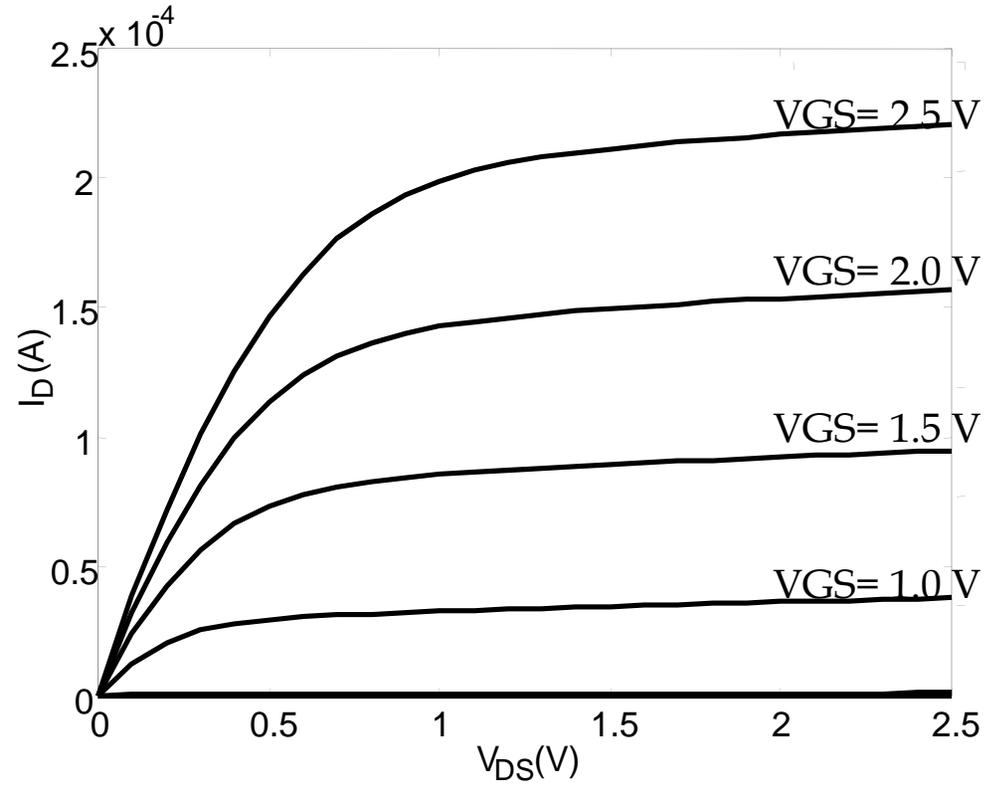
Short Channel



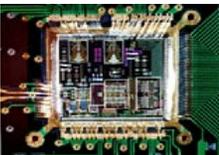
I_D versus V_{DS}



Long Channel

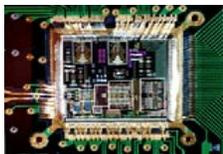
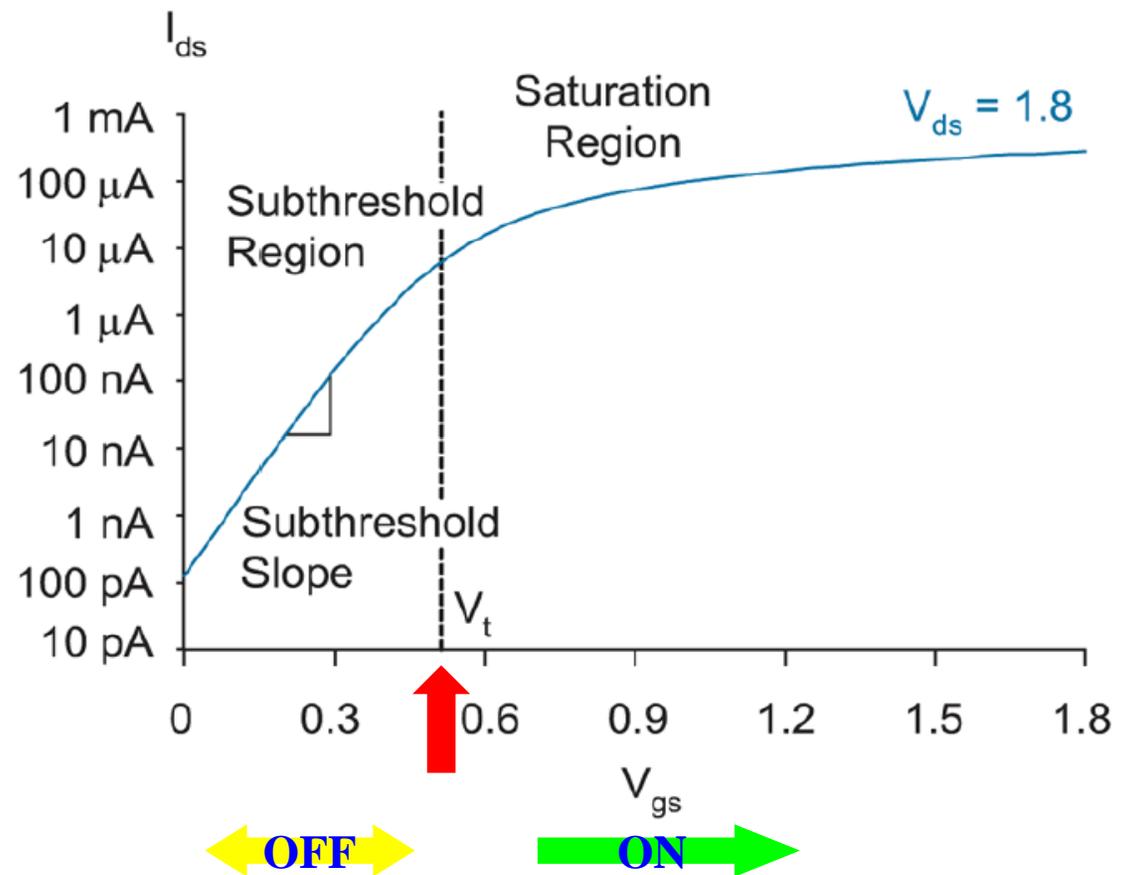


