Advances in Active and Passive Device Modeling for High Frequency IC Design

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New challenges and opportunities in RFIC Development

- RFICs offer highly integrated, low cost chips for a fast growing communications market.

- Advances in Si and SiGe technology allow performance improvements higher operating frequencies, reduced operating voltages and power consumption, etc.

- Rapidly changing process technology often render models obsolete

- Organizations are struggling with improving all aspects of device performance while maintaining up-to-date model libraries

New challenges in RFIC Simulation

- Accurate RF device models and proven simulation technologies

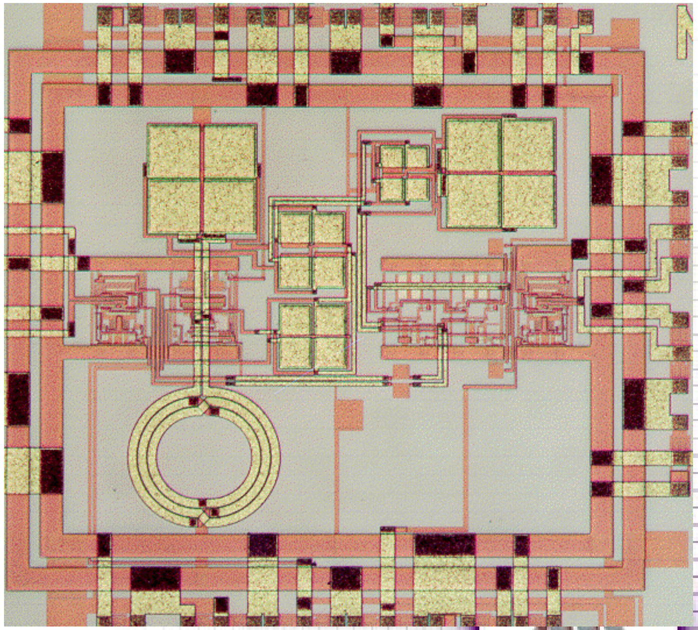
- Realistic waveforms for evolving communication standards

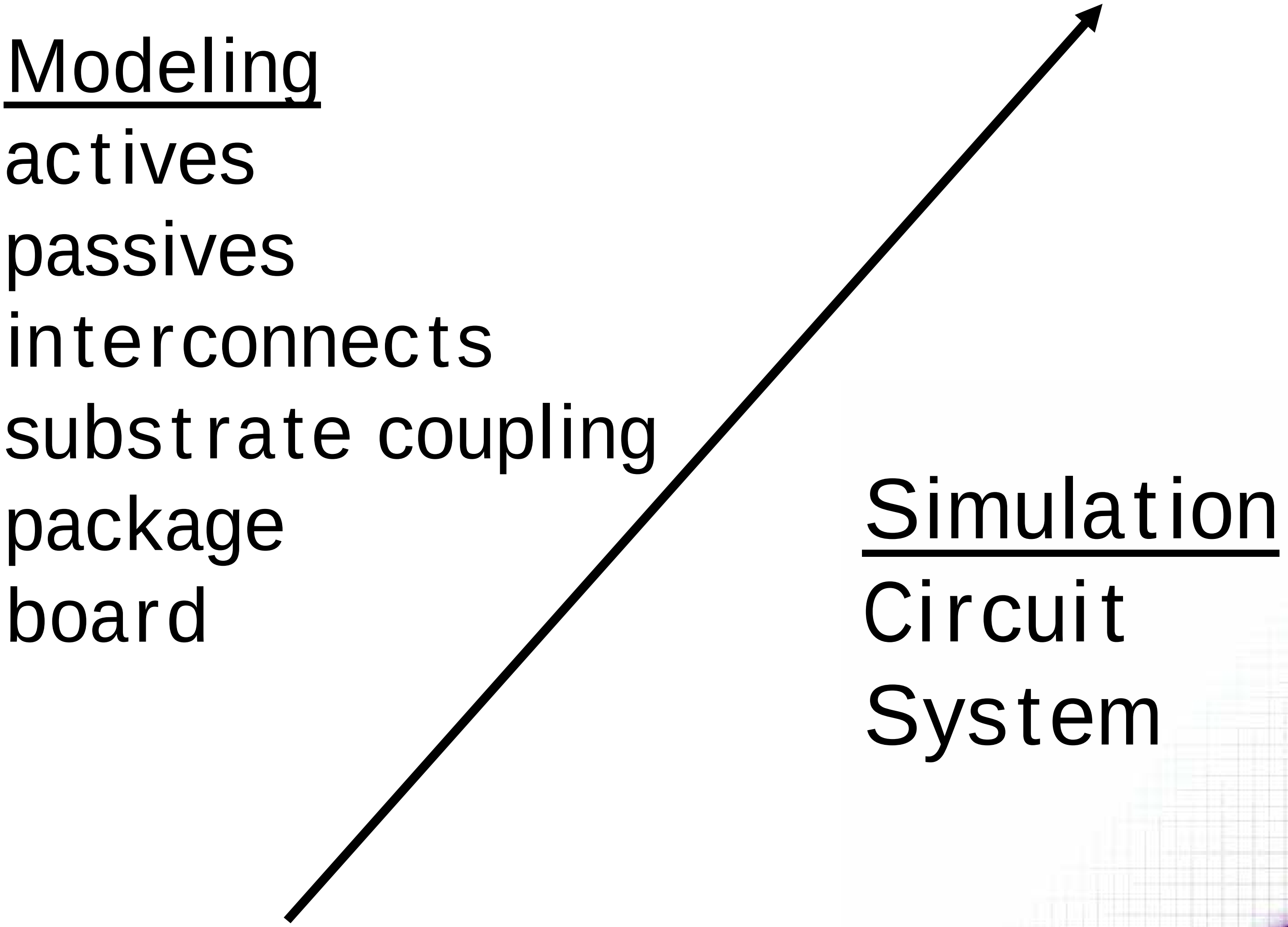
- Accurate model interactions of the desired signal with interfering signals at different frequency and power levels, with different spectral characteristic

- Accurate prediction of communication system figures of merit such as noise performance, ACPR and power consumption.

Advantages of Electromagnetic Simulation in RFIC modeling efforts

- Speed over empirical modeling - eliminates need to construct, measure and develop equivalent circuits for test structures
- Accuracy over test uncertainty
- Model thermal effects
- Investigate substrate coupling
- Allows physical design optimization





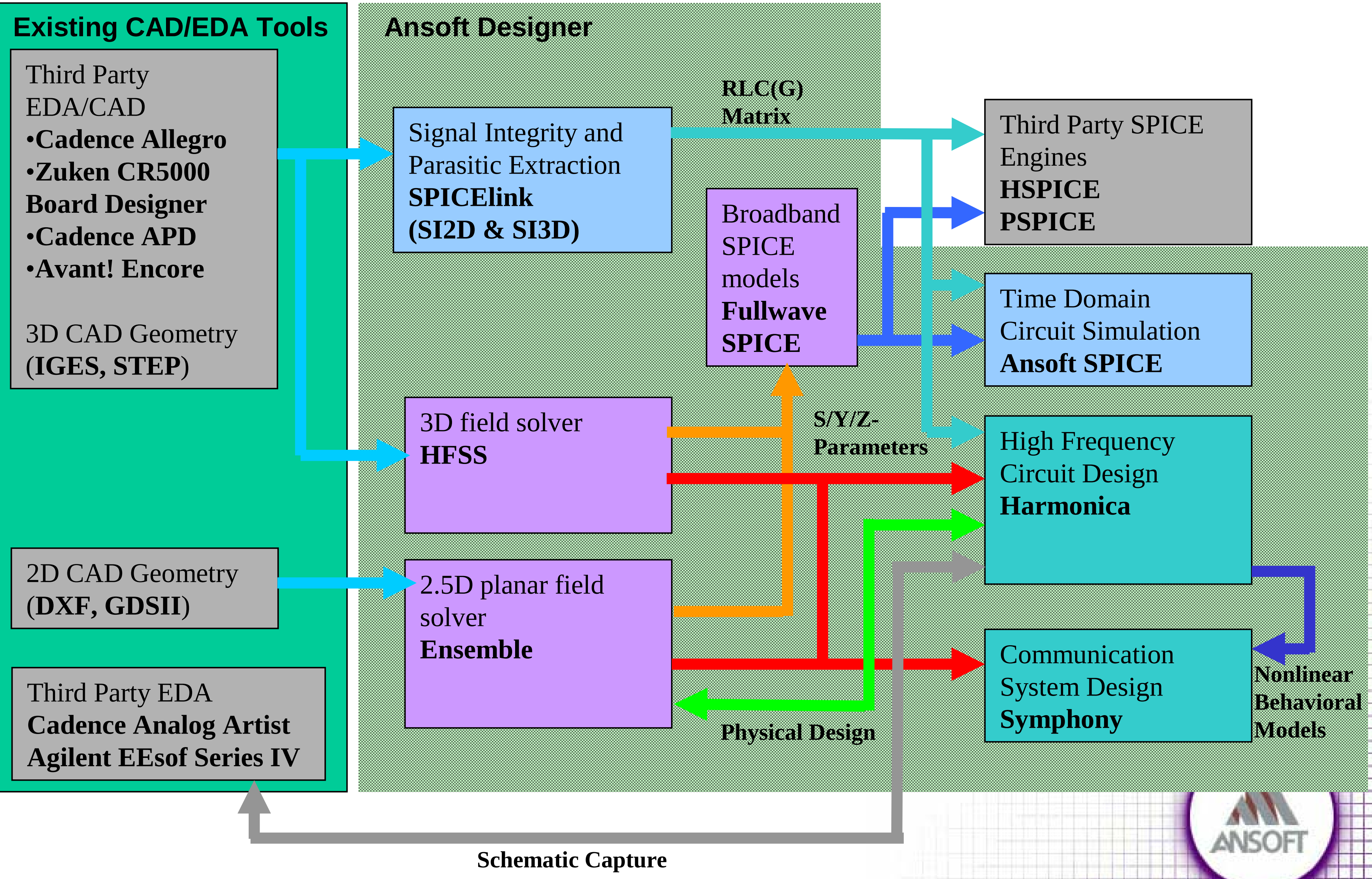
Modeling

- actives
- passives
- interconnects
- substrate coupling
- package
- board

Simulation

- Circuit
- System

EM-based modeling in the Design Flow



Existing CAD/EDA Tools

Third Party EDA/CAD
- **Cadence Allegro**
- **Zuken CR5000 Board Designer**
- **Cadence APD**
- **Avant! Encore**

3D CAD Geometry **(IGES, STEP)**

2D CAD Geometry **(DXF, GDSII)**

Third Party EDA
Cadence Analog Artist
Agilent EEsof Series IV

Ansoft Designer

Signal Integrity and Parasitic Extraction
SPICElink
(SI2D & SI3D)

Broadband SPICE models
Fullwave SPICE

3D field solver
HFSS

2.5D planar field solver
Ensemble

Third Party SPICE Engines
HSPICE
PSPICE

Time Domain Circuit Simulation
Ansoft SPICE

High Frequency Circuit Design
Harmonica

Communication System Design
Symphony

Active Device Modeling

Example:
Multi-Finger Power HBT Model for Nonlinear Circuit Simulation

Y. Zhu, Q. Cai, J. Gerber (Ansoft)
and R. Balasubramanian (IBM)

Multi-Finger HBT modeling

- HBTs offer excellent power handling and linearity
- Self-heating in unit emitter fingers and thermal coupling among fingers lead to non-uniform temperature distribution
- for the same external bias source, non-uniform temperature distribution leads to different bias among fingers
- Thermal effects significantly impact device performance

Multi-Finger HBT modeling

- Proposed Electro-thermal model of Multi-Finger HBT based on multiple unit-finger HBT models + thermal network

- Unit HBT Model
  - Temperature & Bias Scheme Dependences
- Thermal Network
  - Self-Heating & Thermal Coupling

