High Frequency Lumped Element Models for Substrate Noise Coupling

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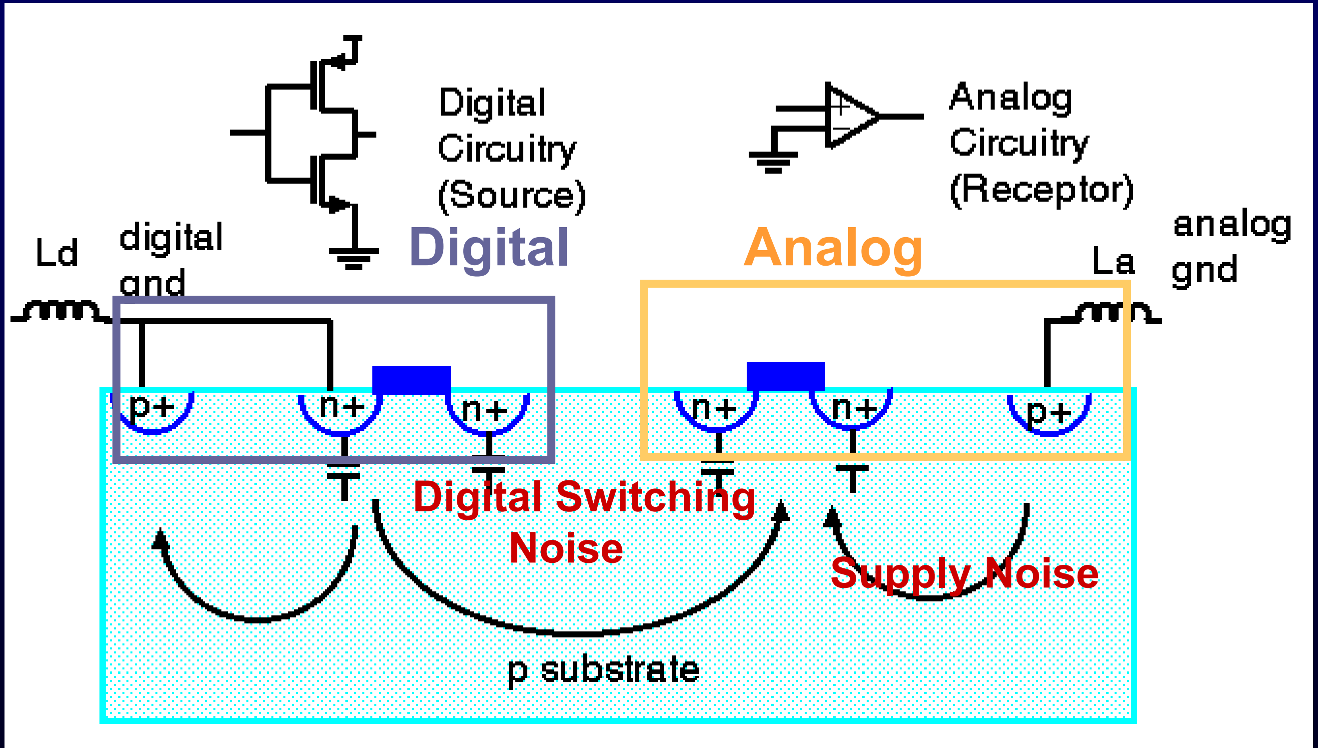
Outline

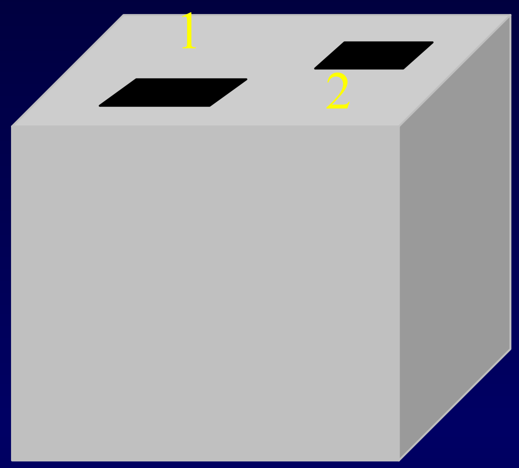
- Introduction
- Numerical methods
- Frequency dependence of substrate parasitics
- Equivalent circuit models for substrate coupling
- Conclusions

