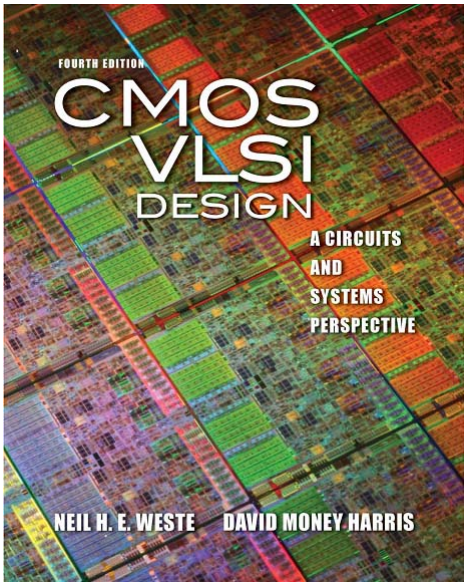


Lecture 4: Nonideal Transistor Theory

Outline

- Nonideal Transistor Behavior
  - High Field Effects
    - Mobility Degradation
    - Velocity Saturation
  - Channel Length Modulation
  - Threshold Voltage Effects
    - Body Effect
    - Drain-Induced Barrier Lowering
    - Short Channel Effect
  - Leakage
    - Subthreshold Leakage
    - Gate Leakage
    - Junction Leakage
- Process and Environmental Variations

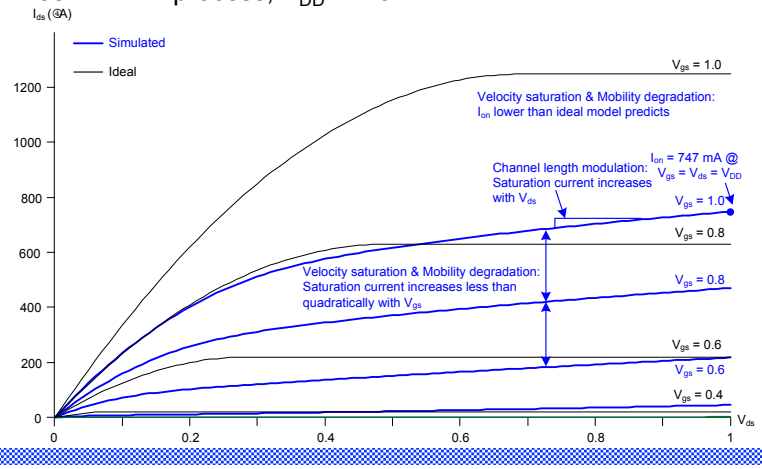
Ideal Transistor I-V

- *Shockley* long-channel transistor models

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

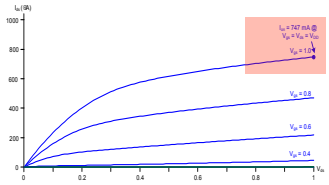
Ideal vs. Simulated nMOS I-V Plot

- 65 nm IBM process, V_{DD} = 1.0 V

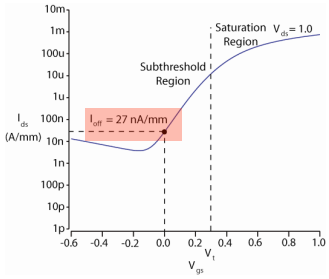


ON and OFF Current

- $I_{on} = I_{ds}$ @ $V_{gs} = V_{ds} = V_{DD}$
  - Saturation



- $I_{off} = I_{ds}$ @ $V_{gs} = 0$, $V_{ds} = V_{DD}$
  - Cutoff



Electric Fields Effects

- Vertical electric field: E_{vert} = _____
  - Attracts carriers into channel
  - Long channel: $Q_{channel} \propto E_{vert}$
- Lateral electric field: E_{lat} = _____
  - Accelerates carriers from drain to source
  - Long channel: $v = \mu E_{lat}$

Coffee Cart Analogy

- Tired student runs from VLSI lab to coffee cart
- Freshmen are pouring out of the physics lecture hall
- V_{ds} is how long you have been up
  - Your velocity = fatigue × mobility
- V_{gs} is a wind blowing you against the glass (SiO_2) wall
- At high V_{gs}, you are buffeted against the wall
  - *Mobility degradation*
- At high V_{ds}, you scatter off freshmen, fall down, get up
  - *Velocity saturation*
    - Don't confuse this with the saturation region

