The Engineering of BSIM for the Nano-Technology Era and Beyond

Mansun Chan, Xuemei Xi, Jin He, and Chenming Hu

E-mail: mchan@eecs.berkeley.edu

Department of Electrical Engineering & Computer Science
University of California at Berkeley
Acknowledgement

- The BSIM project is partially supported by SRC, CMC, Conexant, TI, Mentor Graphics, and Xilinx

- BSIM Team: Prof. Chenming Hu, Dr. Jane Xi, Dr. Jin He, Mark Cao, Pin Su and Hui Wan

- CMC and member companies: Britt Brooks (CMC), Keith Green (TI), Josef Watts (IBM), Peter Lee (Hitachi), Bernd Lemaitre (Infineon), Judy An (AMD), and Kiran Gullap (Motorola)
Outline

- Modeling Tradeoffs
- The Development of the BSIM models
- The need of next generation models
- Modeling infrastructure
- Summary
Role of Compact Model

Numerical Simulator

Physically accurate

Simulation Speed

Compact Model

Table Lookup Model
Model requirements

Question: who are the customers?

<table>
<thead>
<tr>
<th>Interest Group</th>
<th>Primary Interests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Device Engineers</td>
<td>Accurate Physics</td>
</tr>
<tr>
<td>IC Designers</td>
<td>Computational efficiency, Fitting Accuracy, Simplicity</td>
</tr>
<tr>
<td>Foundry’s</td>
<td>Fitting Accuracy, Statistical modeling capability</td>
</tr>
<tr>
<td>CAD Vendors</td>
<td>Fit different technologies, Short development time, Backward compatibility</td>
</tr>
<tr>
<td>Model developer</td>
<td>Simplicity, Short development time</td>
</tr>
</tbody>
</table>

When we cannot do all, how to make trade-offs?
Device Model Tradeoff Polygon

**Ultimate goal of model:** Accurate and Simple

- simplicity
- universality
- physical
- accuracy
- number of parameters
- empirical
- extendibility
BSIM Approach and Philosophy

An Engineering Model
- defined in the original development
- a practical model can be used in circuit simulator

BSIM1
- A fast demonstration model to include first order short channel effects
- mainly for DC simulation

BSIM2
- A semi-physical model with simple parameter extraction procedures
- Improvement over BSIM1 includes better fitting to output resistance and other first order derivatives
- Computer efficient
BSIM Approach and Philosophy

BSIM3

- Starts out as a simple physical model with a small number of parameters
- In the process of model standardization, flexibility is required to fit all different processes (good or bad)
- As a result, many new “engineering” parameters are added and the model become more “empirical” (while the core is still physically based)

BSIM3 emphases

- Physical based core model
- Computational efficient
- Flexible to include new features
- Works with a large numbers of technology
Methodology to achieve the goals

**Flexibility**

- Modularize various physical effects for easy addition and subtraction
- Also help the early adoption of uncertain physics

**Examples:**

- \( R_{out} \) due to DIBL is implemented as \( V_A \) rather \( V_T \)

\[
I_{Dsat} = W C_{ox} v_{sat} (V_G - V_T - V_{Dsat}) \left(1 + \frac{V_D - V_{Dsat}}{V_A}\right) \ldots
\]

- \( NQS \) model added by a subcircuit

![Circuit Diagram]

\[
I = \frac{dQ_{ch}}{dt}
\]

Q_{def}
Methodology to achieve the goals

Computational Efficiency

- By smoothing functions to ensure well behaved characteristics in all operation regions

Examples:

\[ I_{D_{sat/ sub}} = \mu_{eff} C_{ox} \frac{W_{eff}}{2L_{eff}} (V_{G_{eff}})^2 \]

where

\[ V_{G_{eff}} = 2nV_{th} \ln \left[ \exp \left( \frac{V_G - V_T}{2nV_{th}} \right) \right] \]
Methodology to achieve the goals

Fitting a large number of technologies

• By increasing the number of parameters
• Also reflects the increase in complexity in modern technology according to the Moore’s law
• The number of parameters per feature remains more or less constant

![Graph showing the increase in number of parameters over time with BSIM versions BSIM1, BSIM2, BSIM3v3, and BSIM4 marked.]
The need to have fitting parameters

An example

- While model can be perfectly physical, but real device is ugly
- Very difficult to describe all physical non-idealities
- In BSIM3/4, an artificial parameter $V_{off}$ has to be introduced to take care of the non-idealities in the subthreshold characteristics
Parameter Categorization

Physical parameters

• Based on physical device structures and measurements

• Example: $t_{ox}$, $N_{sub}$, $u_0$, $v_{sat}$

Fitting parameters

• Should be treated as secondary parameters for refinement in fitting device data

• Example: $\Delta$, $dvt0w$, $a_0$, $a_1$, $a_2$, $b_0$, $b_1$

• Some of these parameters may not be necessary for good technologies

How to distinguish them?