Considerations for modeling Multi-Finger HBT bias

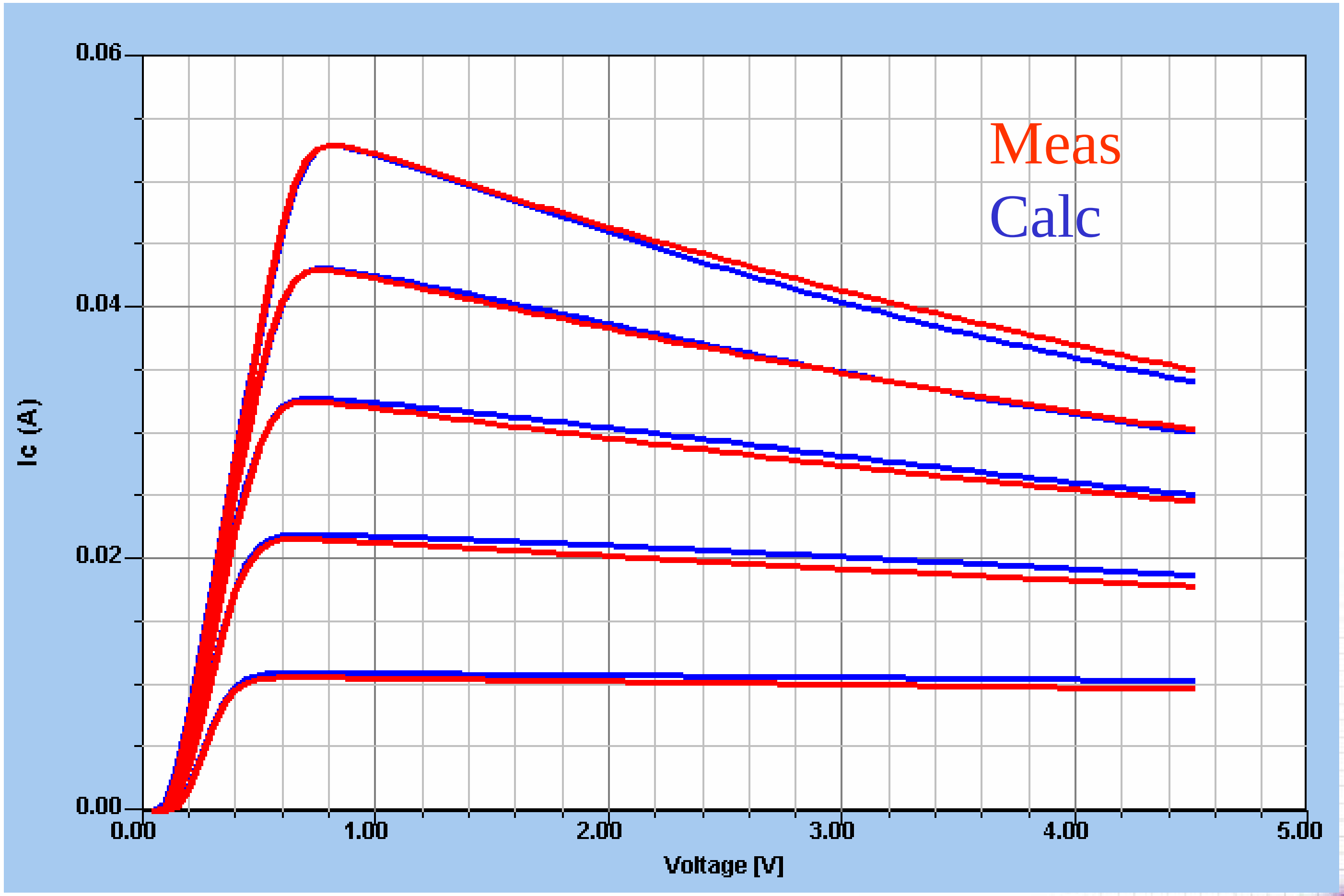
- Constant Base Voltage
    - Ic increases with increasing Vce.

  due to the decrease of the turn-on voltage of the emitter junction.

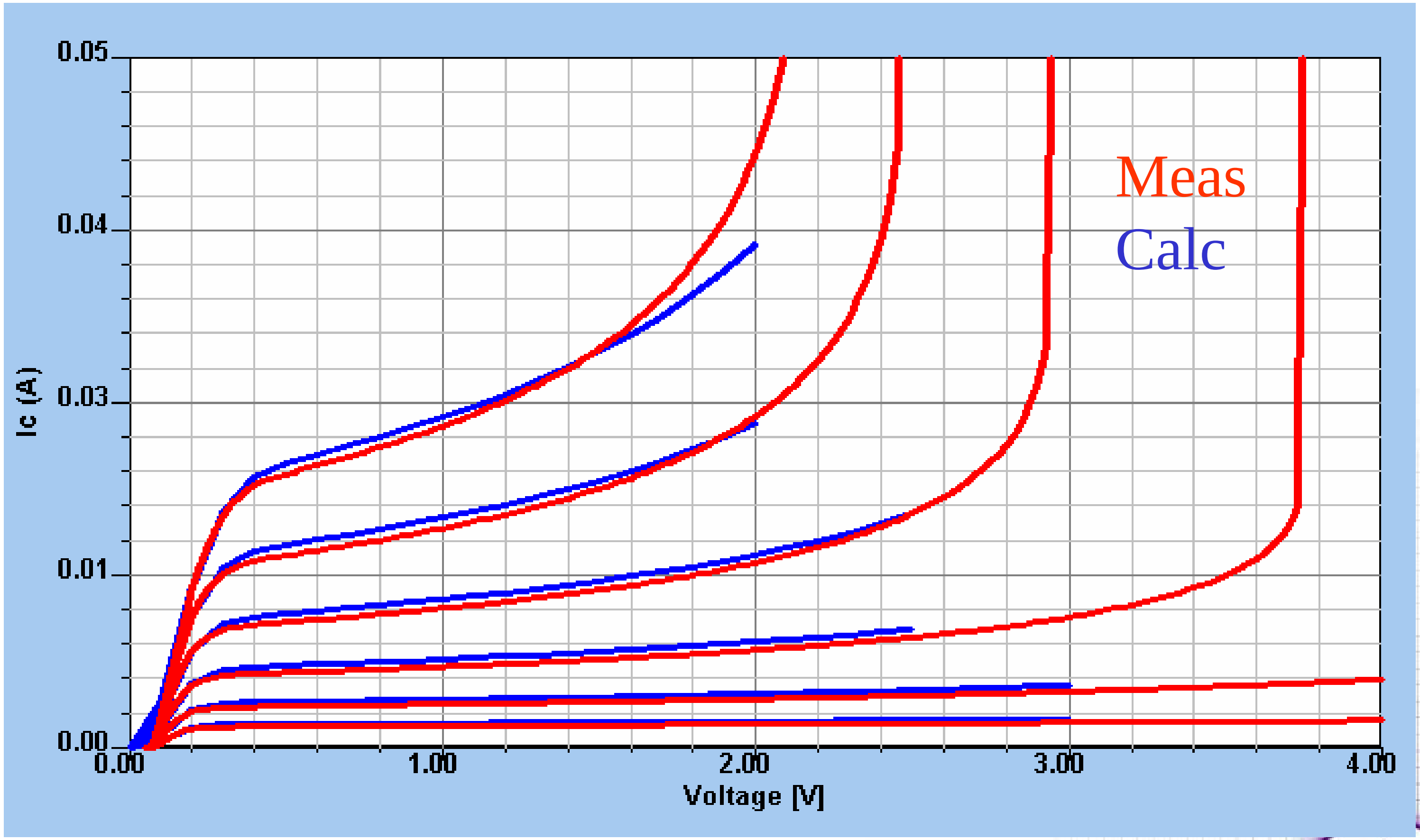
- Constant Base Current
    - Ic decreases with increasing Vce

  due to the increase in the reverse hole injection from the base to emitter

HBT Characteristics under constant Ib



HBT Characteristics under constant Vb

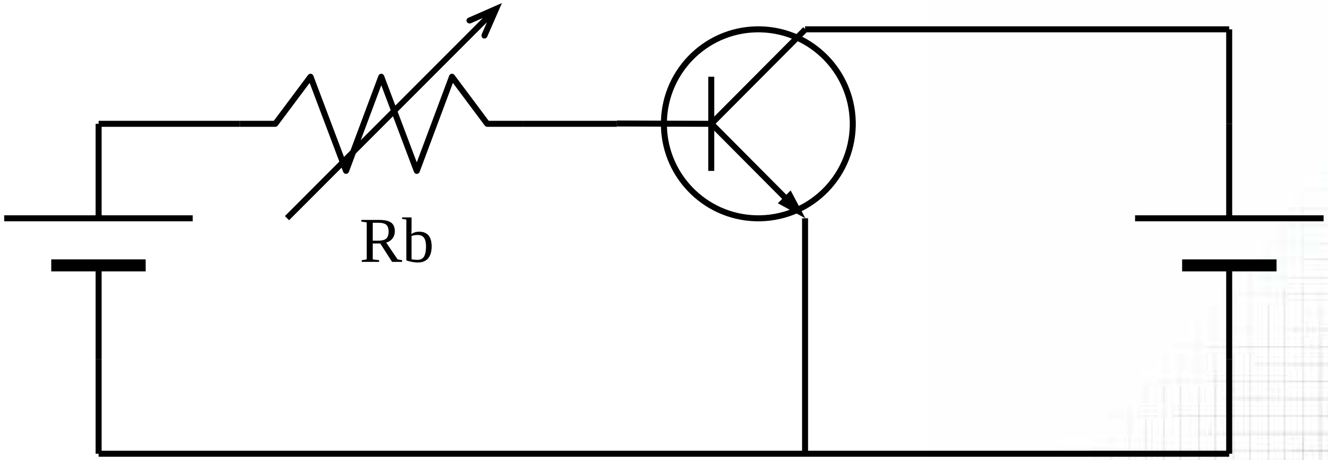


Bias Scheme of HBT

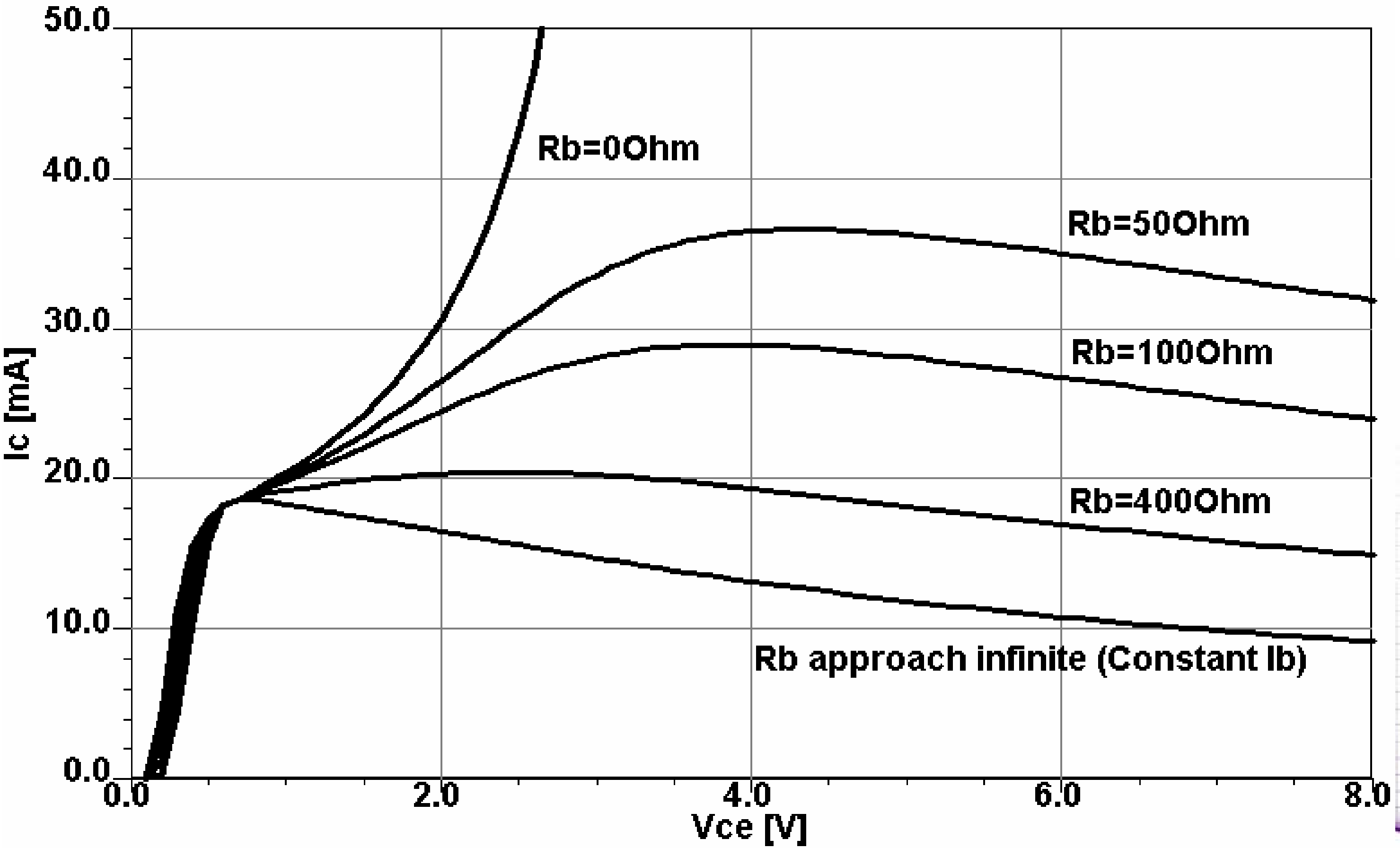
Both a voltage and current source can be represented as a voltage source with a series resistance Rb