Mobility Degradation

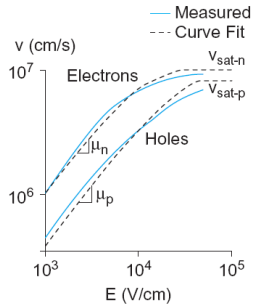
- High E_{vert} effectively reduces mobility
  - Collisions with oxide interface

$$\mu_{\text{eff}-n} = \frac{540\frac{\text{cm}^2}{\text{V}\cdot\text{s}}}{1+\left(\frac{V_{gs}+V_t}{0.54\frac{\text{V}}{\text{nm}}t_{\text{ox}}}\right)^{1.85}} \qquad \mu_{\text{eff}-p} = \frac{185\frac{\text{cm}^2}{\text{V}\cdot\text{s}}}{1+\frac{\left|V_{gs}+1.5V_t\right|}{0.338\frac{\text{V}}{\text{nm}}t_{\text{ox}}}}$$

Velocity Saturation

- At high E_{lat}, carrier velocity rolls off
  - Carriers scatter off atoms in silicon lattice
  - Velocity reaches v_{sat}
    - Electrons: 10^7 cm/s
    - Holes: 8 x 10^6 cm/s
  - Better model

$$v = \begin{cases} \dfrac{\mu_{\text{eff}} E}{1 + \dfrac{E}{E_c}} & E < E_c \\ v_{\text{sat}} & E \geq E_c \end{cases} \qquad E_c = \frac{2 v_{\text{sat}}}{\mu_{\text{eff}}}$$



Vel Sat I-V Effects

- Ideal transistor ON current increases with V_{DD}^2

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

- Velocity-saturated ON current increases with V_{DD}

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

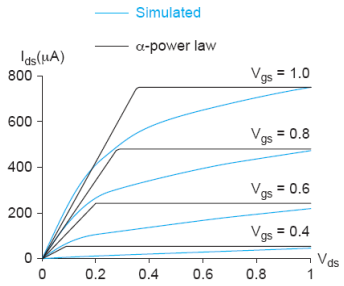
- Real transistors are partially velocity saturated
  - Approximate with α-power law model
  - $I_{ds} \propto V_{DD}^{\alpha}$
  - $1 < \alpha < 2$ determined empirically (≈ 1.3 for 65 nm)

α-Power Model

$$I_{ds} = \begin{cases} 0 & V_{gs} < V_t \quad \text{cutoff} \\ I_{dsat}\dfrac{V_{ds}}{V_{dsat}} & V_{ds} < V_{dsat} \quad \text{linear} \\ I_{dsat} & V_{ds} > V_{dsat} \quad \text{saturation} \end{cases}$$

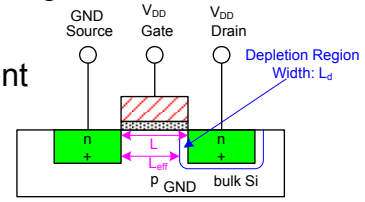
$$I_{dsat} = P_c \frac{\beta}{2}\left(V_{gs} - V_t\right)^{\alpha}$$

$$V_{dsat} = P_v \left(V_{gs} - V_t\right)^{\alpha/2}$$



Channel Length Modulation

- Reverse-biased p-n junctions form a *depletion region*
  - Region between n and p with no carriers
  - Width of depletion L_d region grows with reverse bias
  - $L_{eff} = L - L_d$
- Shorter L_{eff} gives _____ current
  - I_{ds} _____ with V_{ds}
  - Even in saturation



Channel Length Mod I-V

$$I_{ds} = \frac{\beta}{2}\left(V_{gs} - V_t\right)^2\left(1 + \lambda V_{ds}\right)$$

- λ = *channel length modulation coefficient*
  - not feature size
  - Empirically fit to I-V characteristics

Threshold Voltage Effects

- V_t is V_{gs} for which the channel starts to invert
- Ideal models assumed V_t is constant
- Really depends (weakly) on almost everything else:
  - Body voltage: *Body Effect*
  - Drain voltage: *Drain-Induced Barrier Lowering*
  - Channel length: *Short Channel Effect*

Body Effect

- Body is a fourth transistor terminal
- V_{sb} affects the charge required to invert the channel
  - Increasing V_s or decreasing V_b increases V_t

$$V_t = V_{t0} + \gamma\left(\sqrt{\phi_s + V_{sb}} - \sqrt{\phi_s}\right)$$

- ϕ_s = *surface potential* at threshold

$$\phi_s = 2v_T \ln\frac{N_A}{n_i}$$

  - Depends on doping level N_A
  - And intrinsic carrier concentration n_i
- γ = *body effect coefficient*

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

Body Effect Cont.