Substrate Noise Coupling From Digital to Analog

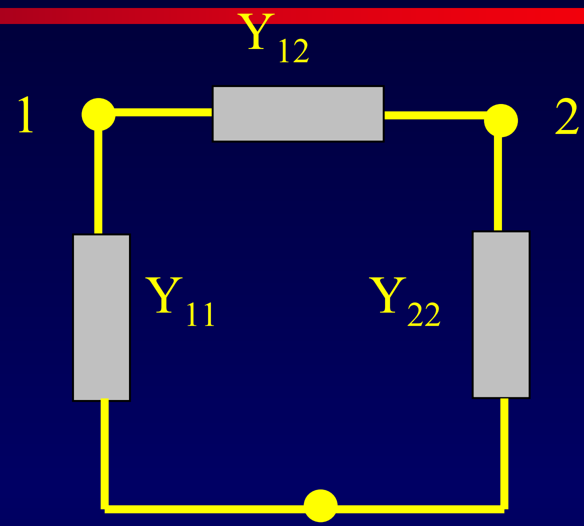
- **Circuit isolation is a key problem for SoC's**
  - ✓ Increasing integration of analog and digital circuits
  - ✓ Increasing operating frequency



Two Contacts and a Generic Lumped Model



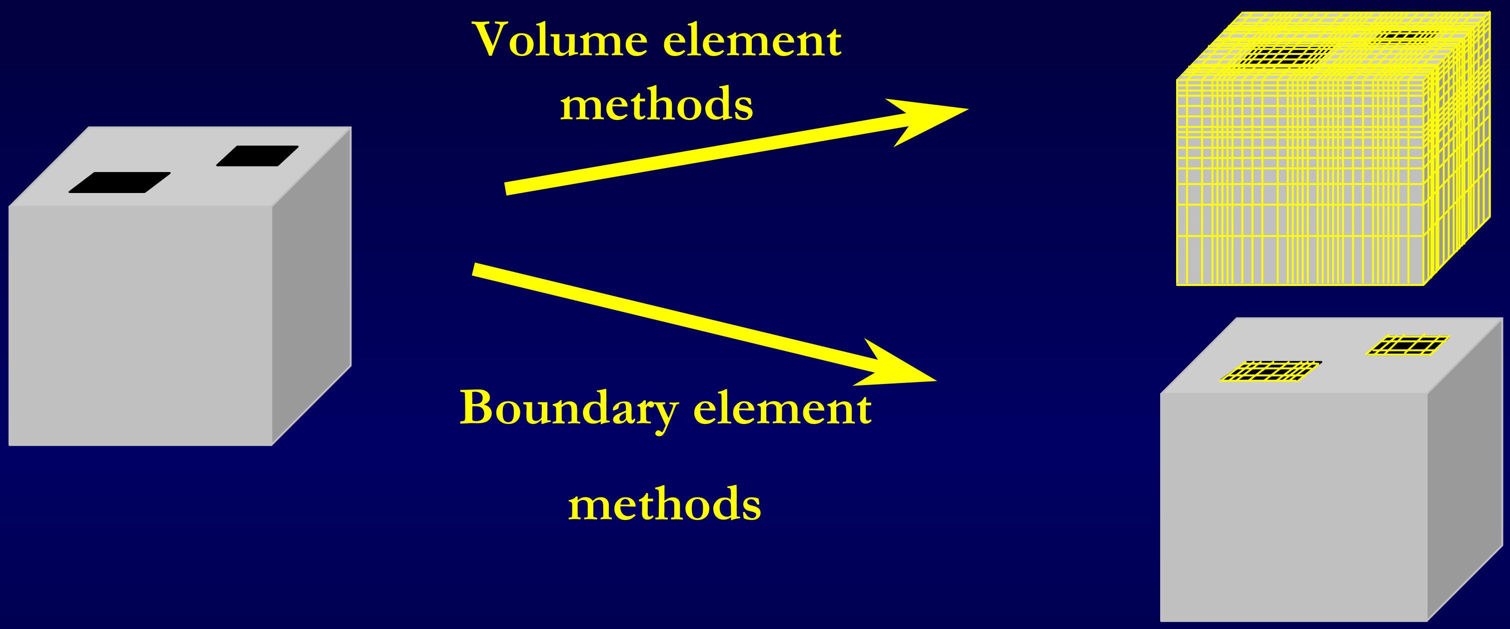
Two contacts in a substrate



Equivalent circuit model

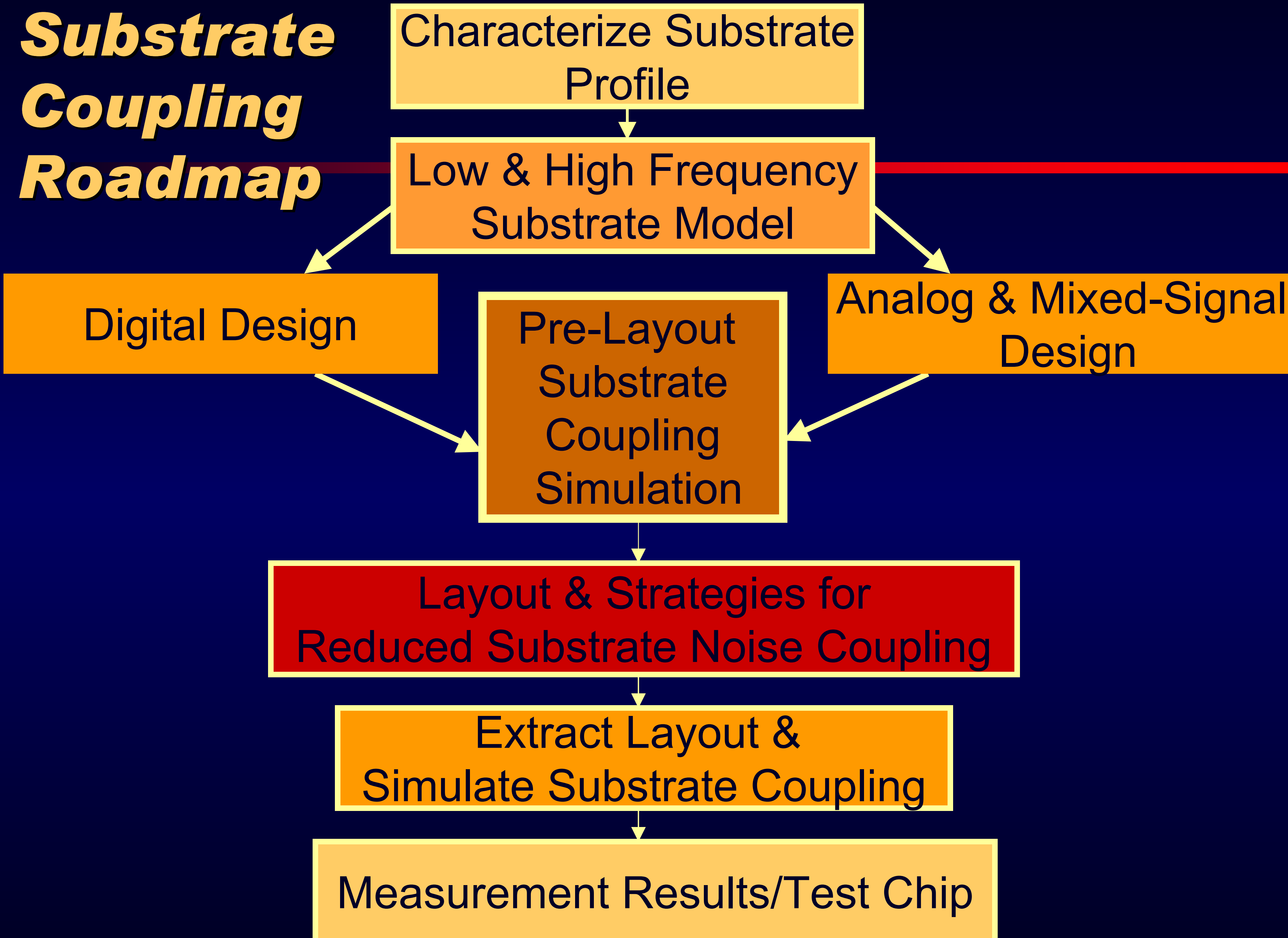
- For frequencies < 1 GHz admittances are modeled as resistors
- For high frequencies dielectric behavior of substrate must be included
  - ✓ Capacitors included in equivalent circuit model

Numerical Methods for Admittance Extraction



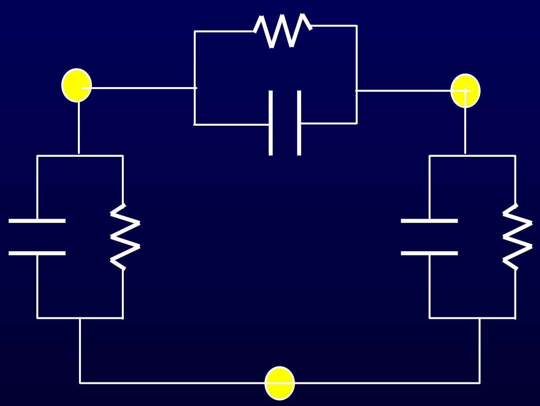
- Volume element methods are versatile but expensive
- Boundary element method is computationally efficient