$$Rb \rightarrow 0: \text{ Voltage Source}$$

$$Rb \rightarrow \infty: \text{ Current Source}$$



Bias Scheme Dependence of HBT



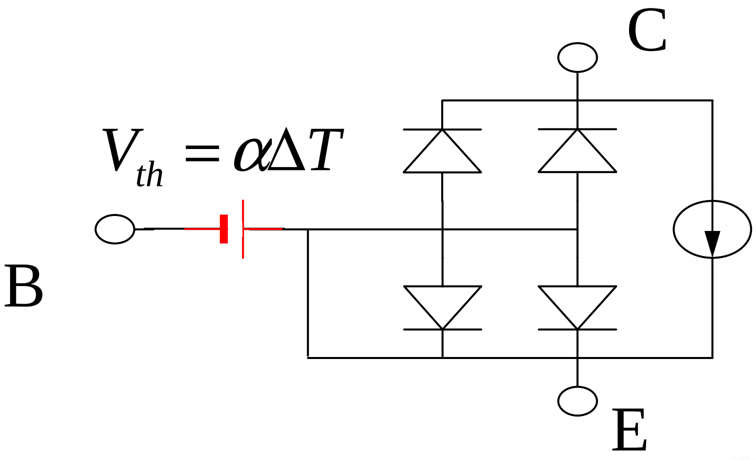
The Ic-Vce characteristics of unit HBT with different values of Rb

Modified Gummel-Pool Model for Self-Heating HBT

The decrease in emitter junction turn-on voltage may be accounted for with a Temperature-dependent base voltage source

$$V_{th} = \alpha \Delta T$$

where α is the thermal electric feedback coefficient and ΔT is the temperature increase.

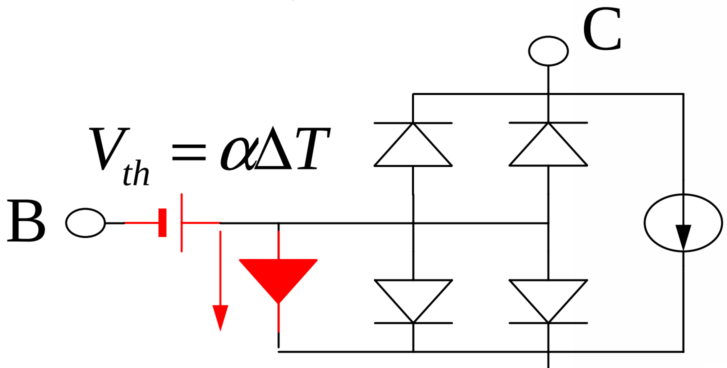


Modified Gummel-Pool Model for Self-Heating HBT

The increase in the reverse hole current component from the base to emitter is realized by adding a diode between these nodes correlated with the electron current component

$$I_P = C I_C \exp(-\Delta E / kT)$$

where ΔE is the effective difference in energy barrier height seen by electrons and holes, and C is the hole and electron current ratio at emitter junction for $\Delta E = 0$.



$$I_P = C I_C \exp(-\Delta E / kT)$$

HBT Thermal Network

Thermal Resistance of an N-finger HBT is represented by a (N x N) Matrix

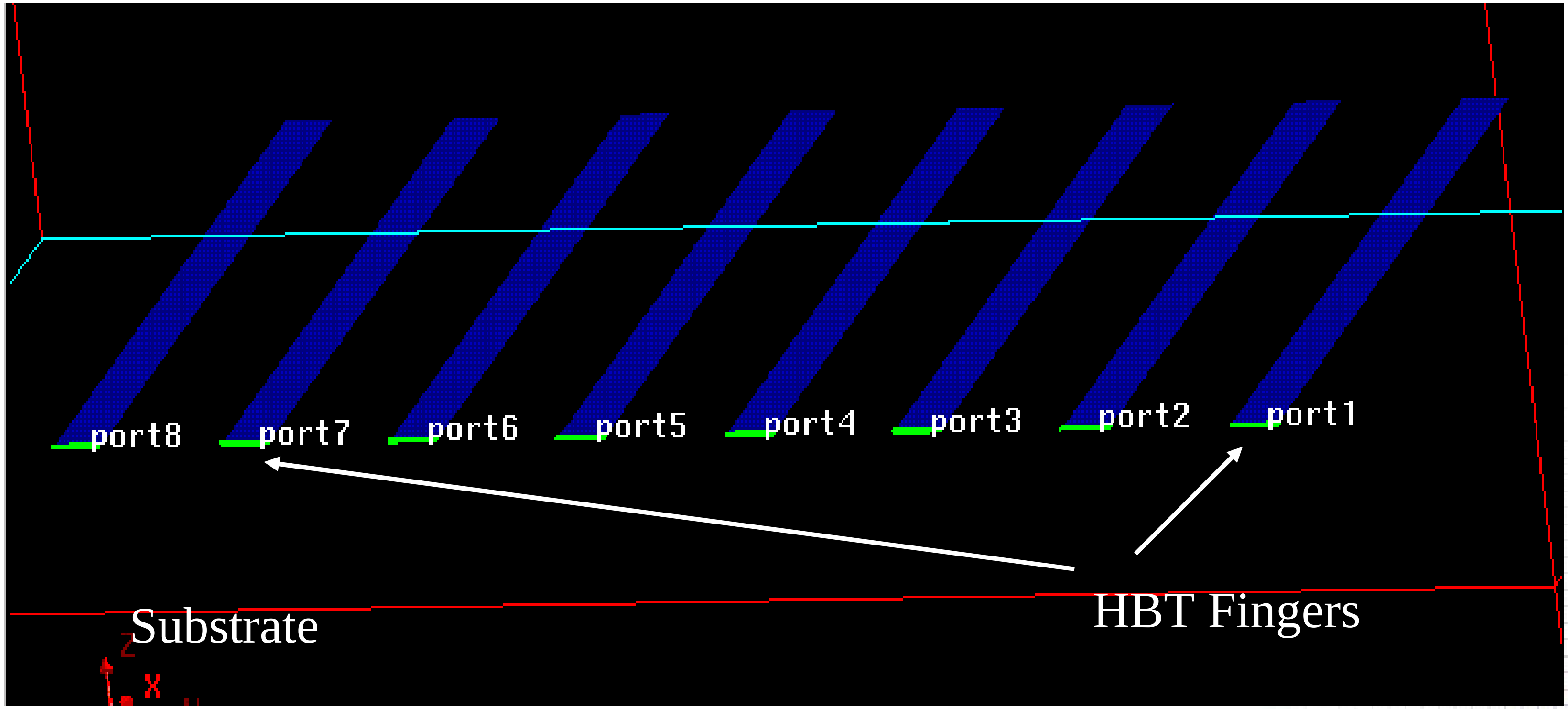
$$\begin{bmatrix} T1 \\ T2 \\ T3 \\ T4 \\ T5 \end{bmatrix} = \begin{pmatrix} R11 & R12 & R13 & R14 & R15 \\ R21 & R22 & R23 & R24 & R25 \\ R31 & R32 & R33 & R34 & R35 \\ R41 & R42 & R43 & R44 & R45 \\ R51 & R52 & R53 & R54 & R55 \end{pmatrix} \begin{bmatrix} I1 \\ I2 \\ I3 \\ I4 \\ I5 \end{bmatrix}$$

Ti — HBT temperature, Ii — HBT current

Rii — Matrix element for self-heating

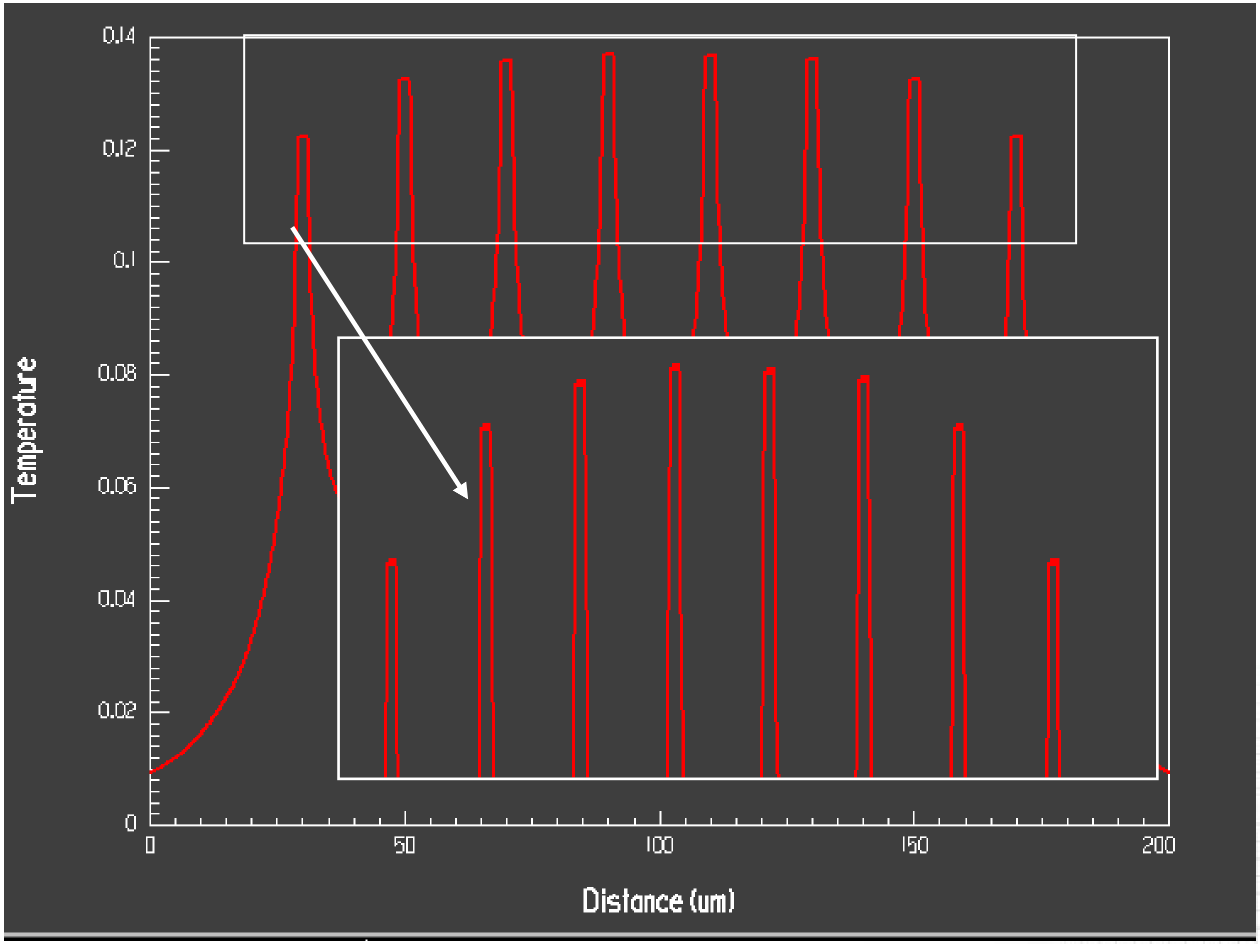
Rij — Matrix element for thermal coupling