Short Channel



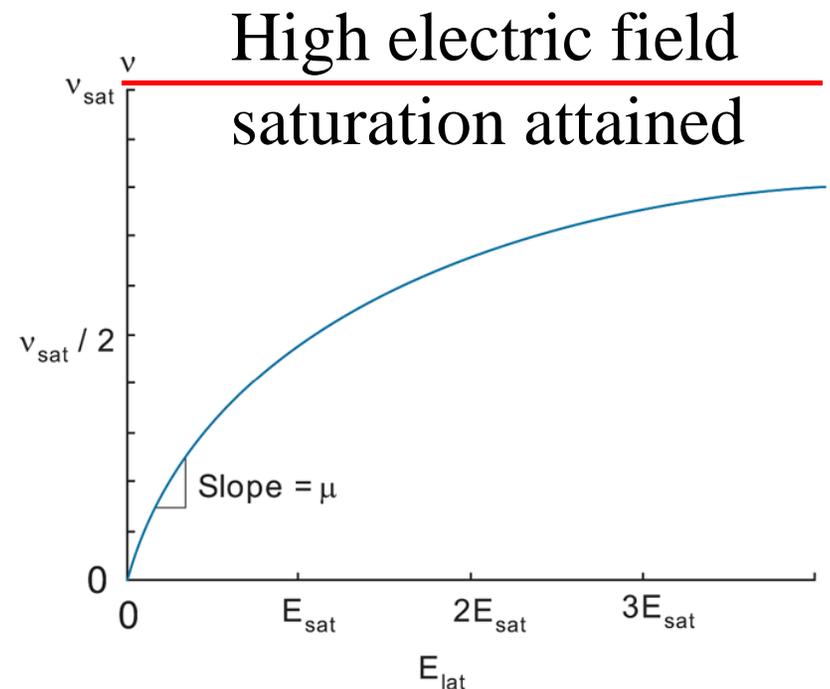
Non-ideal I-V Effects : Study Region wise

- In OFF state i.e. subthreshold region, there is some current flow, which has exponential variation.
- In ON State:
 - Linear Region: Linear variation
 - Saturation Region: Approximately quadratic variation

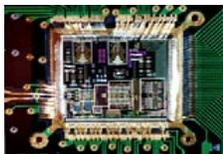


Non-ideal I-V Effects : Velocity Saturation

- Two electric fields:
 - Lateral (V_{ds} / L)
 - Vertical (V_{gs} / t_{ox})
- When lateral electric field is very high carrier velocity does not increase linearly with it.
- High vertical field also scatters the carriers.
- In turn reduces the carrier mobility; effect is called **mobility degradation**.

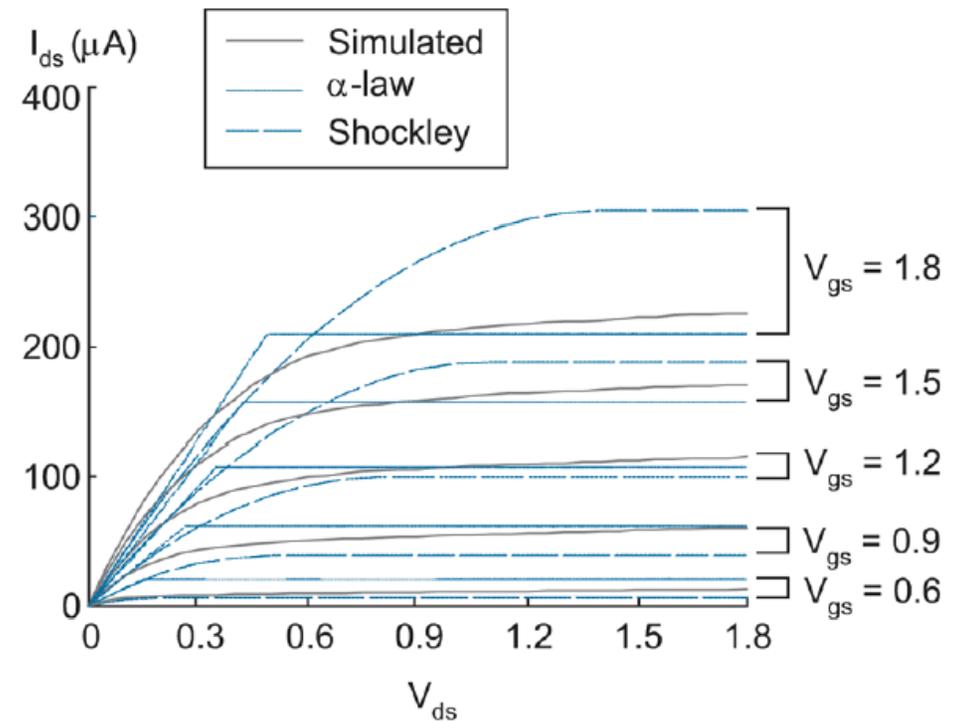


Carrier velocity vs. electric field

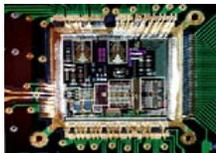


Non-ideal I-V Effects : Velocity Saturation ...

- Carrier saturation velocity, $v_{\text{sat}} = \mu E_{\text{sat}}$
- Typical Values:
 - For electron: $6-10 \times 10^6$ cm / s
 - For hole: $4-8 \times 10^6$ cm / s
- Alpha (α) – Power law model introduced a new parameter called velocity saturation index (α) to model it.

