Physics-Based Device Modeling Using Conformal Mappings

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Outline

I. Introduction to device modeling
II. Theory of conformal mappings
III. Application to MOS modeling
IV. Conclusions
I. Introduction: Levels of System Design

- Mixed-Signal System
  - DIGITAL
    - VHDL
      - Switch-Level Simulation
  - ANALOG
    - Synthesis
      - Electrical Circuit Simulation
        - Numerically efficient models of devices: Compact Models
      - Numerical Device Simulation (FEM, BEM)
        - Mixed-Mode Simulation
I. Introduction: Classification of Compact Models

<table>
<thead>
<tr>
<th>Method</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>Numerical fitting</td>
<td>- mathematical description of device behaviour (look-up tables)</td>
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<tr>
<td></td>
<td>- fitting parameters without any physical meaning</td>
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<tr>
<td>Empirical</td>
<td>- description of physical effects by empirical functions</td>
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<td>- introduction of physically motivated parameters</td>
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<tr>
<td>Physics based</td>
<td>- closed-form solution of equations approximating device physics</td>
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<td>- strong link to physical device parameters</td>
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</tbody>
</table>

- **Predictive ability**: low to high
- **Numerical efficiency**: high to low
- **Effort for parameter extraction**: high to low
II. Theory of Conformal Mappings

Conformal mapping:
analytical technique for solving 2D potential problems

- Laplace equation invariant to conformal mapping
- closed-form solution more likely for simplified geometry
III. Application to MOS Modeling

• Short-channel effects:
  – threshold voltage shift
  – increased subthresh. current
  – drain induced barrier lowering
  – channel length modulation

• Problem described by Poisson equation:

\[ \Delta \Phi = -\frac{\rho(x,y,z)}{\varepsilon} \]

• 2D potential problem (neglecting channel-width effects)
III. Application to MOS Modeling

- **Approximations:**
  - box approx. of source/drain
  - *fictive charge sheets allow for extension of the space charge to the whole substrate*

- Space charge given by one-dimensional function
- Simplified device geometry
- 2D analytical solution by conformal mappings
- No unphysical fitting parameters introduced
III. Application to MOS Modeling

Strategy of decomposition:

\[ \Delta \Phi(x,y) = \Delta \Phi_p(x) + \Delta \phi(x,y) \]

- one-dimensional particular solution of Poisson equation
  \[ \Delta \Phi_p(x) = \frac{\rho(x)}{\varepsilon} \]
- conformal mapping
- solution of 2D Laplace equation
  \[ \Delta \phi(x,y) = 0 \]
- transformation back
III. Application to MOS Modeling

• Result: Physics-based model equations for surface potential
• Electrical device parameters have been derived:
  - threshold voltage
  - subthreshold current
  - AC behaviour
• Model has been extended to account for narrow-channel effects
• Similar model has been derived for lateral bipolar transistor structures
III. Application to MOS Modeling

- Implementation of model via C-source code
- CFAS-Interface
- ELDO circuit simulator
  - Iterative solution of Kirchhoff’s law
  - Standard compact models
III. Application to MOS Modeling

![Graph showing threshold voltage vs effective channel length with MOS modeling application]
III. Application to MOS Modeling

![Graph showing subthreshold current vs effective channel length](image)

- Model
- FE-Simulation
Conclusions

• Conclusions for device modeling in general:
  – effort to keep physical insight in device modeling pays off
  – physics-based models enable for simulations on system level with a strong link to device structure
  – results may be used as starting-point for more exact simulations using FEM