Structure of Multi-Finger HBT

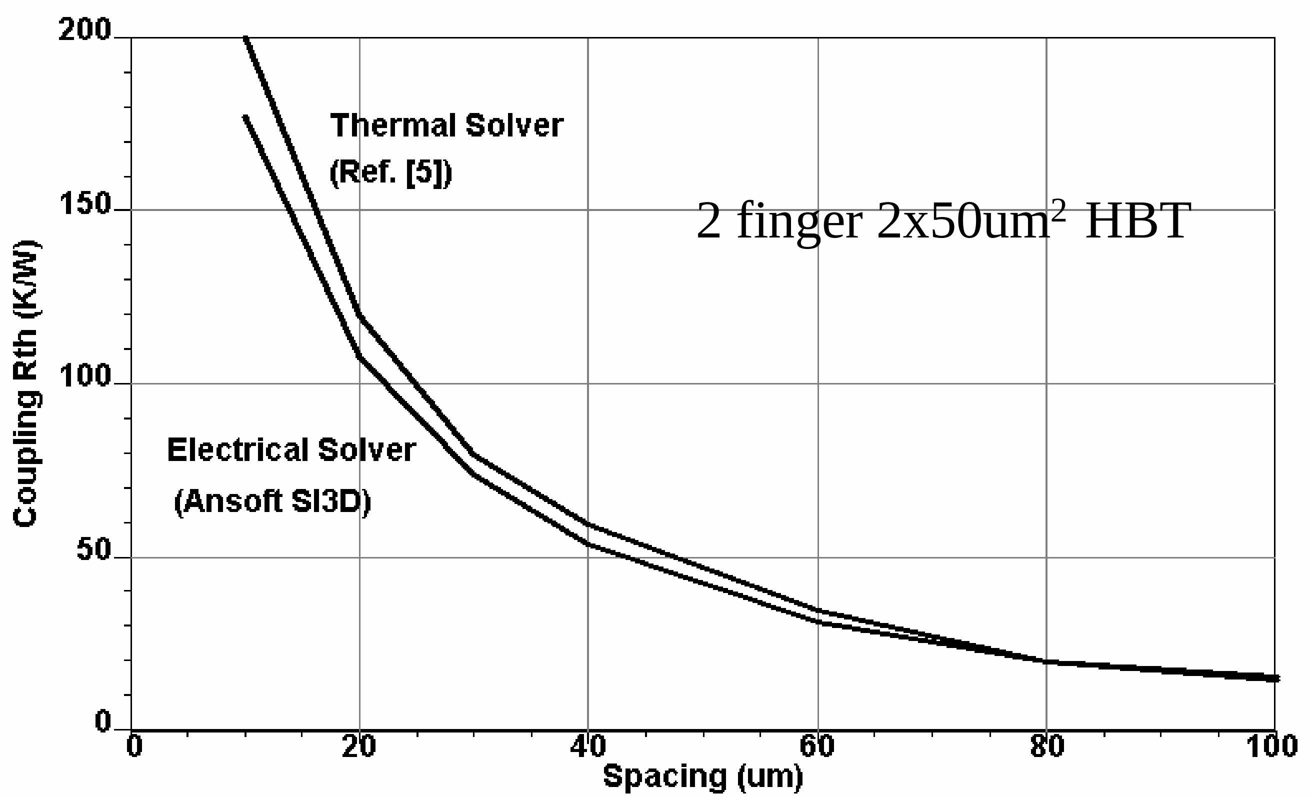


(Thermal network can be extracted from the device structure via electrical field solver, Ansoft SI3D, for example)

Temperature distribution on the Surface of Substrate

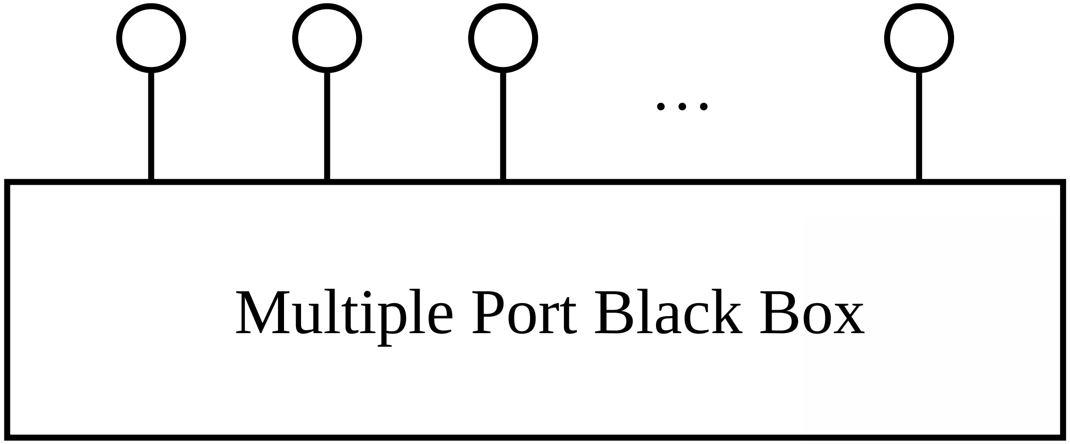


Ansoft SI3D Models Thermal Coupling



2 finger 2x50um^2 HBT

Implementation of Thermal Resistance Matrix

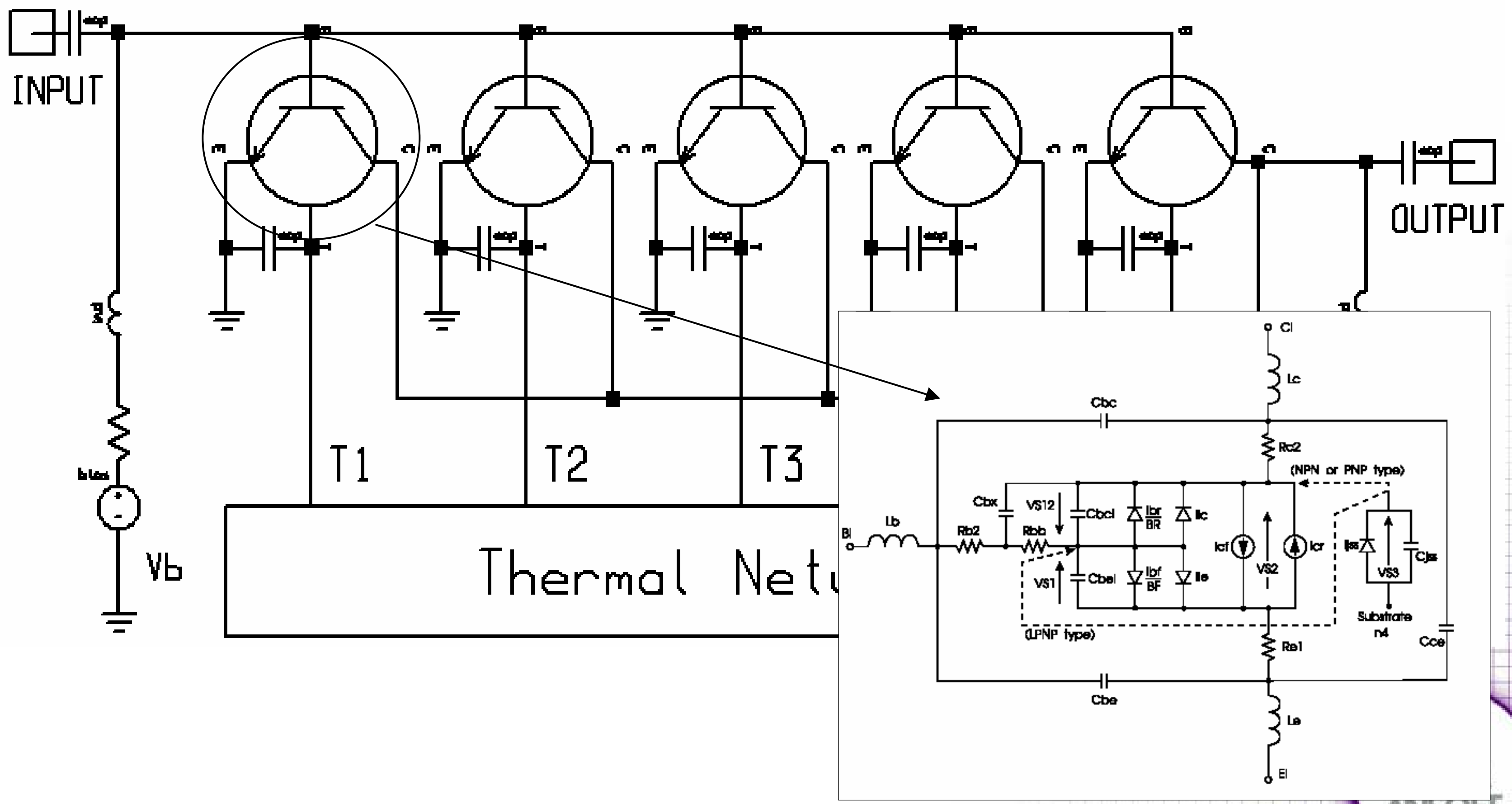


Temperature T ⟺ Voltage V

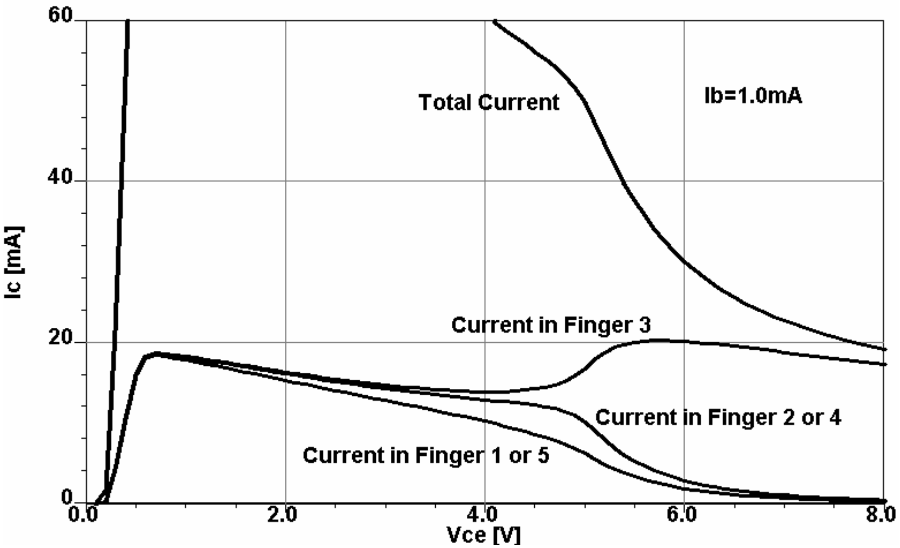
Dissipated Power P ⟺ Current I

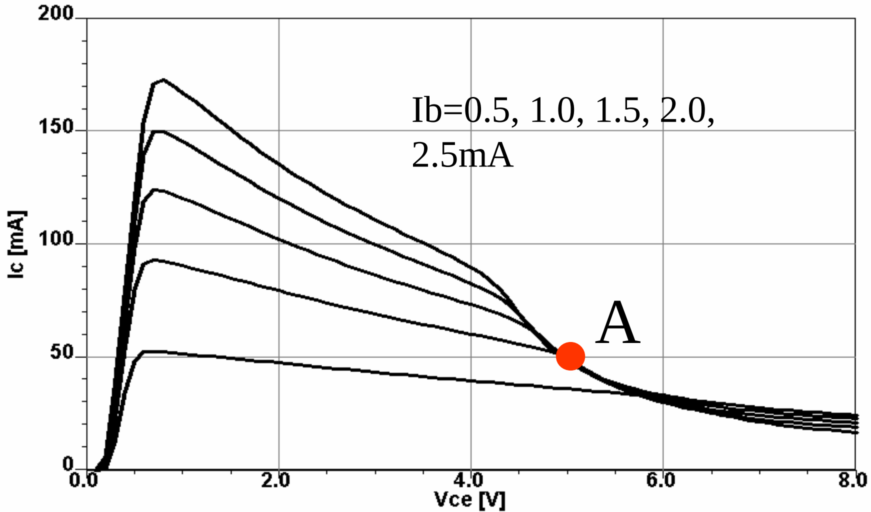
Thermal Resistance Rij ⟺ Electrical Impedance Zij

