High Frequency Lumped Element Models for Substrate Noise Coupling

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Outline

• Introduction
• Numerical methods
• Frequency dependence of substrate parasitics
• Equivalent circuit models for substrate coupling
• Conclusions
Substrate Noise Coupling From Digital to Analog

- Circuit isolation is a key problem for SoC’s
  - Increasing integration of analog and digital circuits
  - Increasing operating frequency
Two Contacts and a Generic Lumped Model

- For frequencies < 1 GHz admittances are modeled as resistors
- For high frequencies dielectric behavior of substrate must be included
  - Capacitors included in equivalent circuit model
Numerical Methods for Admittance Extraction

- Volume element methods are versatile but expensive
- Boundary element method is computationally efficient
**Substrate Coupling Roadmap**

1. Characterize Substrate Profile
2. Pre-Layout Substrate Coupling Simulation
3. Low & High Frequency Substrate Model
4. Analog & Mixed-Signal Design
5. Digital Design
6. Layout & Strategies for Reduced Substrate Noise Coupling
7. Extract Layout & Simulate Substrate Coupling
8. Measurement Results/Test Chip
Previous High Frequency Analysis

- High frequency coupling behavior and models
  - Capacitive behavior [R. Gharpurey, 1997]
  - Inductive behavior [H. Li, et. al, 2002]
  - Equivalent circuit models [H. Lan, 2003]

![Diagram of Model I and Model II](image-url)
High Frequency Numerical Simulator

- EPIC - a Green’s function based solver for Extraction of Parasitics for IC’s
  - Multilayered approximation of substrate doping profile
  - Each layer is characterized by a complex conductivity \( \sigma_c = \sigma + j\omega\epsilon \)
  - Numerically stable implementation
### Lightly And Heavily Doped Substrates

- **Lightly doped substrate**
  - P-type, $0.1 \Omega \cdot \text{cm}$, $1 \mu \text{m}$
  - P-type, $20 \Omega \cdot \text{cm}$, 400 $\mu \text{m}$

- **Heavily doped substrate**
  - P-type, $1 \Omega \cdot \text{cm}$, $1 \mu \text{m}$
  - P-type, $15 \Omega \cdot \text{cm}$, $10 \mu \text{m}$
  - P$^+$ type, $1 \text{m}\Omega \cdot \text{cm}$, 300 $\mu \text{m}$

- Layered approximation for the doping profile
Self admittance behaves capacitively
Coupling between larger contacts more frequency sensitive
Conductance nearly constant for frequencies $< 5$GHz
Susceptance increases linearly for frequencies $< 5$GHz
### Self Admittance Models

- **Model 0 through Model II are existing models**
- **Model III proposed new model**

<table>
<thead>
<tr>
<th>Circuit</th>
<th>Model 0</th>
<th>Model I</th>
<th>Model II</th>
<th>Model III</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Suitable frequency range</strong></td>
<td>$f &lt; 1 \text{ GHz}$</td>
<td>$1 \text{ G} &lt; f &lt; 5 \text{ G}$</td>
<td>$5 \text{ G} &lt; f &lt; 10 \text{ G}$</td>
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<td><strong>Comments</strong></td>
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<td>Cannot model the frequency dependence of $G$</td>
<td>Models the frequency dependence of $G$ and $B$</td>
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The diagrams represent the circuits for each model, where $G$ and $C$ denote conductance and capacitance, respectively.
• Conductance and susceptance in Model II do not fit data simultaneously
**Frequency Dependence of Mutual Admittance** (Y=G+jB)

- Susceptance may be capacitive and/or inductive
- Mutual conductance less frequency sensitive than self conductance
- Conductance decreases with frequency in this case but increases in other cases
## Mutual Admittance Models

### Circuits and Frequency Ranges

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<tr>
<td></td>
<td>[ G ]</td>
<td>[ G_1 ]</td>
<td>[ G_1 ]</td>
<td>[ G_2, G_1 ]</td>
<td>[ L, G_2, G_1 ]</td>
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### Notes
- Model 0 through Model III are existing models
- Model IV proposed new model
New Mutual Admittance Model and Simulations Comparison

Existing models cannot be used if inductive behavior occurs
Conclusions

- Suitable frequency ranges for models have been identified
- Frequency dependence of self admittance differs from that of mutual admittance
- Proposed new self coupling and mutual coupling models
  - Better accuracy and larger suitable frequency range than that of existing models
  - Good agreement with numerical simulation results
- **Next step:** Extend results to develop scalable high frequency substrate coupling model