Substrate Coupling Roadmap

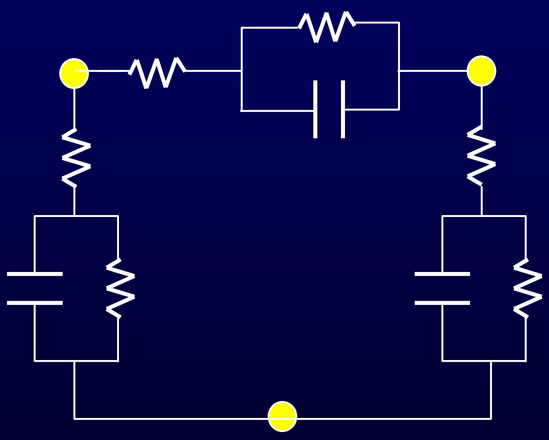


Previous High Frequency Analysis

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



Model I

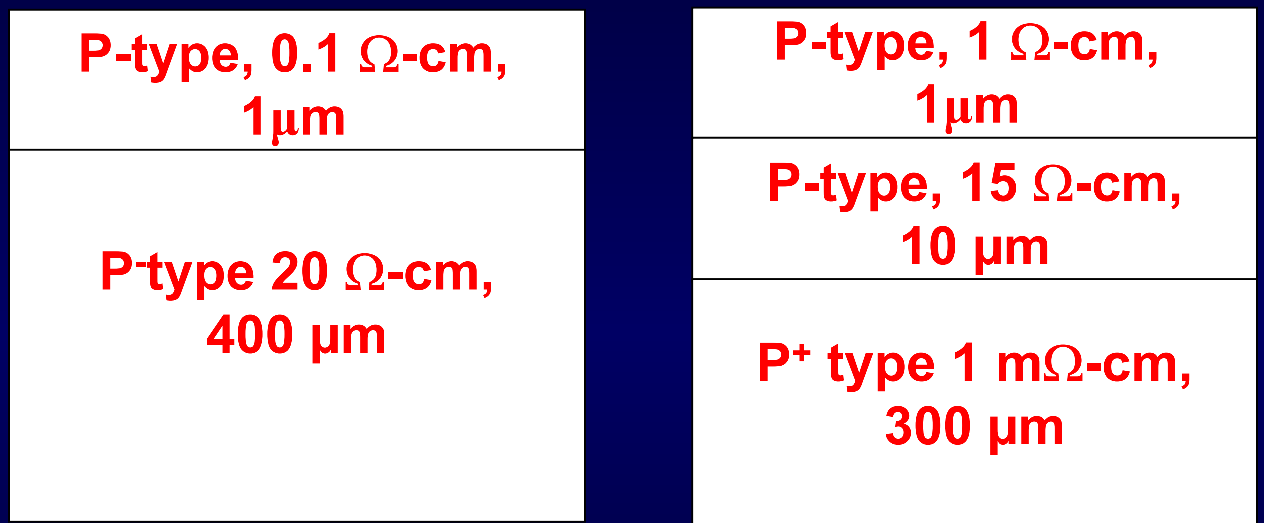


Model II

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 $\sigma_c = \sigma + j\omega\varepsilon$
  - ✓ Numerically stable implementation