Electro-thermal Model of HBT in Ansoft Designer



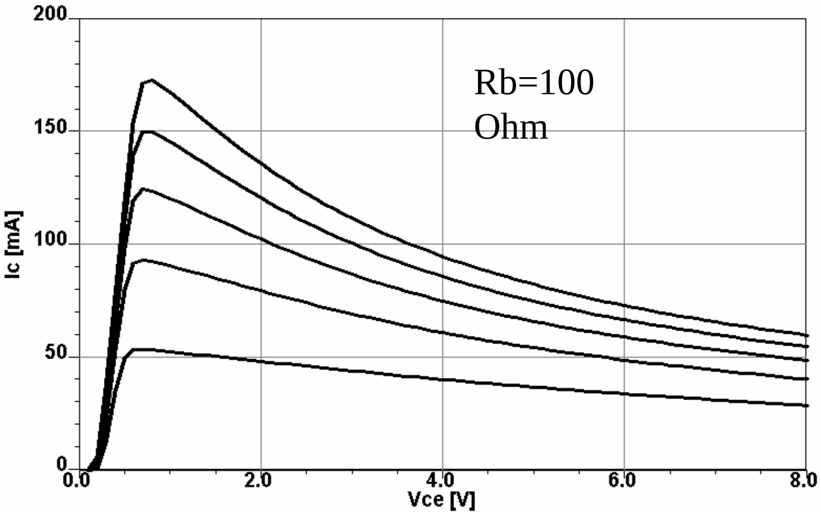
Calculated Collector Currents in Each Finger



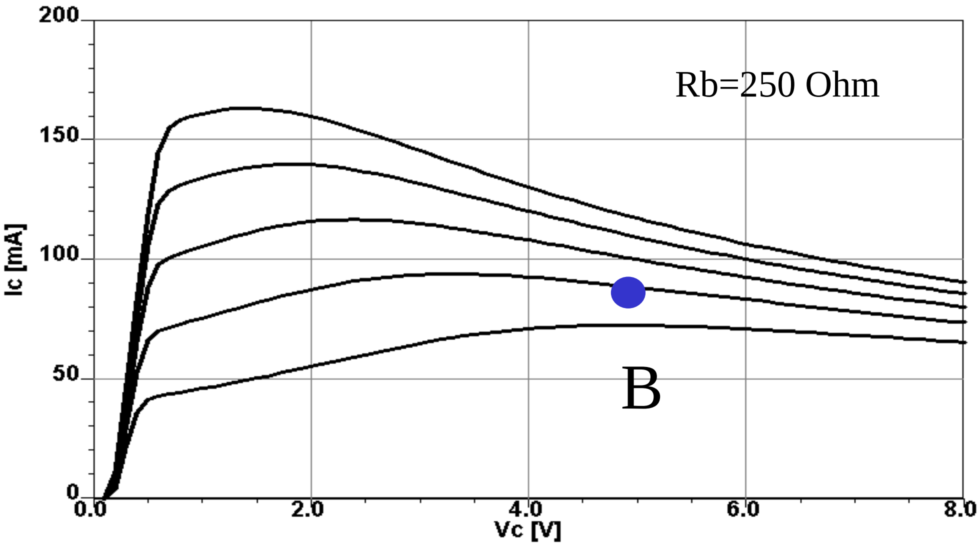


Calculated Collector Current in a 5-Finger HBT

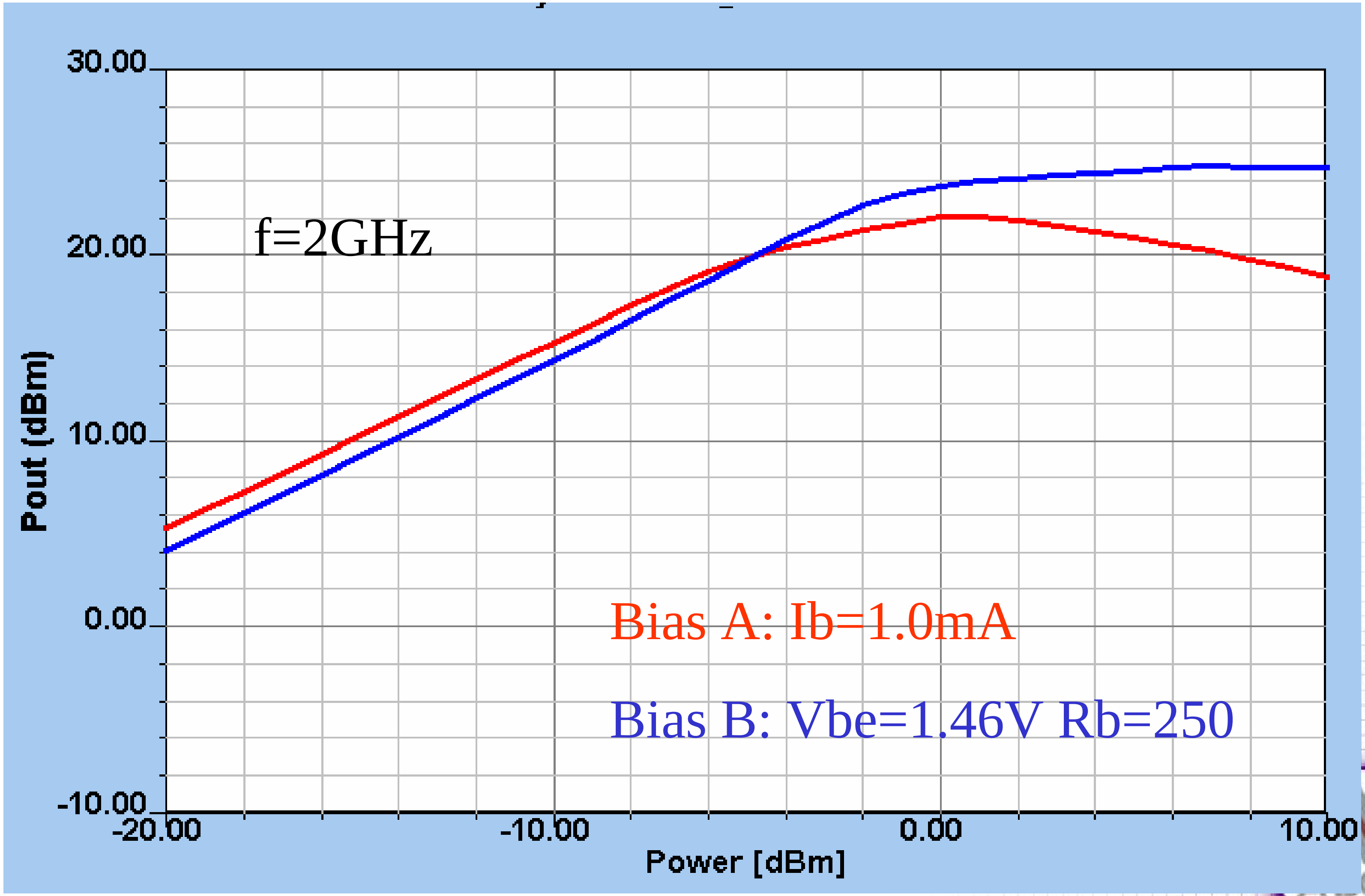
Calculated Collector Currents under Constant Ib



Calculated Collector Currents under Constant Vb



Calculated Output Power versus Input Power

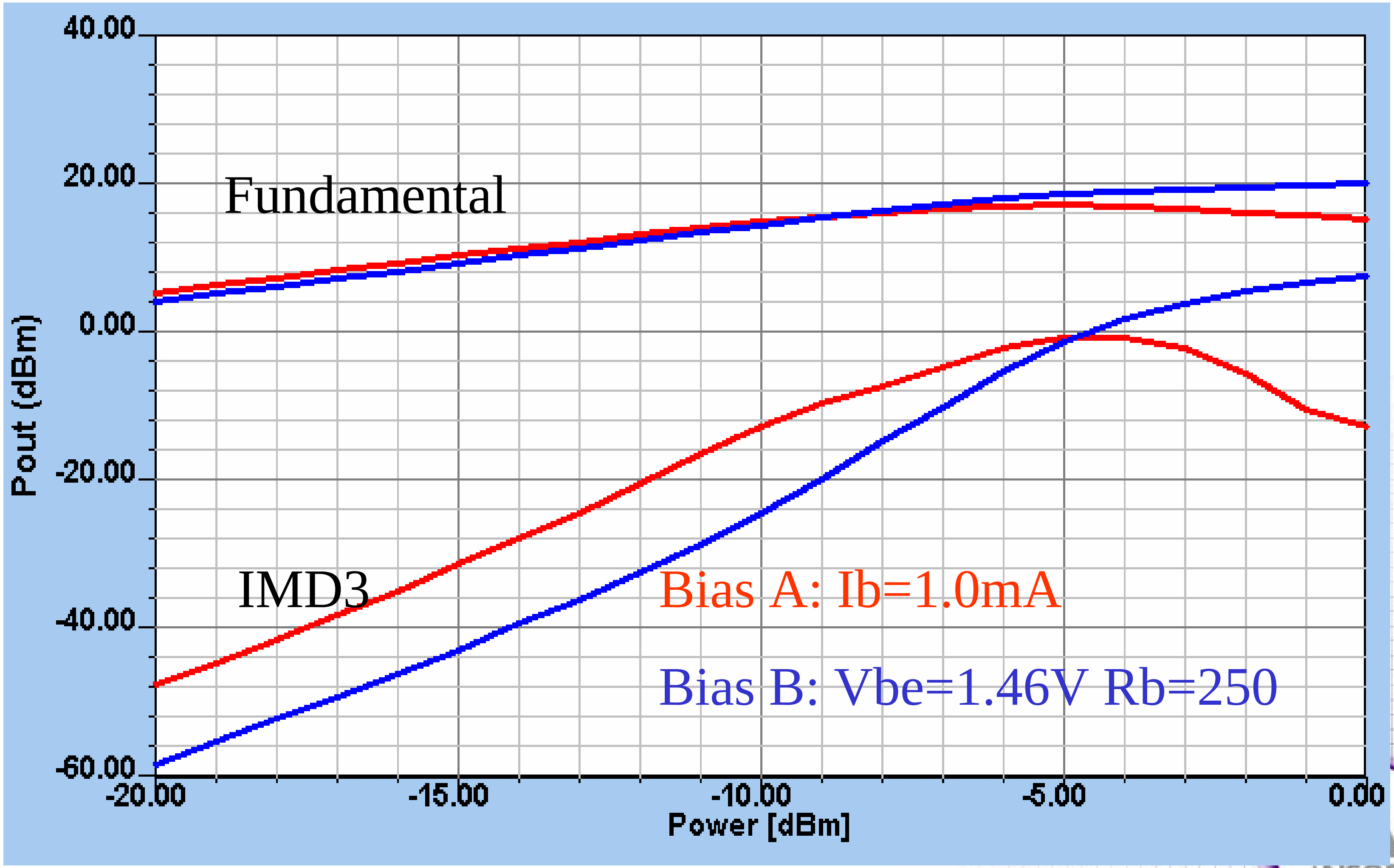


f=2GHz

Bias A: Ib=1.0mA

Bias B: Vbe=1.46V Rb=250

Calculated Fundamental and IMD3 Behaviors



Summary

- Multi-finger HBT model based on
  - Temperature & bias scheme dependent unit HBT model
  - Thermal network representing self-heating & thermal coupling
- Implement of thermal network for circuit simulation
- Reproduced current collapse and related behaviors in multi-finger HBT
- A practical tool for both device and circuit design

Passive Component Modeling - Spiral Inductors

SH Myoung (Ansoft Korea), D Vye (Ansoft) and D. Wu (Altra Broadband)

Considerations for Inductor Design

- Inductance
- Quality Factor
- Self-Resonance Frequency

Design Goal

- Outer Dimensions
- Metal Thickness & Metal Width
- Turn Spacing & Number of Turns
- Substrate & Oxide Thickness

Parameter

- Skin Depth of Conductor
- Substrate Resistivity
- Field Excitation (Port)
- Test & Measurements Setup

Accuracy

Inductor behavior influences overall Circuit & System performance

- Inductor performance critical to filters, VCOs, matching circuits for amplifiers, etc.