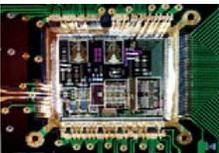


I-V characteristics for nMOS transistor with velocity saturation



Non-ideal I-V Effects: Channel Length Modulation

- The reverse biased p-n junction between the drain and body form a depletion region.
- The length of depletion region L_d increases with the drain to body voltage V_{db} .
- The depletion region shortens the channel length, $L_{eff} = L - L_d$.
- It is very important for short channel transistors.

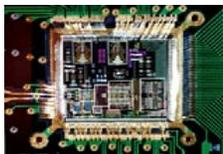


Non-ideal I-V Effects : Body Effect

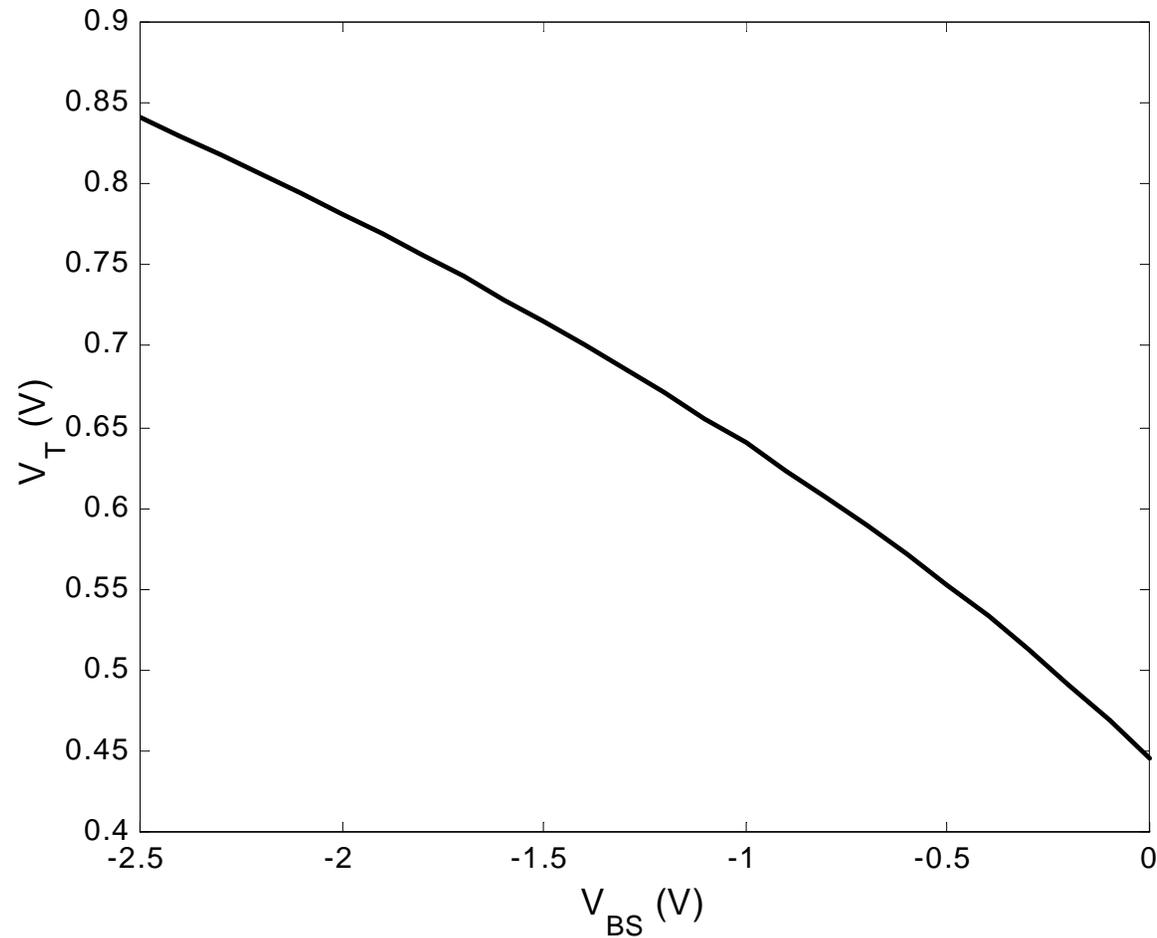
- The potential difference between source and body V_{sb} can affect the threshold voltage.
- It is modeled using surface potential and body effect coefficient, which in turn depend on the doping level.
- Sometimes intentionally body biased is used to decrease the subthreshold leakage.
- Results in increase in threshold as:

$$V_{th} = V_{T0} + \text{Change on } V_{th}$$

$$V_{th} = V_{FB} + \Phi_s + \gamma \sqrt{\Phi_s - V_{bs}} = V_{TH0} + \gamma \left(\sqrt{\Phi_s - V_{bs}} - \sqrt{\Phi_s} \right)$$