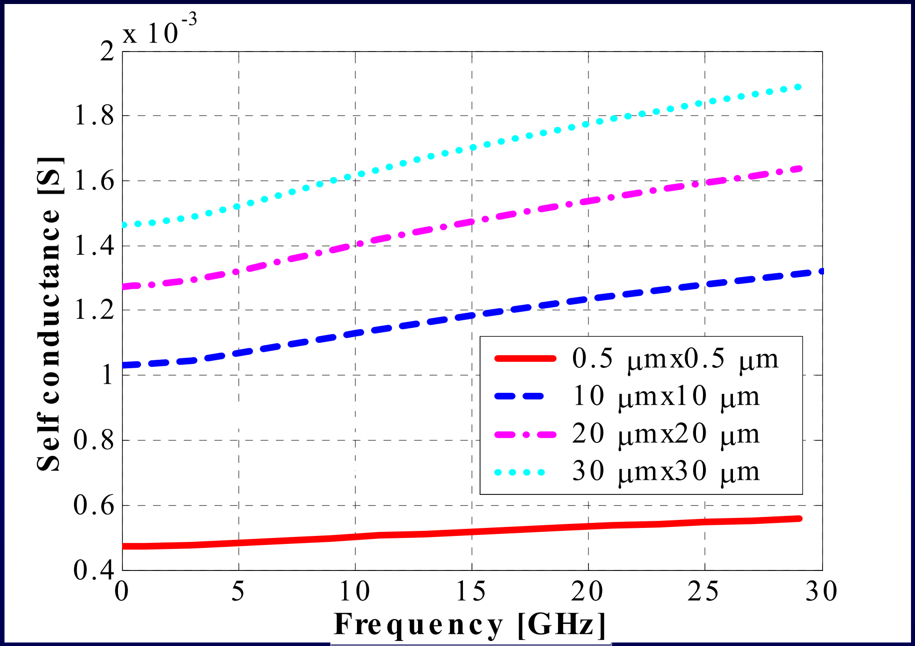
Lightly And Heavily Doped Substrates

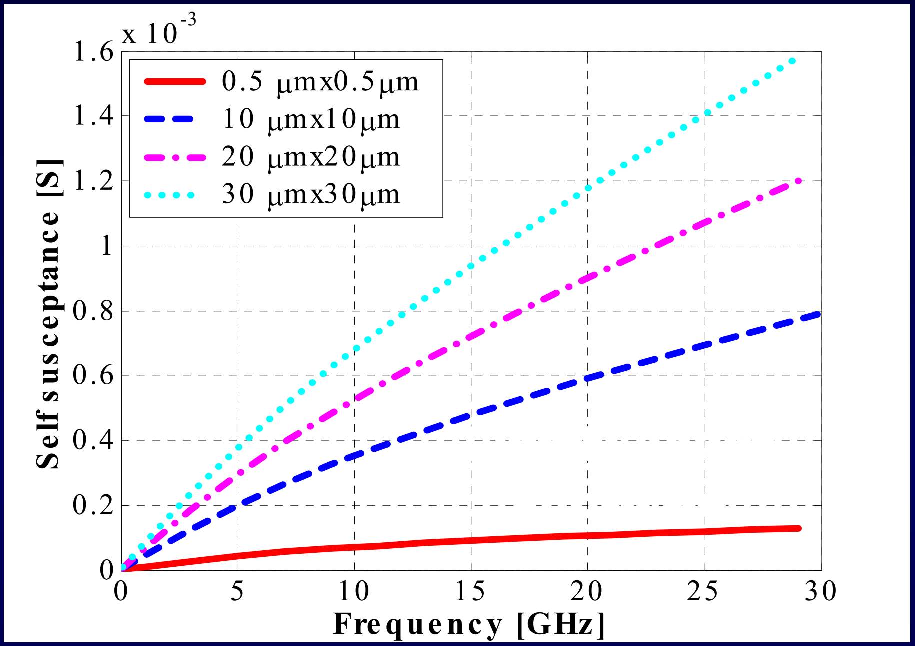


Lightly doped substrate   Heavily doped substrate

- Layered approximation for the doping profile

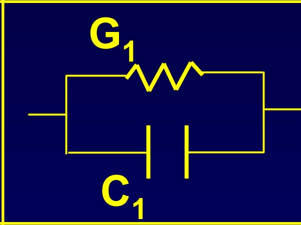
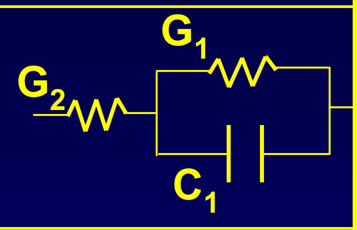
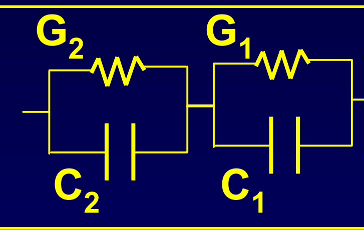
Frequency Dependence of Self Admittance (Y=G+jB)