- VCO phase noise is directly related to Q of passive networks

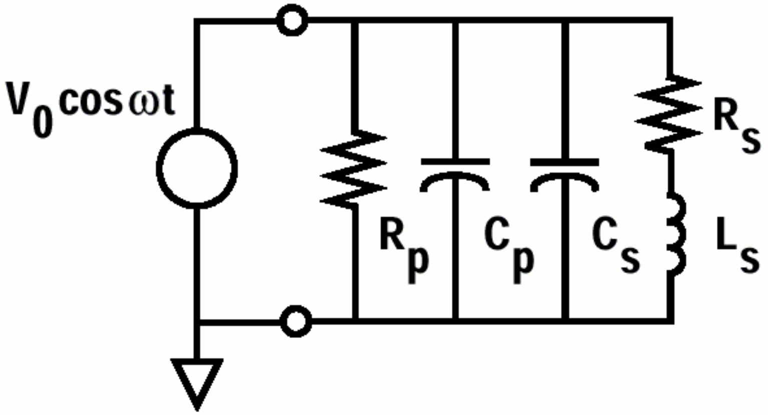
- Inductor often dominates the tank Q in the 1-2GHz range

- Spiral Inductors often dominate space consumption

Ansoft Serenade Design Environment

Spiral Inductor Design – What are the considered?

Definition of Inductor Quality Factor



$$Q = 2\pi \frac{|\text{Peak Magnetic Energy} - \text{Peak Electric Energy}|}{\text{Energy Loss in One Oscillation Cycle}}$$

$$\frac{\omega L_s}{R_s} \times \underbrace{\frac{R_p}{R_p + [(\omega L_s / R_s)^2 + 1] \cdot R_s}}_{\text{Substrate Loss Factor}} \times \underbrace{\left(1 - \frac{R_s^2 (C_p + C_s)}{L_s} - \omega^2 L_s (C_p + C_s)\right)}_{\text{Self-Resonance Factor}}$$

Inductor Q is limited by physical phenomena that convert electromagnetic energy to heat

- At lower frequencies,

  Series resistance of the coil is a dominant factor in determining Q

- At higher frequencies,

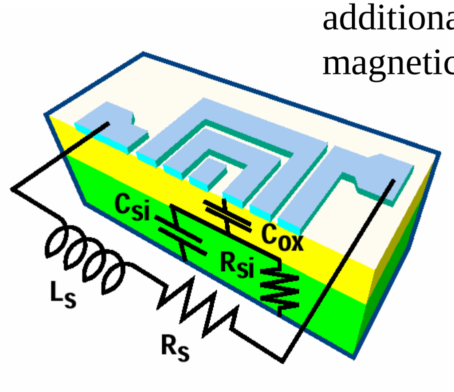
  Eddy currents in metal layers (skin and proximity effects)

  reduce current flow to smaller areas, increasing heat conversion and limiting Q

  Substrate is source of additional bulk losses

  electrically induced currents flow into the lossy substrate through displacement current injection

  additional losses occur for significantly conductive substrates due to magnetically induced currents (bulk eddy currents) severely limiting Q



Spiral Inductor Designs

Improving Q via new processes -
(material properties, shielding, metal thickness, etc.)

a. Highly inductive metal layers to reduce resistive losses

b. Multi-metal layer to increase relative thickness and reduce losses

c. Stacked (or series connected multi-layer) inductor to reduce area

d. Thick oxide or floating inductor to isolate inductor from lossy substrate

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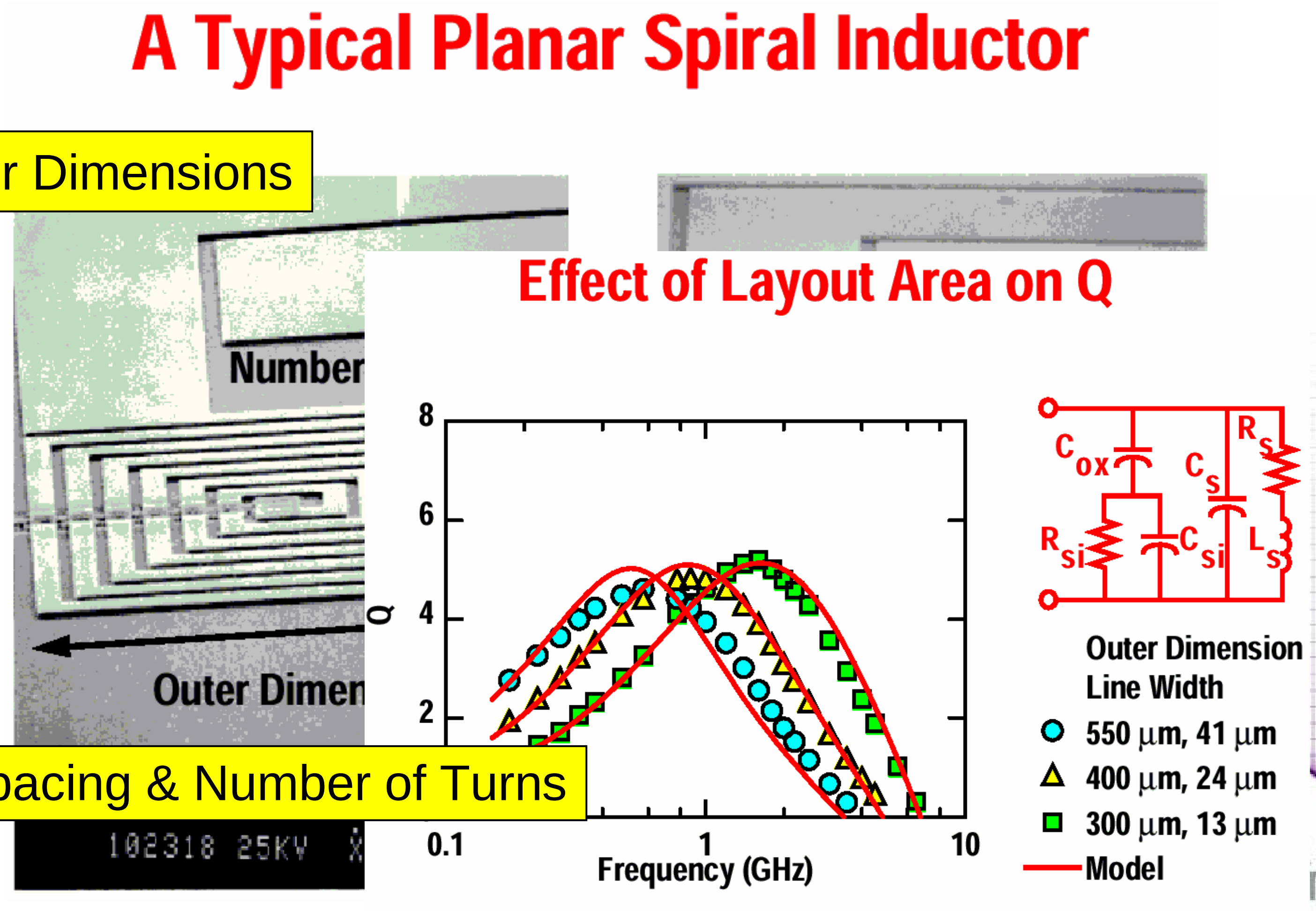
Spiral Inductor Design – What are the considered?

- Outer Dimensions
- Turn Spacing & Number of Turns



A Typical Planar Spiral Inductor

Effect of Layout Area on Q

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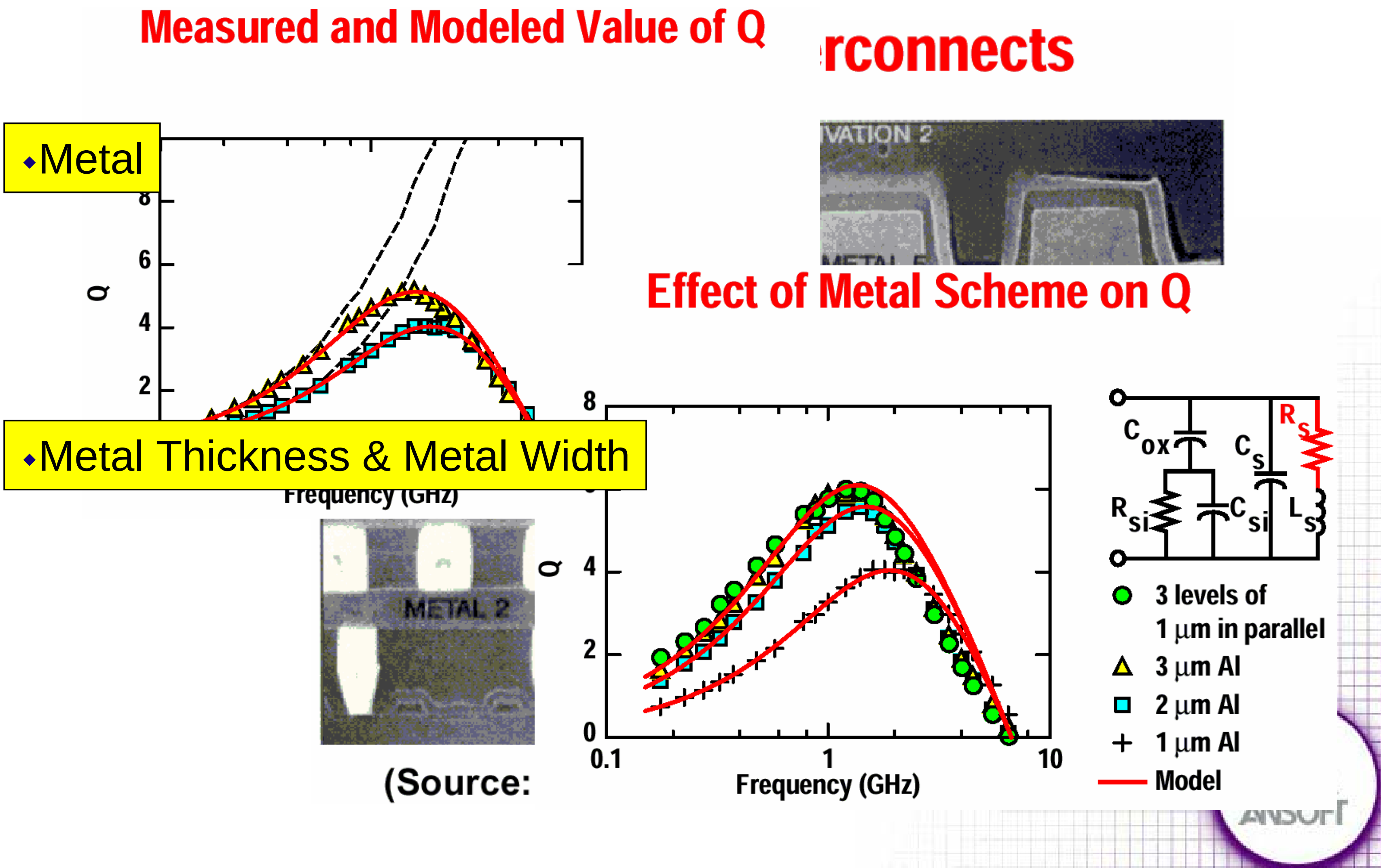
Spiral Inductor Design

- Metal
- Metal Thickness & Metal Width



Measured and Modeled Value of Q

rconnects

Effect of Metal Scheme on Q

(Source:

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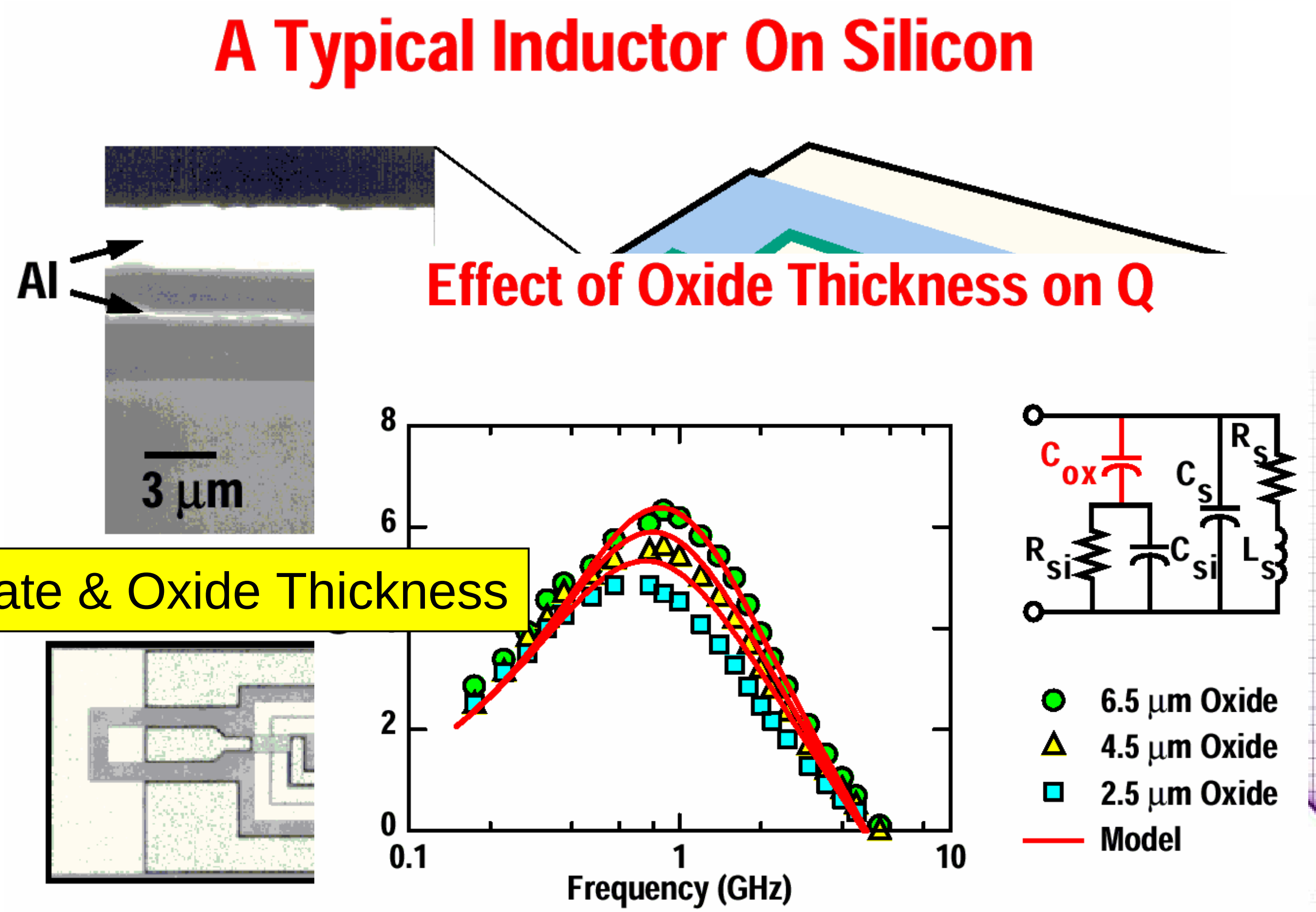
Spiral Inductor Design – What are the considered?



A Typical Inductor On Silicon

Effect of Oxide Thickness on Q

- Substrate & Oxide Thickness

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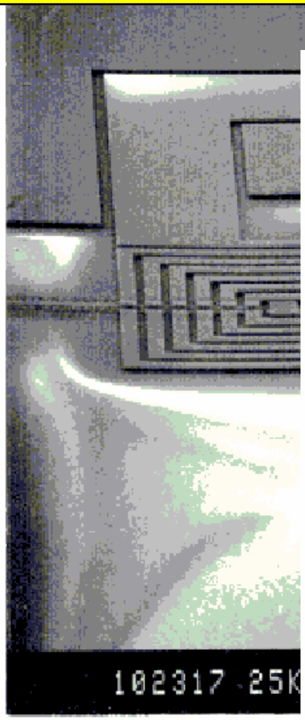
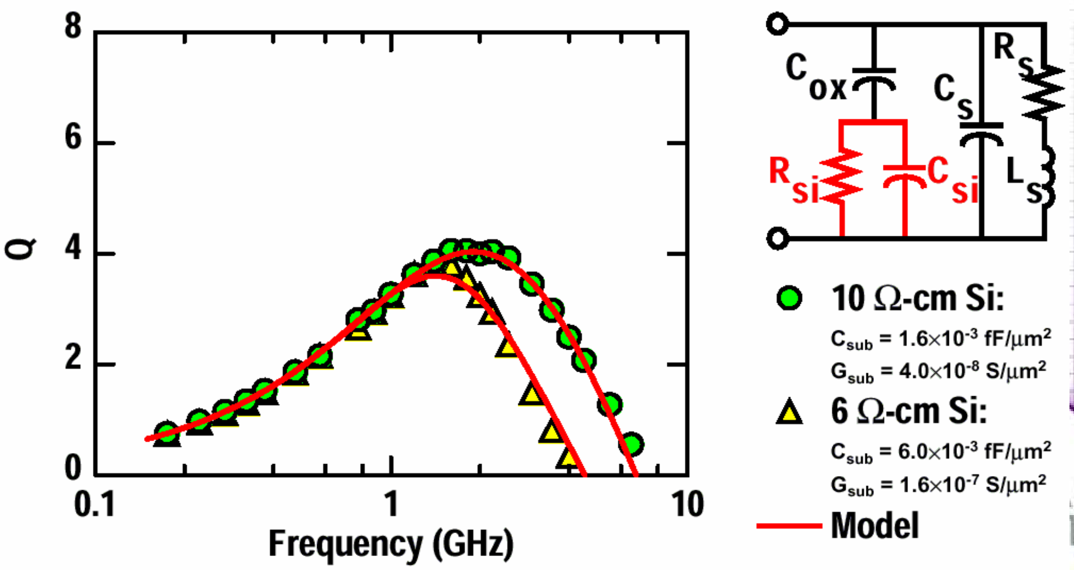
Spiral Inductor Design – What are the considered?

Suspended Inductors

- Substrate & Oxide Thickness



Effect of Substrate Resistivity on Q



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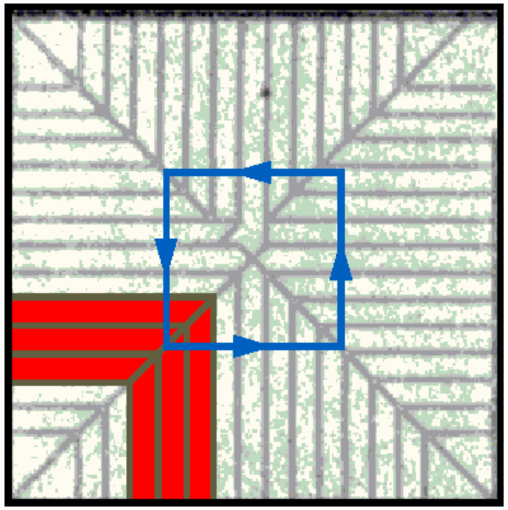
Spiral Inductor Design – What are the considered?

Patterned Ground Shield Design

- Pattern
  - Orthogonal to spiral (induced loop current)
- Resistance
  - Low for termination of the electric field
  - Avoid attenuation of the magnetic field



🟥 Ground Strips

— Slot between Strips

← Induced Loop Current

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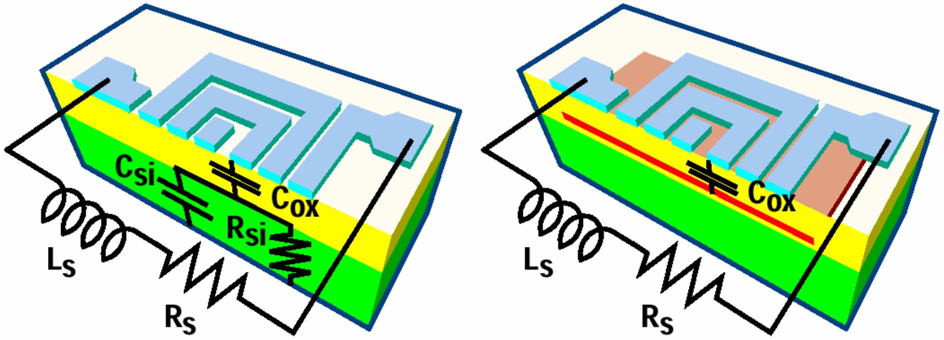
Spiral Inductor Design – What are the considered?

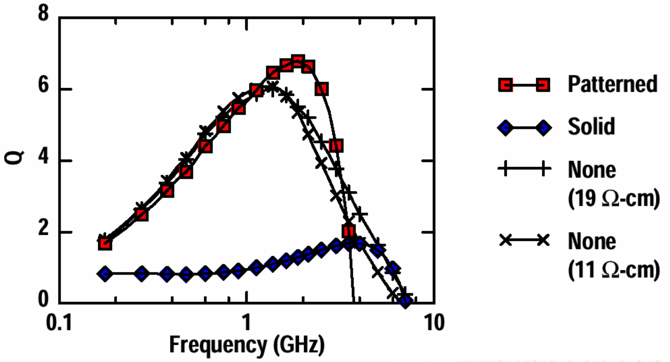
Circuit Models of On-Chip Inductors



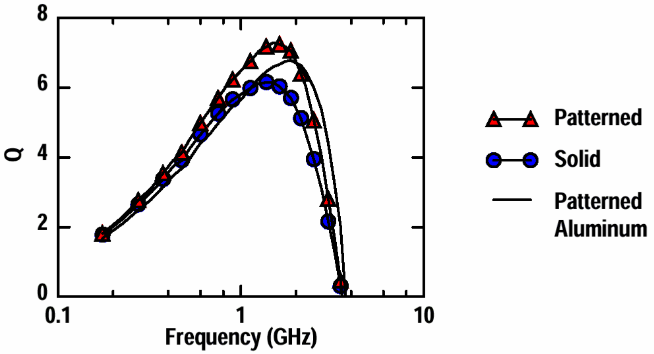
Conventional Design

With Patterned Ground Shield

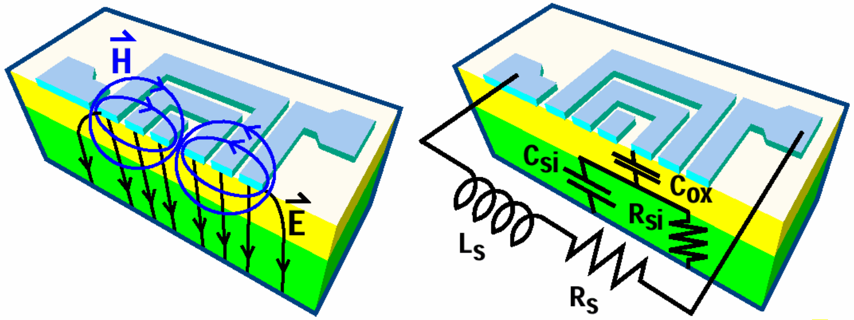
Effect of Aluminum Ground Shields on Q

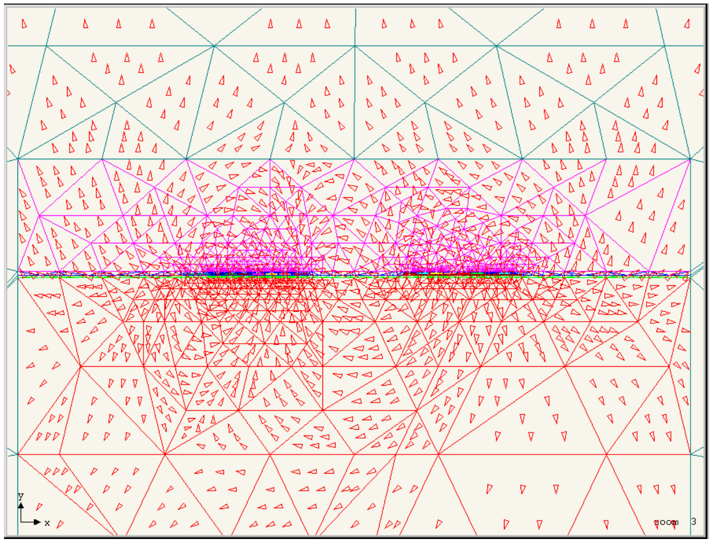


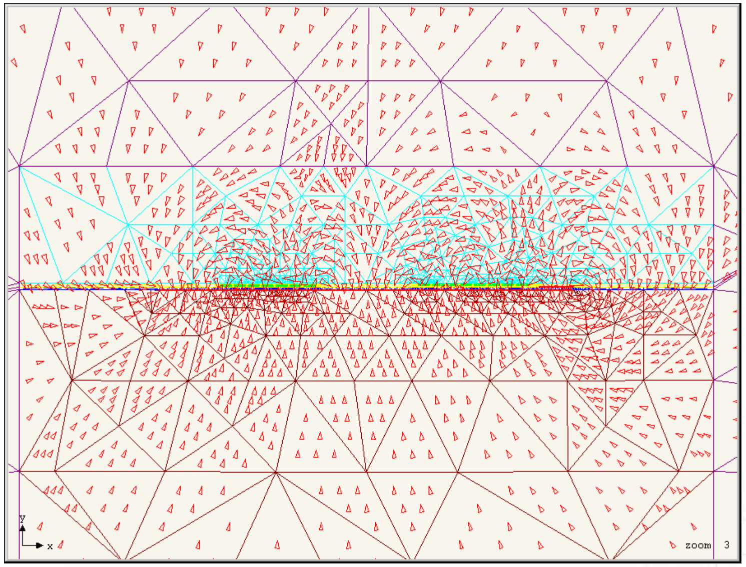
Effect of Polysilicon Ground Shields on Q