• Need better documentation
Verification of Predictivity

Predictive Technology Model

- http://www-device.eecs.berkeley.edu/~ptm
Simulation with Limited Parameters

**Simulation of TSMC 0.18\(\mu\)m process**

- parameters used: \(W, L, \text{TOX}, U0, UA, \text{VSAT}, \text{VTH0}, \text{PCLM}, XJ\)

![Graph 1: Simulation with Limited Parameters](image1)

- \(I_D\) vs. \(V_G\) for \(V_D = 1.8\) V and \(V_D = 0.1\) V.

![Graph 2: Simulation with Limited Parameters](image2)

- \(I_D\) vs. \(V_D\) for \(V_G = 2.0\) V and \(V_G = 1.0\) V.
The Fourth Generation Models

**BSIM4 Goal**
- An all-in-one model to include as many features as possible
- A more integrated model and Modularization is slightly de-emphasized
- Many features deal with frontier effects in technology progress

**New features**
- Refinement of BSIM3 I-V model
- Gate tunneling model
- Intrinsic gate resistance model
- Substrate resistance model
- Holistic Noise Model
- Layout dependent parasitic model
Next Generation Models

Current modeling methodology

- Defined by SPICE written by FORTRAN style of programming
- Model infrastructure has not changed for more than 2 decades and model just becoming more complicated

The needs defined by technology roadmap

- High speed and mixed-signal simulation
- Predication of statistical variation

New modeling methodology?

- Should device physics be the only concern of modeling?
- Can some experience in Software Engineering be borrowed?
New modeling issues to be addressed

- Transient based simulation
  - Current modeling approach based on DC I-V and add a charge model to include capacitive effects
  - DC I-V may not be realistic in actual switching

- Distributed Network in AC simulation
  - Need to develop the correct network topology for high frequency simulation

- Statistical modeling
  - Process variation getting more and more important in circuit design
  - Need a new mode of simulation in SPICE
Issues to be addressed

DC NQS Modeling

- It is a DC non-equilibrium condition

\[ i = i_{DC}(V_D, V_S, V_G, V_B) + \frac{dQ(V_D, V_S, V_G, V_B)}{dt} \]

- Currently being treated as:

\[ i = i_{DC}(V_D, V_S, V_G, V_B, t) \]

- Time component have to be introduced to the DC current
Issues to be addressed

**AC NQS Modeling**

- It is at DC equilibrium condition and different from the time domain NQS effects
- Need an accurate RC distributed network model based on DC equilibrium biasing point
- More nodes may need to be introduced
Statistical Simulation

What is needed from the model?

- Model parameters should be more closely linked to process parameters
- Correlation between parameters are more explicit
- Need more careful considerations in the “Effective” concept

What is needed from the simulator?

- Monte-Carlo type of simulation control
- Can it be done more effectively in SPICE by adding a new mode?
Device Modeling Infrastructure

Long model development time

- Technology is developing faster than ever, but model development time remains long
- More time is devoted to debugging than to physical formulation

![Graph showing simulation speed, engineering time, and bug fix over time.](image)
Device Modeling Infrastructure

Modularizing the model

- Define the core model and independent modules
- Selection of modules can be done by the user or circuit simulator
- Can include 3rd party modules
- Possibility for open source architecture
Device Modeling Infrastructure

**High maintenance cost**
- Develop better workflow and infrastructure
- Push more work to the computer, like numerical differentiation
- Introducing software engineering methodology like automatic code generation
- Develop a fast model development environment

**Need better coordination with CAD infrastructure**
- Decide what to be done and where
- Example 1: derivative should be calculated by the model or the circuit simulator
- Example 2: Layout dependent parasitics extraction by layout extractor
Summary

- The BSIM models follows the basic Meyer model for flexibility and computation efficiency
- Relatively simple core with large tuning flexibility to fit lots of real technologies
- Transient and AC based modeling approach is being investigated
- Should seriously address the issue of Statistical Modeling
- Probably need to re-think a little on the infrastructure on device modeling