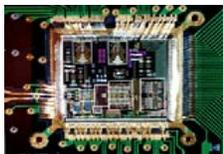
Non-ideal I-V Effects : The Body Effect



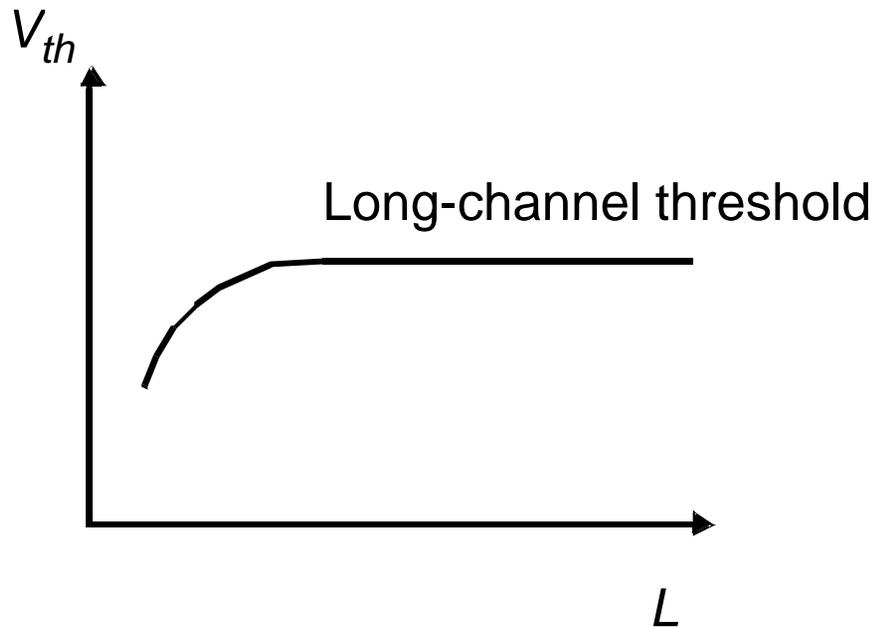
Non-ideal I-V Effects : Subthreshold Conduction

- In OFF state, undesired leakage current flow.
- It contributes to power dissipation of idle circuits.
- Drain-Induced-Barrier-Lowering (DIBL) an prominent effect for short channel transistors also impacts subthreshold conduction by lowering V_{th} .
- It increases as the V_{th} decreases or V_{gs} increases.
- It increases as the temperature increases.
- If v_t is the thermal voltage and I_0 is the current at V_{th} then the subthreshold current is :

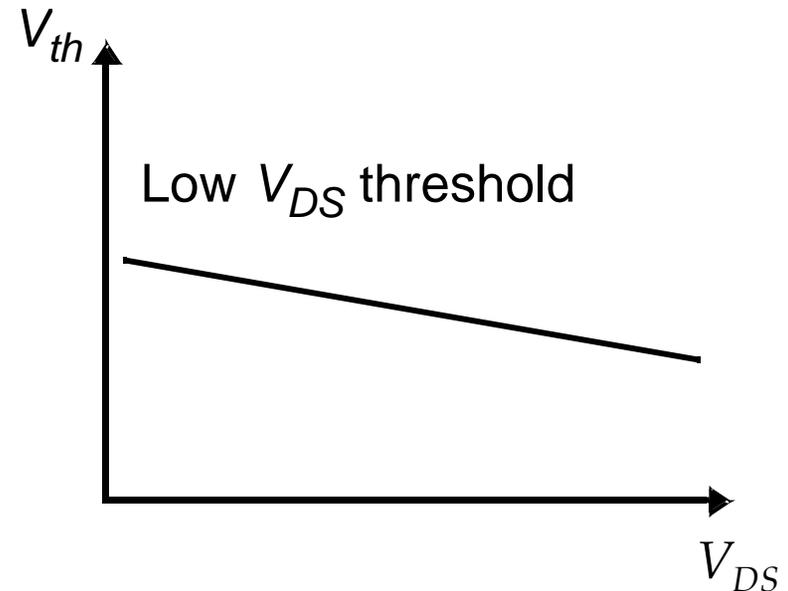
$$I_{ds} = I_0 \left[1 - \exp\left(-\frac{V_{ds}}{v_t}\right) \right] \cdot \exp\left(\frac{V_{gs} - V_{th} - V_{off}'}{nv_t}\right) \quad I_0 = \mu C_{ox} \left(\frac{W}{L}\right) v_t^2 e^{1.8}$$



Non-ideal I-V Effects : Subthreshold Conduction

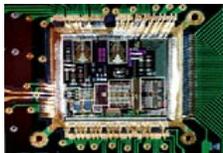


Threshold as a function of the length (for low V_{DS})