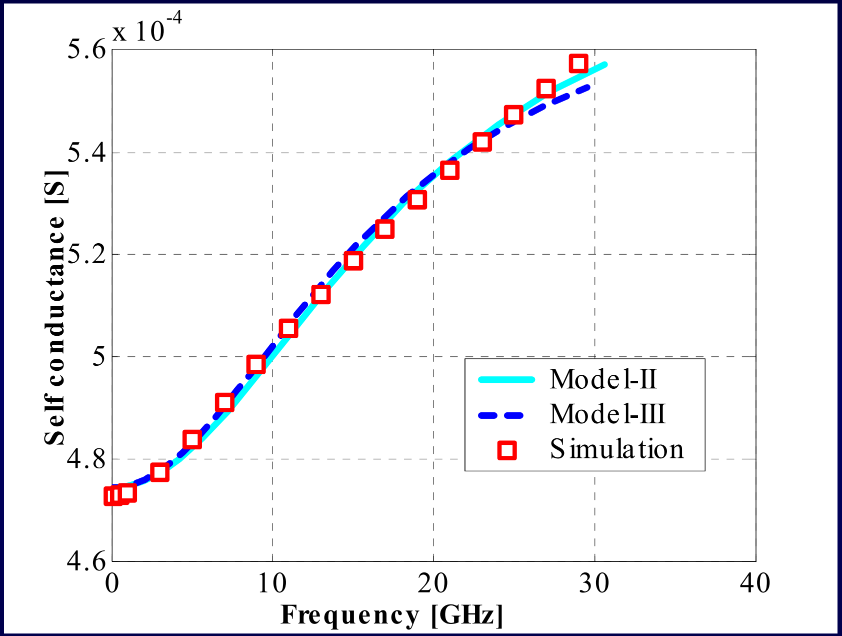
- Self admittance behaves capacitively
- Coupling between larger contacts more frequency sensitive
- Conductance nearly constant for frequencies < 5GHz
- Susceptance increases linearly for frequencies < 5GHz

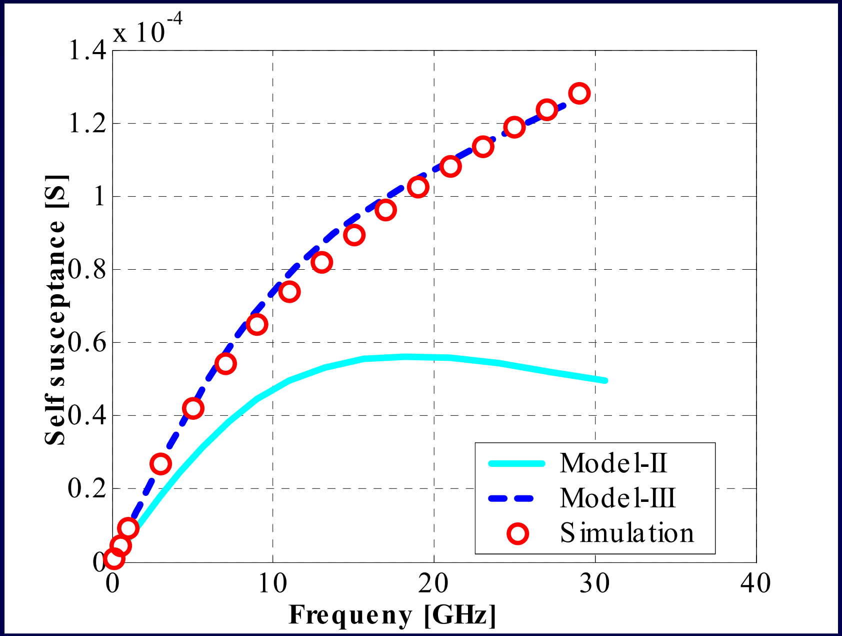
Self Admittance Models

	Model 0	Model I	Model II	Model III
Circuit				
Suitable frequency range	f < 1 GHz	1 G < f < 5 G	5 G < f < 10 G	f > 5 GHz
Comments	Simplest low frequency model	Cannot model the frequency dependence of G	Models the frequency dependence of G and B	Similar to Model II but with better agreement with simulations

