EECS240 – Spring 2010

Lecture 3: MOS Models for Design

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Why Modeling?

- Analog circuits more sensitive to detailed transistor behavior
  - Precise currents, voltages, etc. matter
  - Digital circuits have much larger "margin of error"
- Models allow us to reason about circuits
  - Provide window into the physical device and process
  - "Experiments" with SPICE much easier to do

Levels of Abstraction

- Best abstraction depends on questions you want to answer
- Digital functionality:
  - MOSFET is a switch
- Digital performance:
  - MOSFET is a current source and a switch
- Analog characteristics:
  - MOSFET described by BSIM with 100's of parameters?
  - MOSFET described by measurement results?

Why Not Square Law?

- Square law model most widely known:

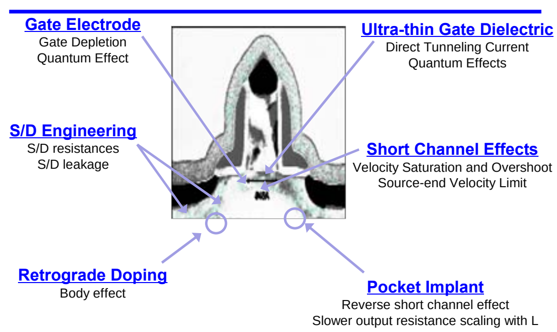
$$I_{D,sat} = \frac{1}{2}\cdot\mu_n\cdot C_{ox}\cdot\frac{W}{L}\cdot(V_{GS}-V_{th})^2$$

- But, totally inadequate for "short-channel" behavior
- Also doesn't capture *moderate* inversion
  - (i.e., in between sub-threshold and strong inversion)

Square Law Model Assumptions

- Charge density determined only by vertical field
- Drift velocity set only by lateral field
- Neglect diffusion currents ("magic" V_{th})
- Constant mobility
- And many more…

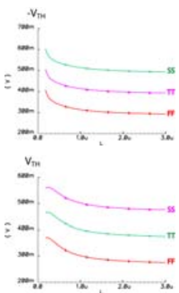
A Real Transistor



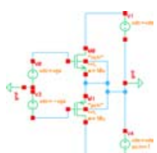
To Make Matters Worse…

- Run-to-run parameter variations:
  - E.g. implant doses, layer thickness, dimensions
  - Affect V_{TH}, μ, C_{ox}, $R_\square$, …
- In SPICE use device "corners": nominal / slow / fast parameters (tt, ss, ff)
  - E.g. fast: low V_{TH}, high μ, high C_{ox}, low $R_\square$
  - Combine with supply & temperature extremes
  - Pessimistic but numerically tractable
    → improves chances for working Silicon

Corner example: V_{TH}



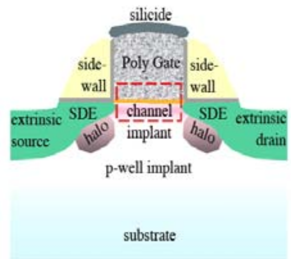
- Corners just shift V_{th}
  - Probably not real
  - (PMOS doesn't look real anyways)
- Variations probably bigger than reality too
  - Fab wants you to buy everything they make



Now What?

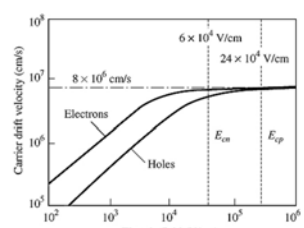
- Rely purely on simulator to tell us how devices behave?
  - Models not always based on real measurements
  - Model extraction is hard
  - Models inherently compromise accuracy for speed
- Need to know about important effects
  - So that know what to look for
  - Model might be wrong, or doesn't automatically include some effects
    - E.g., gate leakage

V_{TH}: Halo Doping



V_{TH}: Reverse Short-Channel Effect

I_D: Velocity Saturation



- Drift velocity initially increases linearly with field
- Eventually carriers hit a "speed limit"
- In the limit, $I_D \propto (V_{GS}-V_{th})$

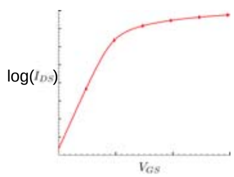
I_D: Vertical Field Mobility Reduction

- Mobility actually depends on gate field
  - “Hard to run when there is wind blowing you sideways (into a wall)”
- More technical explanation:
  - E-field pushes carriers close to the surface
  - Enhanced scattering lowers mobility

$$\mu = \frac{\mu_0}{1 + \theta(V_{GS} - V_T) + \theta_B V_{SB}}$$

I_D: Sub-Threshold Region

- Current doesn’t really go to 0 at $V_{GS} = V_{th}$
- Lateral BJT:



I_D: Weak Inversion Channel Potential

- “Base” controlled through capacitive divider

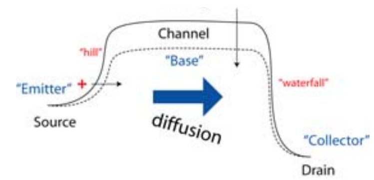
$$\delta V_{ch} \approx \frac{C_{ox}}{C_{dep} + C_{ox}} \delta V_g = \frac{\delta V_g}{n}$$

- Non-ideality factor of channel control *n* > 1:

$$n = 1 + \frac{C_{dep}}{C_{ox}} = 1 + \frac{\epsilon_{dep} t_{ox}}{\epsilon_{ox} t_{dep}}$$

- (*n* varies somewhat with bias – const. approx. usually OK)

I_D: Weak Inversion Current



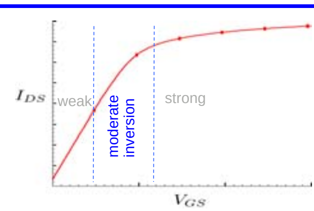
- Current set by diffusion – borrow BJT equation:

$$I_{ds} = \frac{W}{L} I_{ds,0} e^{\frac{q(V_{gs} - V_T)}{nkT}} \left(1 - e^{\frac{-qV_{DS}}{kT}}\right)$$

I_D: Operating in Weak Inversion

- Usually considered “slow”:
  - “large” C_{GS} for “little” current drive (see later)
- But, weak (or moderate) inversion becoming more common:
  - Low power
  - Submicron L means “high speed” even in weak inversion
- Not well modeled, matching poor:
  - V_{TH} mismatch amplified exponentially
  - Avoid in mirrors

I_D: Moderate Inversion



- Moderate inversion: both *drift* and *diffusion* contribute to the current.
- Closed form equations for this region don’t really exist.

I_D: Patching Models?

- Have "good" models for weak inversion and strong inversion.
  - Why not just interpolate in between?
- Example (EKV):

$$I_{DS} = \frac{W}{L}\mu C_{ox}(2n)\left(\frac{kT}{q}\right)^2\left(\left(\ln\left(1+e^{\frac{q(V_{GB}-V_{T0}-nV_{SB})}{2nkT}}\right)\right)^2-\left(\ln\left(1+e^{\frac{q(V_{GB}-V_{T0}-nV_{DB})}{2nkT}}\right)\right)^2\right)$$

Output Resistance: CLM

- "Channel Length Modulation"
  - Depletion region varies with V_{DS}
  - Changes effective channel length
- If perturbation is small:

$$I \propto \frac{1}{L-\delta L(V_{ds})} \approx \frac{1}{L}\left(1+\frac{\delta L(V_{ds})}{L}\right) \longrightarrow \frac{I_{ds}}{I_{ds0}} = (1+\lambda V_{ds})$$

Output Resistance: DIBL

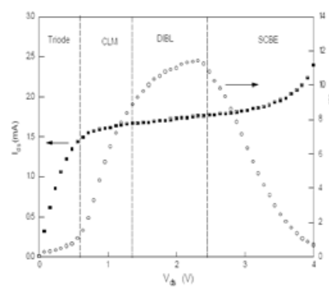
- "Drain Induced Barrier Lowering"
- Drain controls the channel too
  - Charge gets imaged – lowers effective V_{th}
  - Model with $V_{th} = V_{th0} - \eta V_{DS}$

Output Resistance: SCBE

- "Substrate Current Body Effect"
- At high electric fields, get "hot" electrons
  - Have enough energy to knock electrons off Si lattice (impact ionization)
- Extra e^- - h^+ pairs – extra (substrate) current
  - Models usually empirical

$$I_{sub} = \frac{A_i}{B_i} I_{ds}(V_{ds}-V_{dsat})exp\left(-\frac{B_i l}{V_{ds}-V_{dsta}}\right)$$

Output Resistance Mechanisms



- All effects active simultaneously
- CLM at relatively low fields
- DIBL dominates for high fields
- SCBE at very high fields