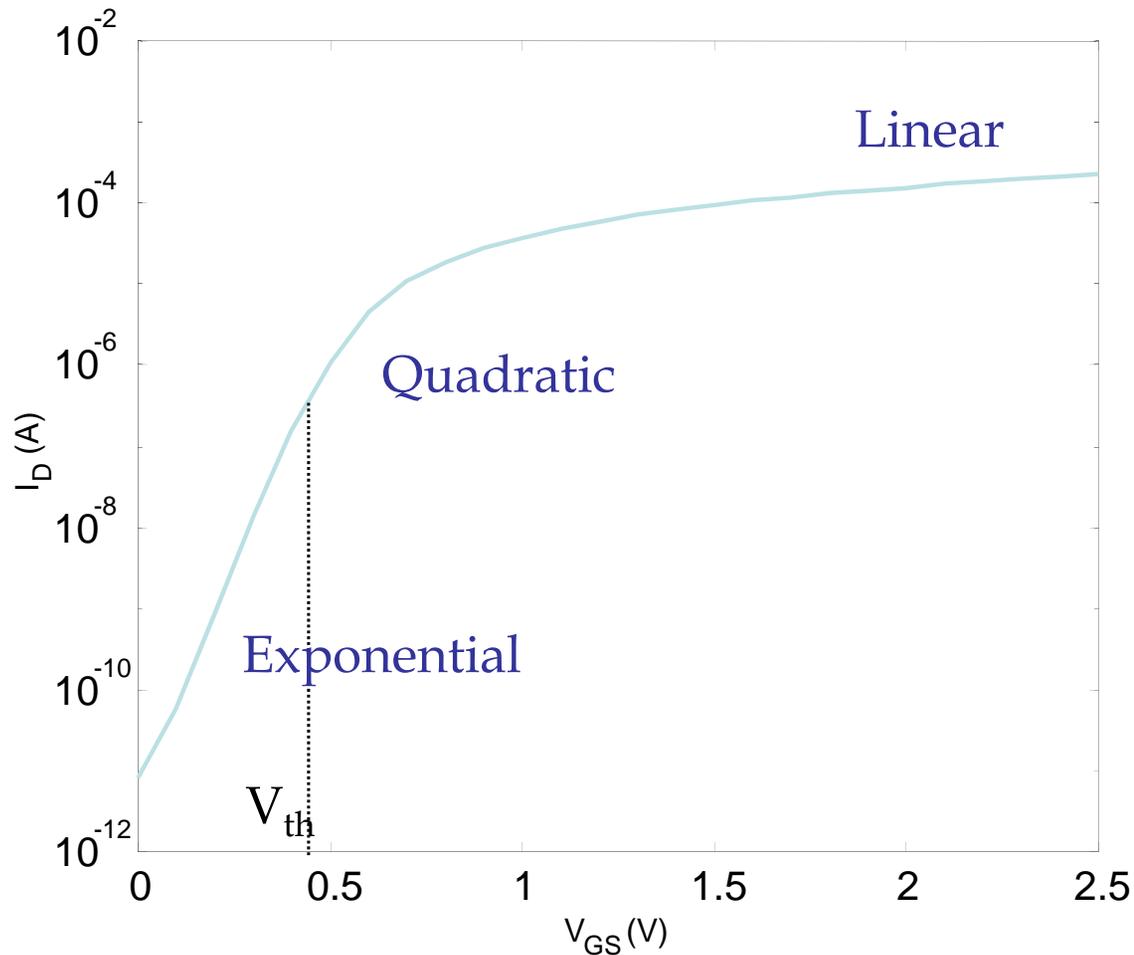


Drain-induced barrier lowering (for low L)

Subthreshold Variations



Non-ideal I-V Effects : Subthreshold Conduction



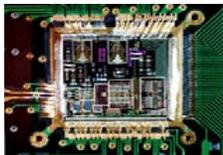
The Slope Factor

$$I_D \sim I_0 e^{\frac{qV_{GS}}{nkT}}, \quad n = 1 + \frac{C_D}{C_{ox}}$$

S is ΔV_{GS} for $I_{D2}/I_{D1} = 10$

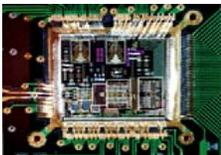
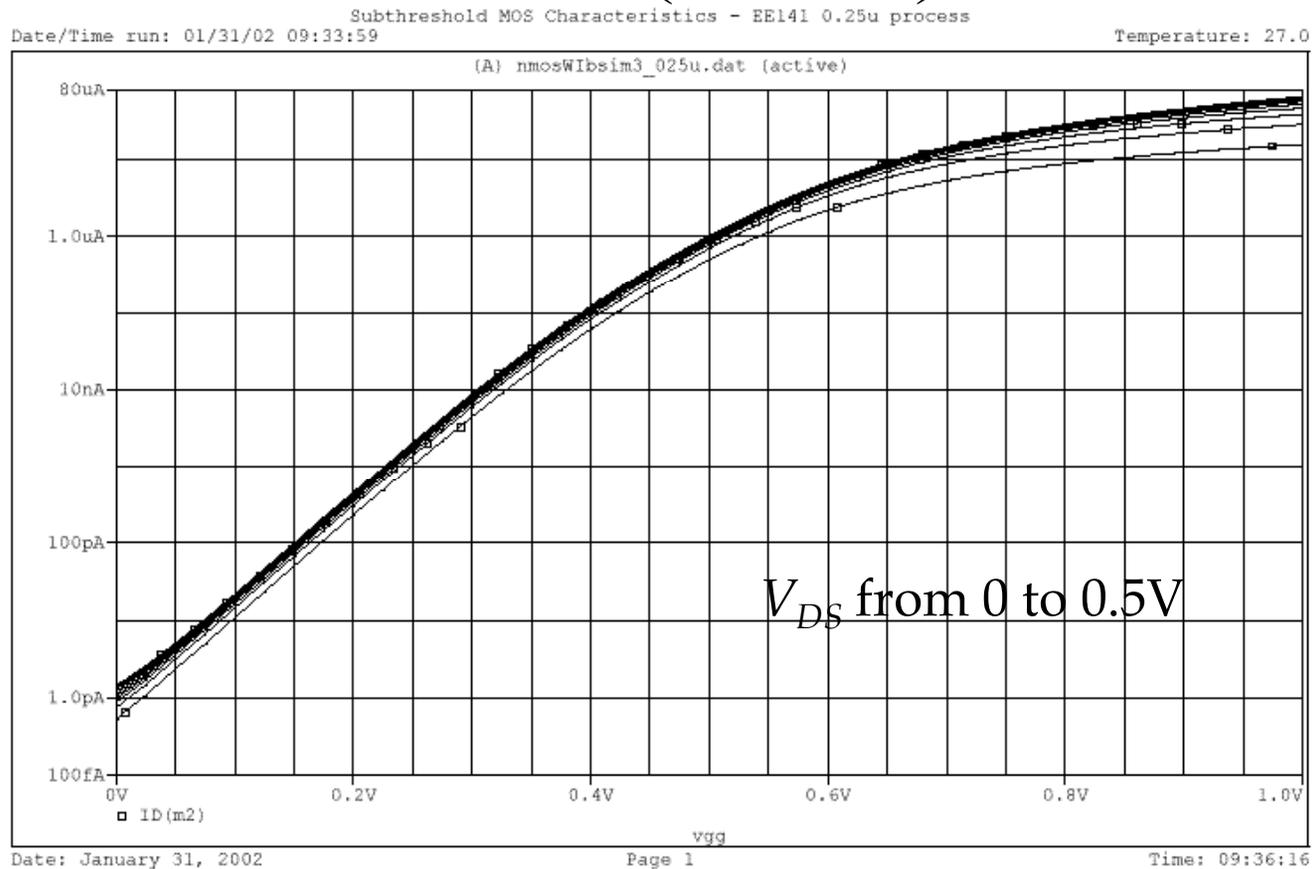
$$S = n \left(\frac{kT}{q} \right) \ln(10)$$