- For small source-to-body voltage, treat as linear

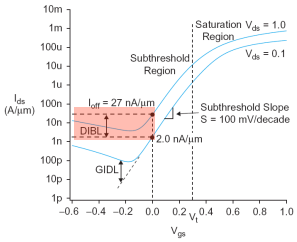
$$V_t = V_{t0} + k_\gamma V_{sb}$$

$$k_\gamma = \frac{\gamma}{2\sqrt{\phi_s}} = \frac{\sqrt{\frac{q\varepsilon_{si}N_A}{v_T \ln\frac{N_A}{n_i}}}}{2C_{ox}}$$

DIBL

- Electric field from drain affects channel
- More pronounced in small transistors where the drain is closer to the channel
- Drain-Induced Barrier Lowering
  - Drain voltage also affect V_t

$$V_t' = V_t - \eta V_{ds}$$



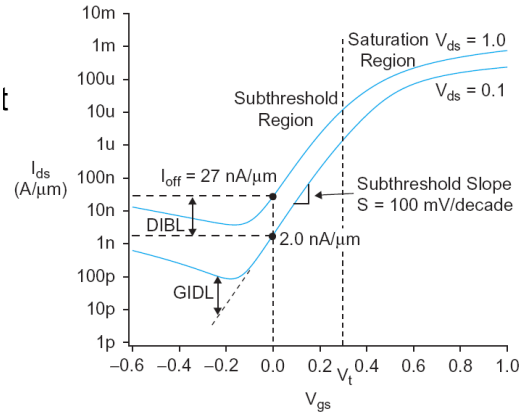
- High drain voltage causes current to _____

Short Channel Effect

- In small transistors, source/drain depletion regions extend into the channel
  - Impacts the amount of charge required to invert the channel
  - And thus makes V_t a function of channel length
- Short channel effect: V_t increases with L
  - Some processes exhibit a reverse short channel effect in which V_t decreases with L

Leakage

- What about current in cutoff?
- Simulated results
- What differs?
  - t



Leakage Sources

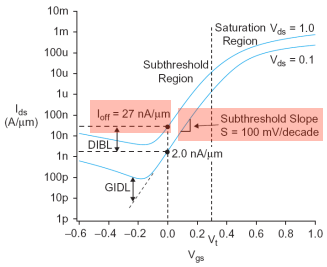
- Subthreshold conduction
  - Transistors can't abruptly turn ON or OFF
  - Dominant source in contemporary transistors
- Gate leakage
  - Tunneling through ultrathin gate dielectric
- Junction leakage
  - Reverse-biased PN junction diode current

Subthreshold Leakage

- Subthreshold leakage exponential with V_{gs}

$$I_{ds} = I_{ds0} e^{\frac{V_{gs} - V_{t0} + \eta V_{ds} - k_\gamma V_{sb}}{n v_T}} \left(1 - e^{\frac{-V_{ds}}{v_T}}\right)$$

- n is process dependent
  - typically 1.3-1.7
- Rewrite relative to I_{off} on log scale



$$I_{ds} = I_{off} 10^{\frac{V_{gs} + \eta(V_{ds} - V_{dd}) - k\gamma V_{sb}}{S}} \left(1 - e^{\frac{-V_{ds}}{v_t}}\right)$$

$$S = \left[\frac{d(\log_{10} I_{ds})}{dV_{gs}}\right]^{-1} = n v_T \ln 10$$

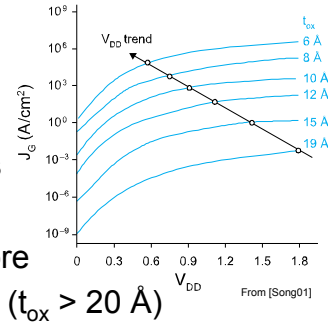
- S ≈ 100 mV/decade @ room temperature

Gate Leakage

- Carriers tunnel thorough very thin gate oxides
- Exponentially sensitive to t_{ox} and V_{DD}

$$I_{gate} = WA\left(\frac{V_{DD}}{t_{ox}}\right)^2 e^{-B\frac{t_{ox}}{V_{DD}}}$$