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

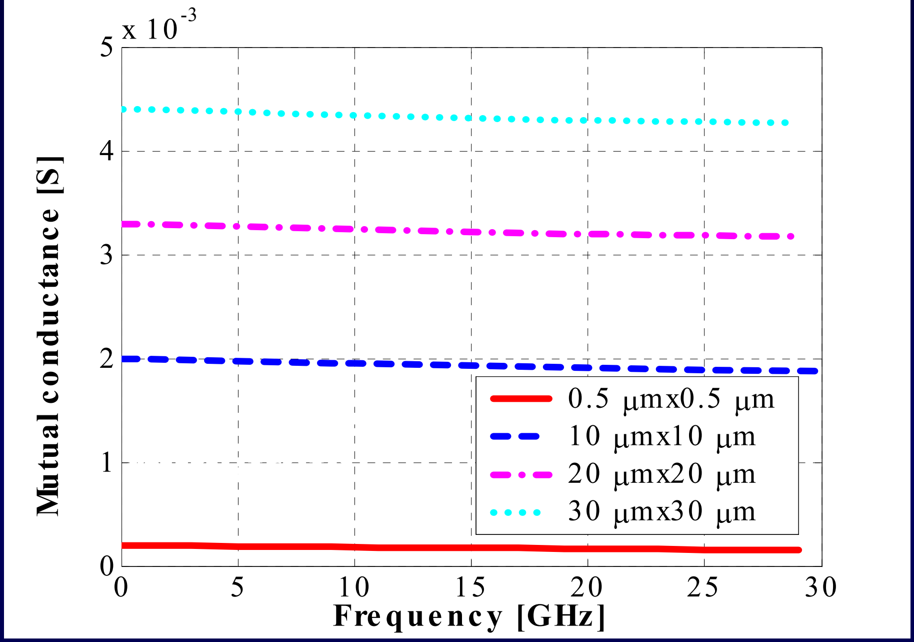
Self Admittance Model II and Model III Comparisons

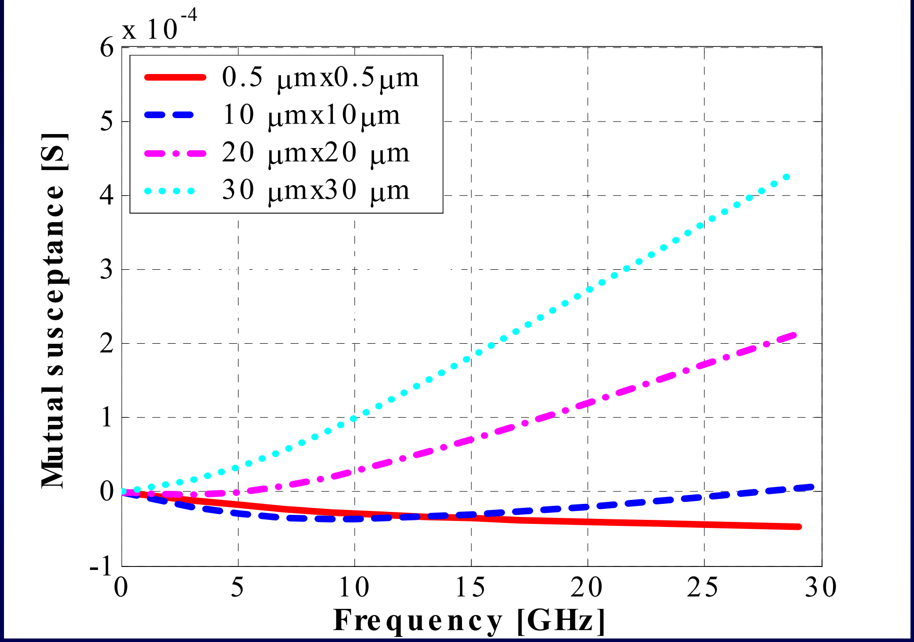




- Conductance and susceptance in Model II do not fit data simultaneously

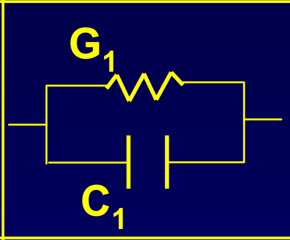
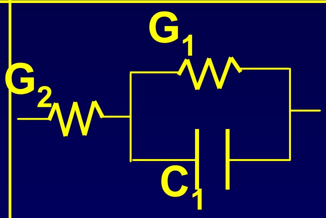
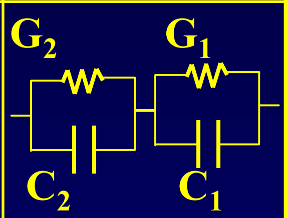
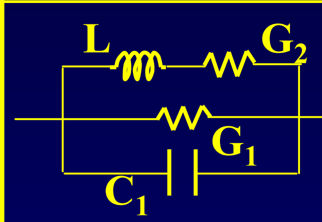
Frequency Dependence of Mutual Admittance (Y=G+jB)