Typical values for S :
60 .. 100 mV/decade



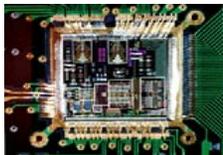
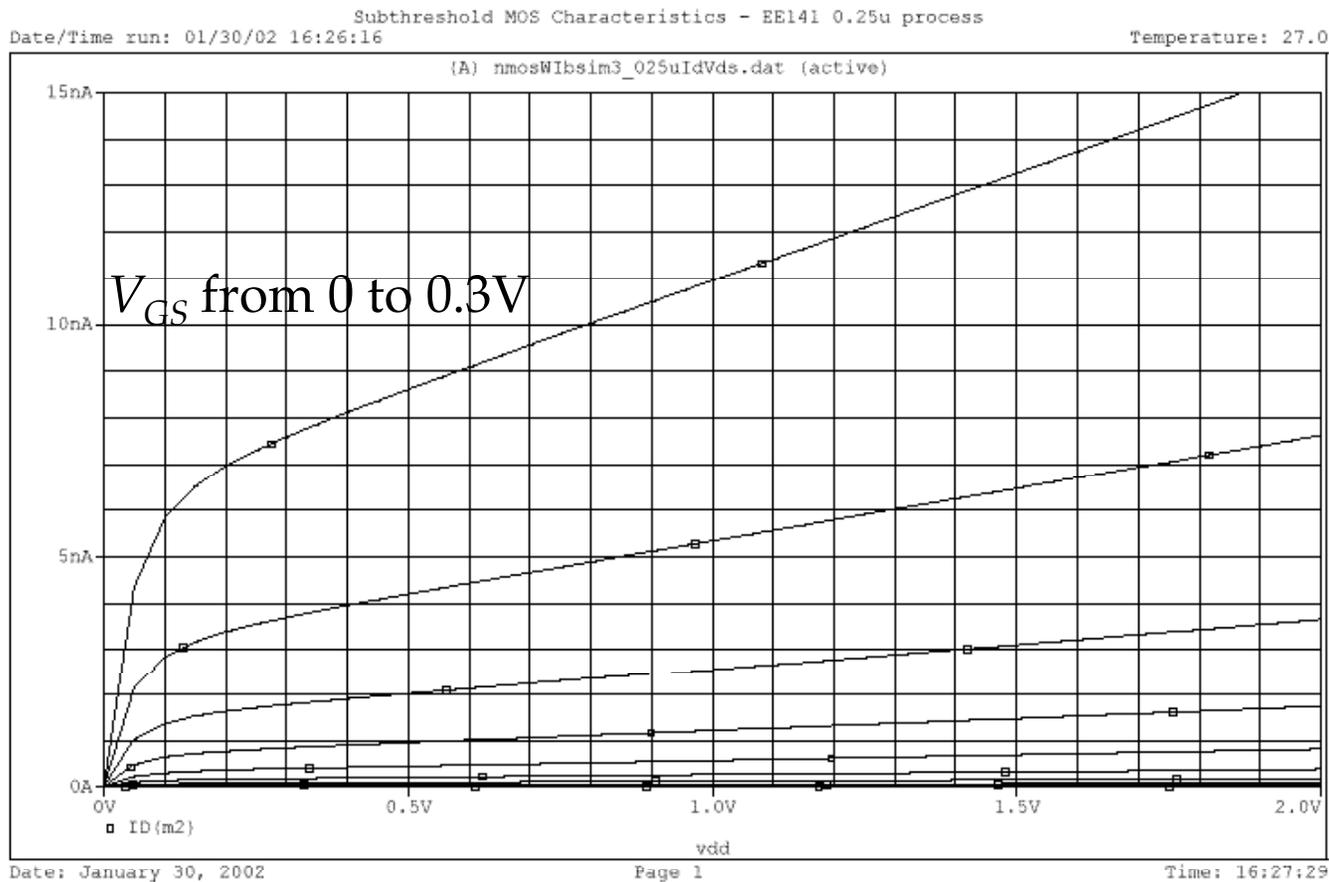
Non-ideal I-V Effects : Subthreshold Conduction (I_D vs V_{GS})

$$I_D = I_0 e^{\frac{qV_{GS}}{nkT}} \left(1 - e^{-\frac{qV_{DS}}{kT}} \right)$$



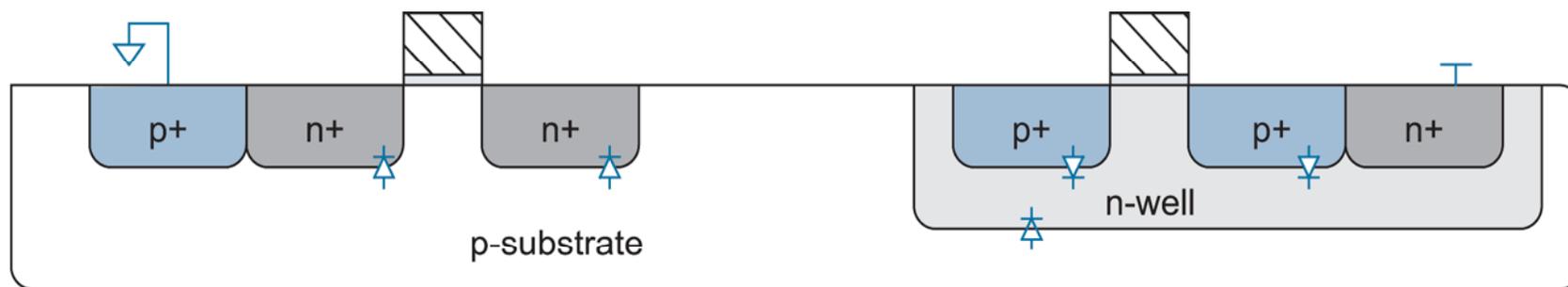
Non-ideal I-V Effects : Subthreshold Conduction (I_D vs V_{DS})

$$I_D = I_0 e^{\frac{qV_{GS}}{nkT}} \left(1 - e^{-\frac{qV_{DS}}{kT}} \right) (1 + \lambda \cdot V_{DS})$$

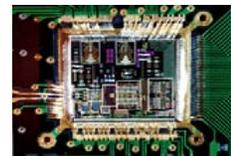


Non-ideal I-V Effects : Junction Leakage

- The pn junctions between diffusion, substrate and well are all junction diodes.
- These are reversed biased as substrate is connected to GND and well connected to V_{dd} .
- However, reversed biased diode also conduct small amount of current.