Comprehensive Model: BSIM

- ***Berkeley Short-channel IGFET Model (BSIM)***
  - Industry standard model for modern devices
  - BSIM3v3 is model for this course
- Typically 40-100+ parameters
  - Advanced software and expertise needed to perform extraction

BSIM "Hand Calculation" Model

- **Requires many, many, many… assumptions**
- **Vertical mobility degradation:**

Define: $u_d = \frac{UA}{t_{ox}}$ mobility degradation coefficient

$u_d \approx 0.5\text{V}^{-1}$ for t_{ox}=10nm

- **Velocity saturation:**

Define: $E_C = \frac{2v_{sat}}{U0}$ critical E-field for velocity saturation

$E_C \approx 2\times10^4\,\text{V/cm}$ (typical value)

Strong Inversion Current

$$V_{Dsat} = (V_G - V_T)\left[\frac{1+u_d(V_G-V_T)}{1+\left(u_d+\frac{1}{E_cL}\right)(V_G-V_T)}\right]$$

$$I_{Dlin} = \mu_0 C_{ox}\frac{W}{L}\left(V_G - V_T - \frac{V_D}{2}\right)V_D\left[\frac{1}{1+u_d(V_G-V_T)+\left(\frac{V_D}{E_CL}\right)}\right] = I_{Dlin(long)}\left[\frac{1}{1+u_d(V_G-V_T)+\left(\frac{V_D}{E_CL}\right)}\right]$$

$$I_{Dsat} = \mu_0 C_{ox}\frac{W}{2L}\left[\frac{(V_G-V_T)^2}{1+\left(u_d+\frac{1}{E_CL}\right)(V_G-V_T)}\right] = I_{Dsat(long)}\left[\frac{1}{1+\left(u_d+\frac{1}{E_CL}\right)(V_G-V_T)}\right]$$

Equations of Derivatives

$$g_{msat} = \frac{I_{Dsat}}{(V_G-V_T)}\left[1+\frac{I_{Dsat}}{I_{Dsat(long)}}\right] = \frac{I_{Dsat}}{(V_G-V_T)}\left[1+\frac{1}{1+\left(u_d+\frac{1}{E_CL}\right)(V_G-V_T)}\right]$$

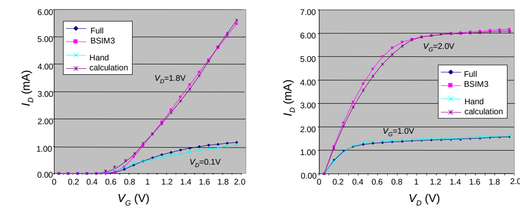
$$r_{out} = \frac{2\{(V_D-V_{Dsat})+[1+u_d(V_G-V_T)](V_G-V_T)\}L^2}{\mu_0C_{ox}WlP_{CLM}[1+u_d(V_G-V_T)](V_G-V_T)^2} = \frac{\{(V_D-V_{Dsat})+[1+u_d(V_G-V_T)](V_G-V_T)\}L}{I_{Dsat(long)}lP_{CLM}[1+u_d(V_G-V_T)]}$$

with $l = \sqrt{3t_{ox}x_j}$

- **Required parameters** *W, L, TOX, U0, UA, VSAT, VTH0, PCLM, XJ*

Fitting Results

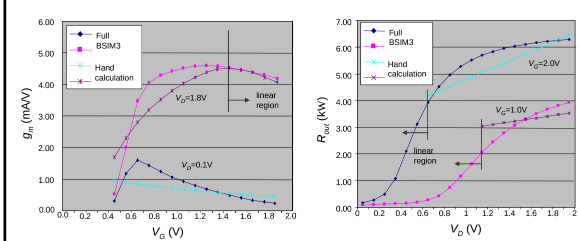
Comparison between full and simplified model



Parameter detail: **TSMC 0.18um process**

t_{ox}: 4.1nm, W=10mm, V_{T0}=0.39V

Weakness of Model First Derivatives



"Hand Model" Conclusion

- **<u>Even "simple" model is not convenient</u>**
  - **r_o is key for gain, but really hard to model**
  - **Missing important regions such as moderate inversion**
- **Hand models really best to build intuition**
- **But for design (i.e., how to choose W, L, etc.):**
  - **Will learn how to use the simulator as a "calculator"**