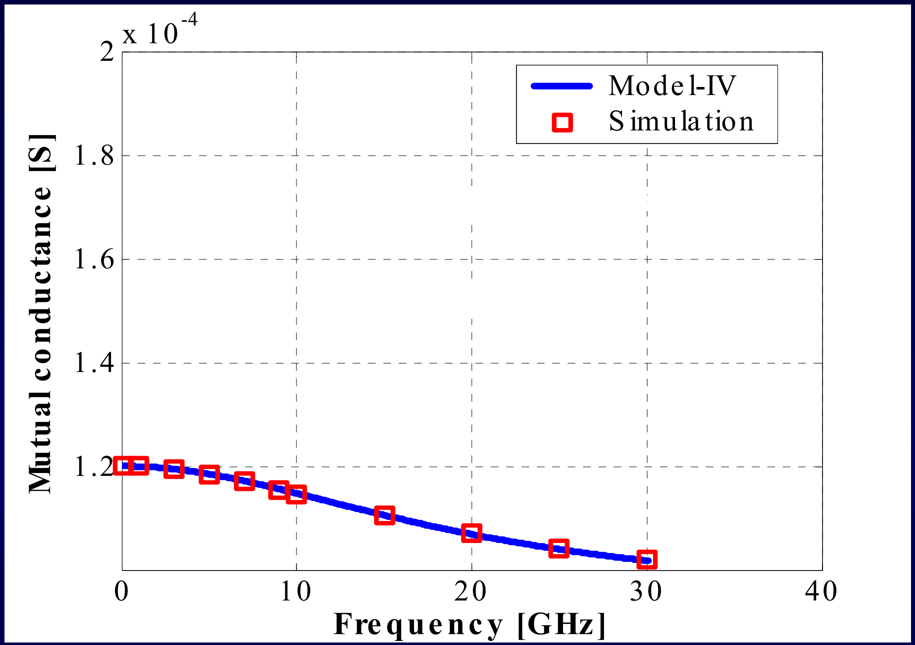
- Susceptance may be capacitive and/or inductive
- Mutual conductance less frequency sensitive than self conductance
- Conductance decreases with frequency in this case but increases in other cases

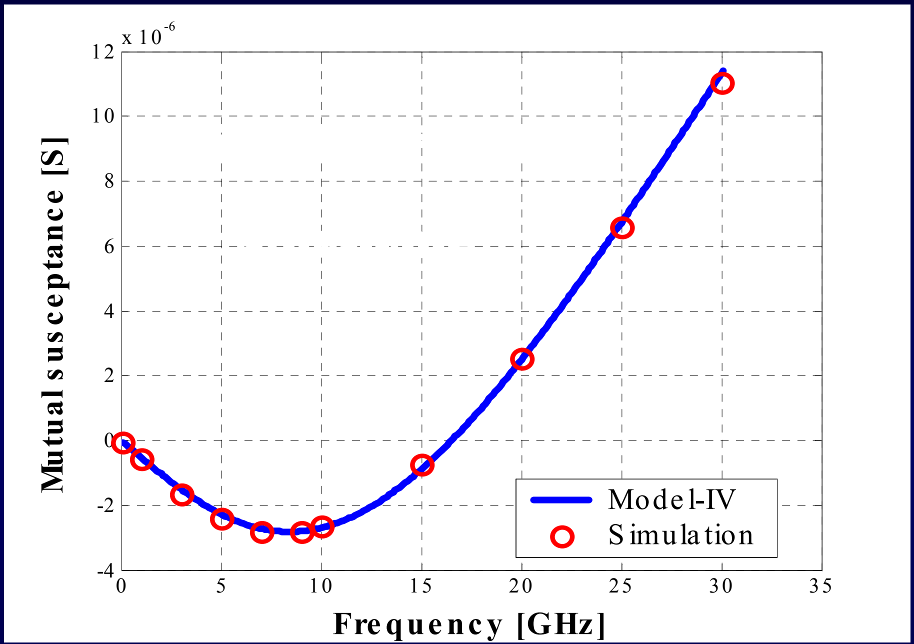
Mutual Admittance Models

	Model 0	Model I	Model II	Model III	Model IV
Circuit					
Suitable frequency range	$f < 1$GHz	1 G < f < 5 G	5 G < f < 10 G	f > 5 GHz	f > 1GHz
Comments	Simplest low frequency model	Cannot model the frequency dependence of G. Capacitive coupling only	Models the frequency dependence of G and B. Capacitive susceptance	Similar to Model II but with better agreement with simulations	Suitable for both capacitive and inductive coupling. Very good agreement with simulations

- Model 0 through Model III are existing models
- Model IV proposed new model

New Mutual Admittance Model and Simulations Comparison





- Existing models can not 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***