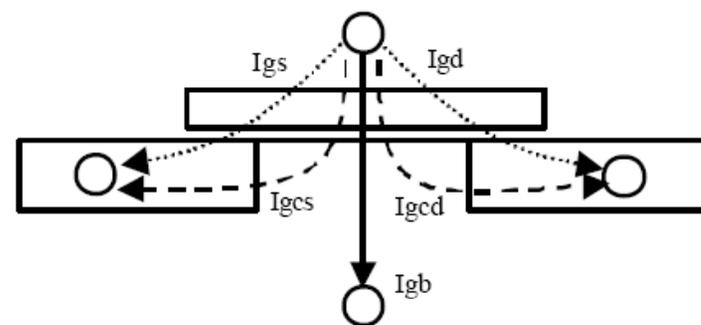


Reverse-biased diodes in CMOS circuits

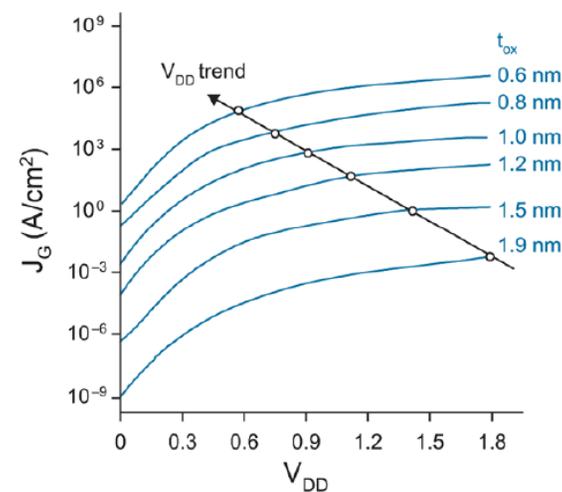


Non-ideal I-V Effects : Tunneling

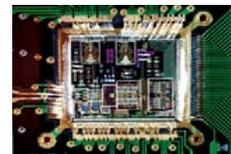
- There is a finite probability for carrier being pass through the gate oxide.
- This results in tunneling current thorough the gate oxide.
- The effect is predominate for lower oxide thickness.
- Substituting gate oxide with other dielectric with high-K is as an alternative.



Gate current components

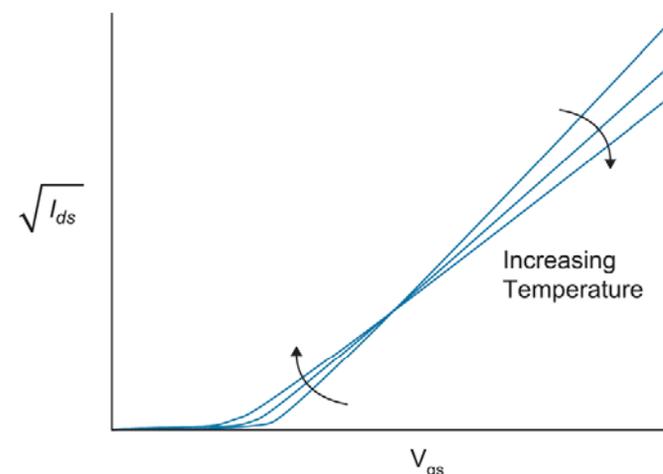


Gate leakage current from

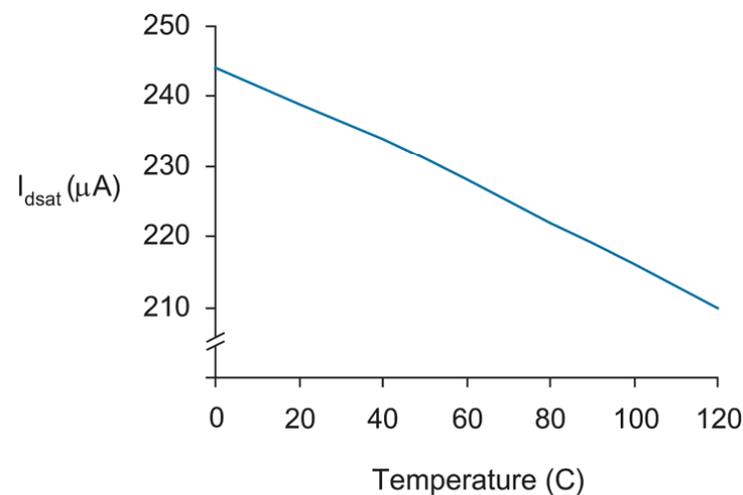


Non-ideal I-V Effects : Temperature

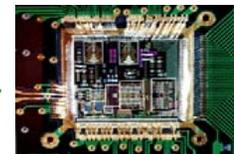
- Carrier mobility decreases with temperature.
- The magnitude of threshold voltage is linear with the increase in temperature.
- The junction leakage increases with temperature.
- In summary: ON state current decreases and OFF state increases with temperature.
- Thus circuit performance is improved by cooling, hence heat sink, radiators, cooling fans !!