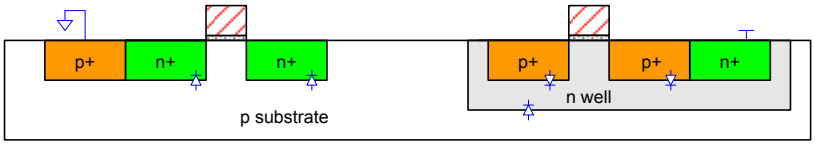
  - A and B are tech constants
  - Greater for electrons
    - So nMOS gates leak more



- Negligible for older processes (t_{ox} > 20 Å)
- Critically important at 65 nm and below (t_{ox} ≈ 10.5 Å)

Junction Leakage

- Reverse-biased p-n junctions have some leakage
  - Ordinary diode leakage
  - Band-to-band tunneling (BTBT)
  - Gate-induced drain leakage (GIDL)



Diode Leakage

- Reverse-biased p-n junctions have some leakage

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

- At any significant negative diode voltage, $I_D = -I_s$
- I_s depends on doping levels
  - And area and perimeter of diffusion regions
  - Typically < 1 fA/μm^2 (negligible)

Band-to-Band Tunneling

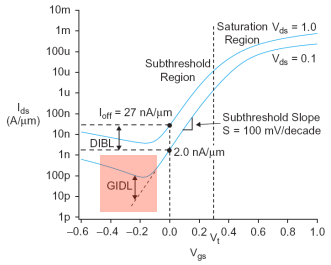
- Tunneling across heavily doped p-n junctions
  - Especially sidewall between drain & channel when *halo doping* is used to increase V_t
- Increases junction leakage to significant levels

$$I_{BTBT} = WX_j A \frac{E_j}{E_g^{0.5}} V_{dd} e^{-B\frac{E_g^{1.5}}{E_j}} \qquad E_j = \sqrt{\frac{2qN_{halo}N_{sd}}{\varepsilon(N_{halo}+N_{sd})}}\left(V_{DD} + v_T \ln\frac{N_{halo}N_{sd}}{n_i^2}\right)$$

  - X_j: sidewall junction depth
  - E_g: bandgap voltage
  - A, B: tech constants

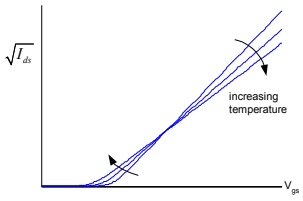
Gate-Induced Drain Leakage

- Occurs at overlap between gate and drain
  - Most pronounced when drain is at V_{DD}, gate is at a negative voltage
  - Thwarts efforts to reduce subthreshold leakage using a negative gate voltage



Temperature Sensitivity

- Increasing temperature
  - Reduces mobility
  - Reduces V_t
- I_{ON} _____ with temperature
- I_{OFF} _____ with temperature

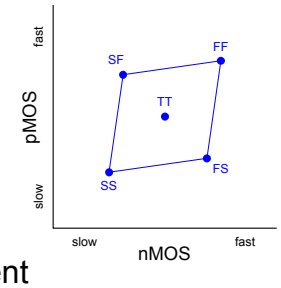


So What?

- So what if transistors are not ideal?
  - They still behave like switches.
- But these effects matter for…
  - Supply voltage choice
  - Logical effort
  - Quiescent power consumption
  - Pass transistors
  - Temperature of operation

Parameter Variation

- Transistors have uncertainty in parameters
  - Process: L_{eff}, V_t, t_{ox} of nMOS and pMOS
  - Vary around typical (T) values
- Fast (F)
  - L_{eff}: _____
  - V_t: _____
  - t_{ox}: _____
- Slow (S): opposite
- Not all parameters are independent for nMOS and pMOS



Environmental Variation

- V_{DD} and T also vary in time and space
- Fast:
  - V_{DD}: _____
  - T: _____

Corner	Voltage	Temperature
F	1.98	0 C
T		
S	1.62	125 C

Process Corners

- Process corners describe worst case variations
  - If a design works in all corners, it will probably work for any variation.
- Describe corner with four letters (T, F, S)
  - nMOS speed
  - pMOS speed
  - Voltage
  - Temperature

Important Corners

- Some critical simulation corners include

Purpose	nMOS	pMOS	V_{DD}	Temp
Cycle time	S	S	S	S
Power	F	F	F	F
Subthreshold leakage	F	F	F	S