-V characteristics of nMOS transistor in saturation at various temperatures

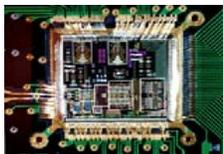


I_{dsat} vs. temperature



Non-ideal I-V Effects : Geometry

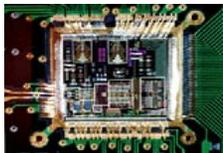
- Width and length for each device should be appropriately chosen for current matching.
- The actual dimension of the device may differ due to several reasons:
 - Manufactures using mask of wrong dimension
 - More lateral diffusion of source and drain
- **NOTE:** Combination of threshold, effective channel length, channel length modulation, etc reduces the current carrying capacity by half.



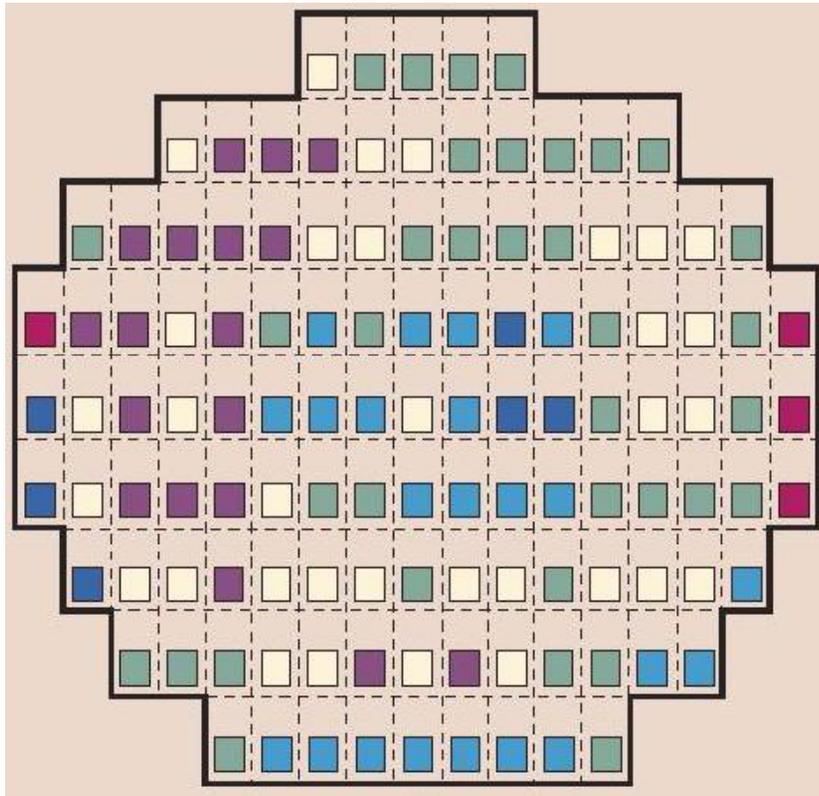
Variability: Origin and Sources

- Ion implantation
- Chemical mechanical polishing (CMP)
- Chemical vapor deposition (CVD)
- Sub-wavelength lithography
- Lens aberration
- Materials flow
- Gas flow
- Thermal processes
- Spin processes
- Microscopic processes
- Photo processes

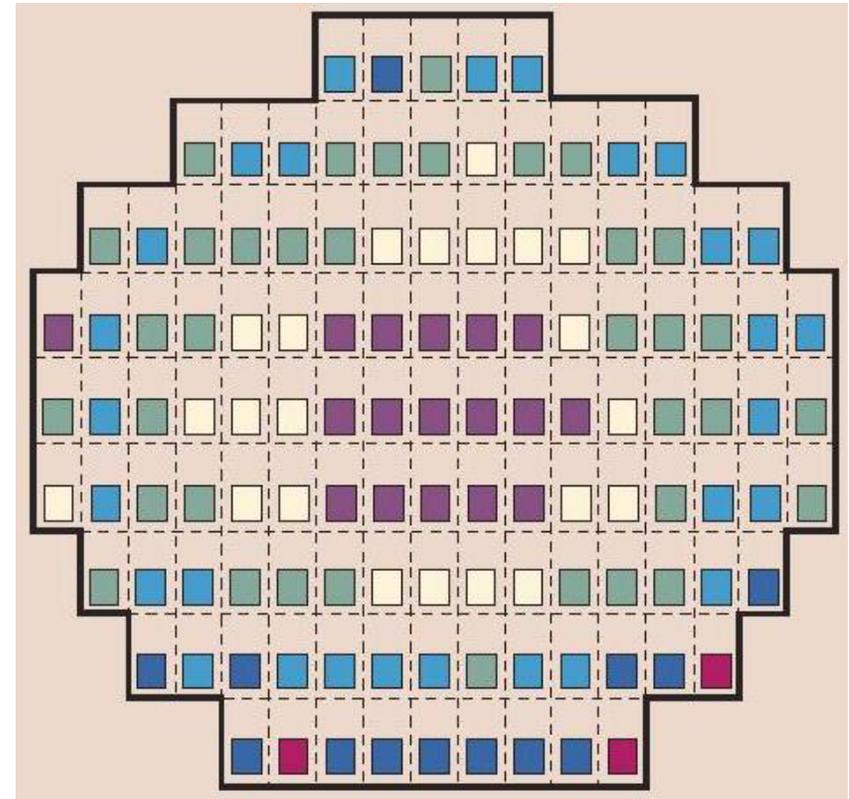
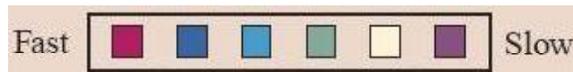
Source: Singhal, DAC Booth 2007



Variability: The Impact in a Wafer ...



Source–drain resistance is different for different chips in a same die.



Gate-to-source and gate-to-drain overlap capacitance is different for different chips in a same die.

Source: Bernstein et al., IBM J. Res. & Dev., July/Sep 2006.