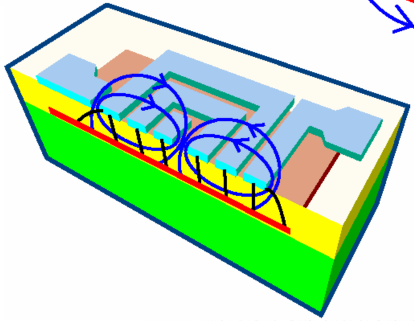
Electromagnetic Fields of Conventional On-Chip Inductors

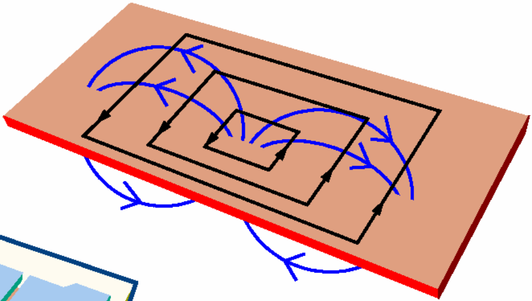






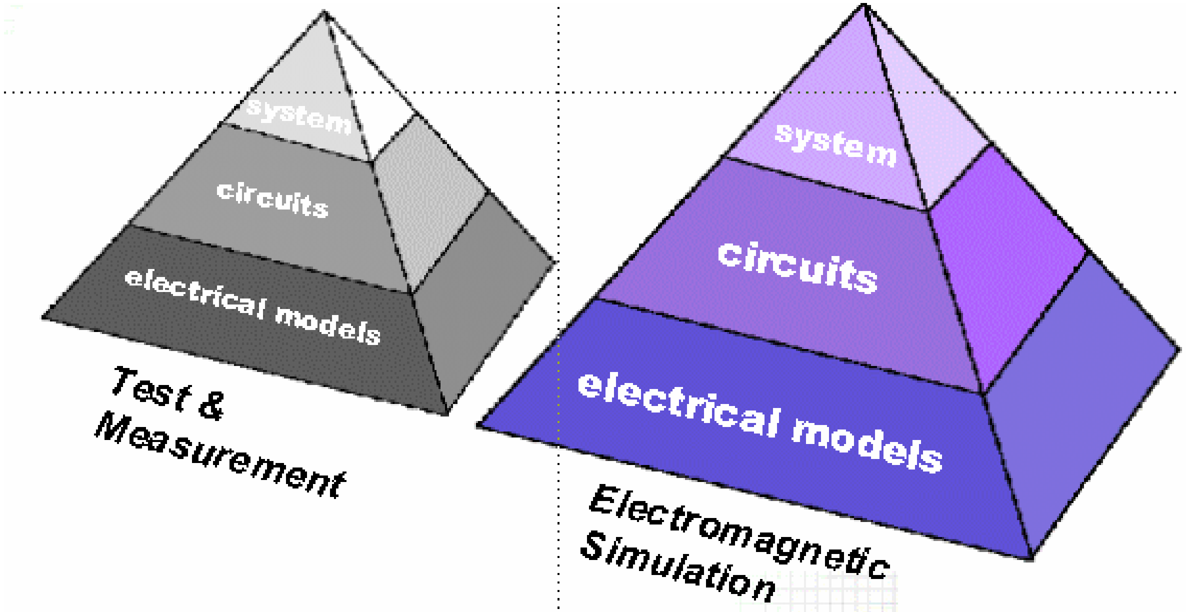
Problems with Solid Ground Shield





Induced Loop Current
and Magnetic Field

Spiral Inductor Modeling



- Component characterization
- Component representation for circuit simulation
- Component optimization

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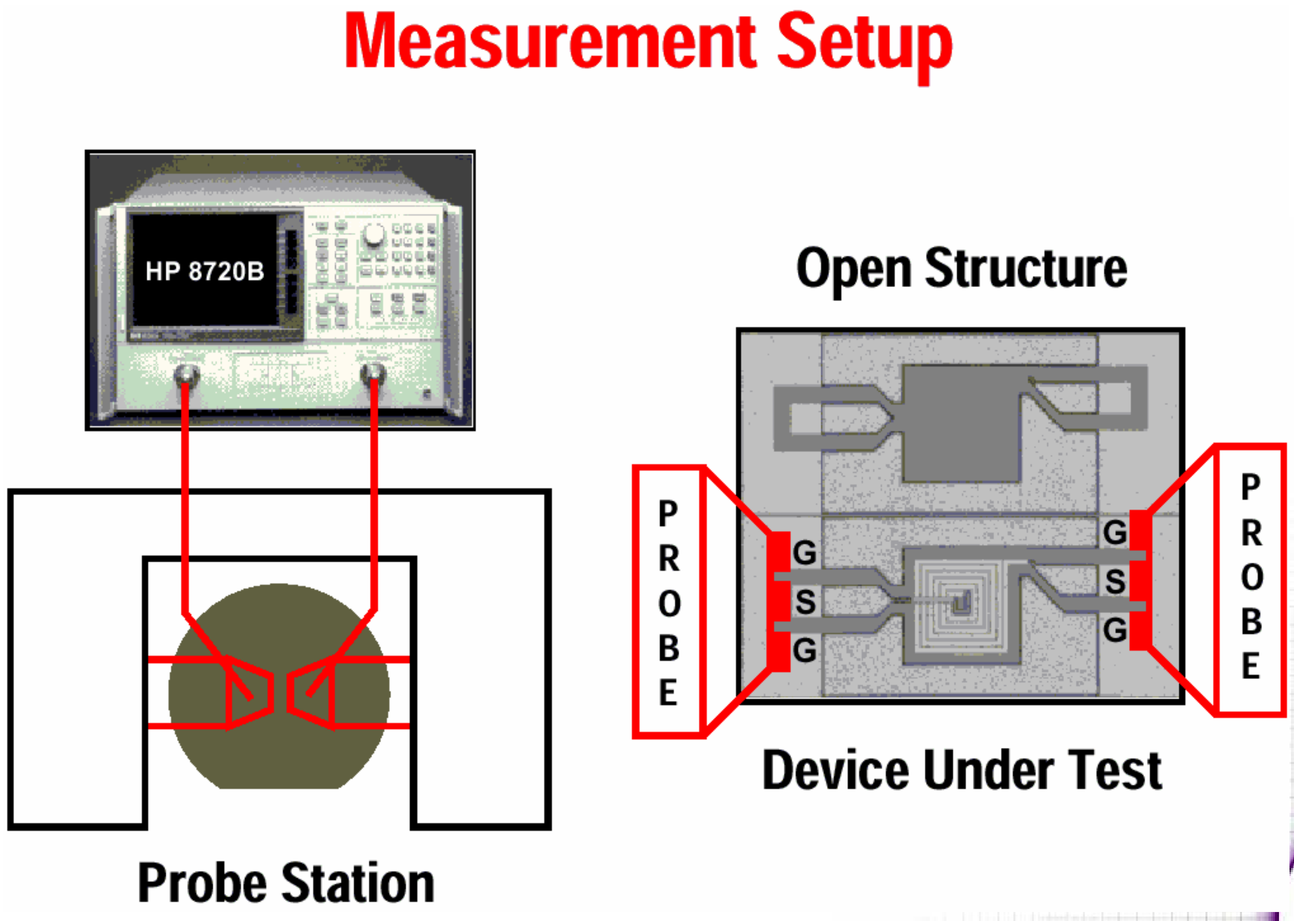
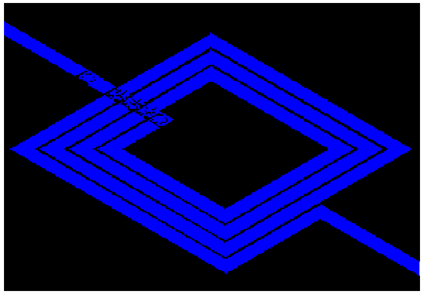
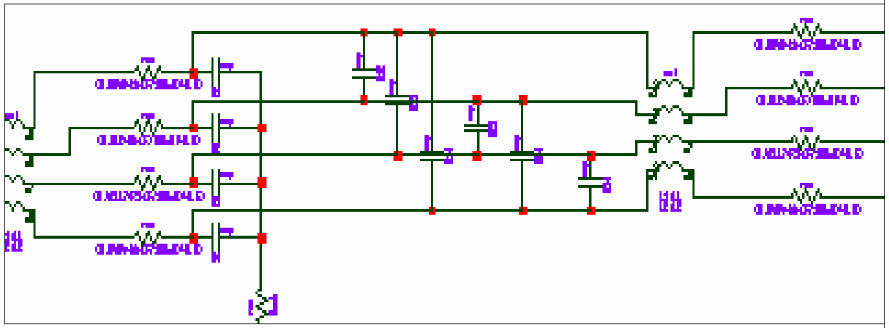
Spiral Inductor Design – What are the considered?

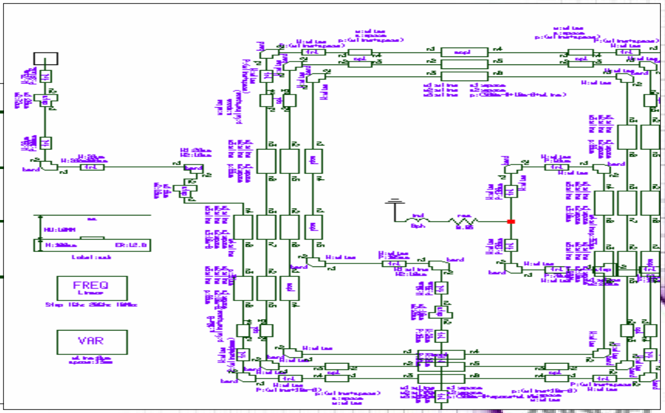


Optional Methods for Characterizing Passive Components



- S-parameters
    - Planar Electromagnetic (2.5D or 3D - MoM)
    - 3D Electromagnetic simulation
- RLC matrix based on quasi-static Electromagnetic simulation
- Full-wave SPICE equivalent circuit (for time domain simulation)
- Empirically derived lumped equivalent circuit
- Equivalent circuit based on distributed transmission and coupled line models

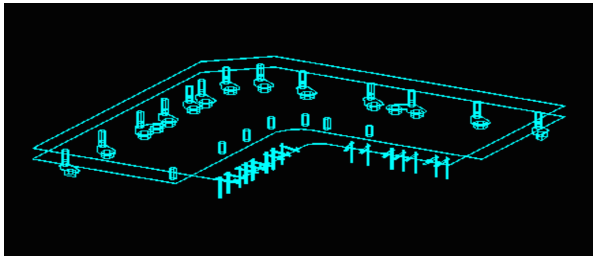


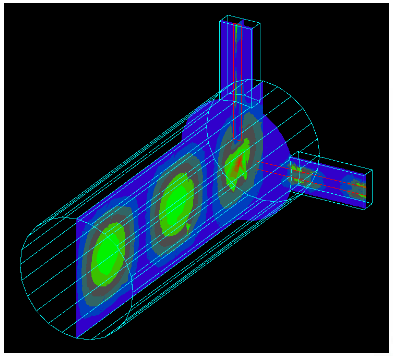


Ansoft Electromagnetics

EM Methods Overview

Application of Simulation Tools Depends on Electrical Size of Structure

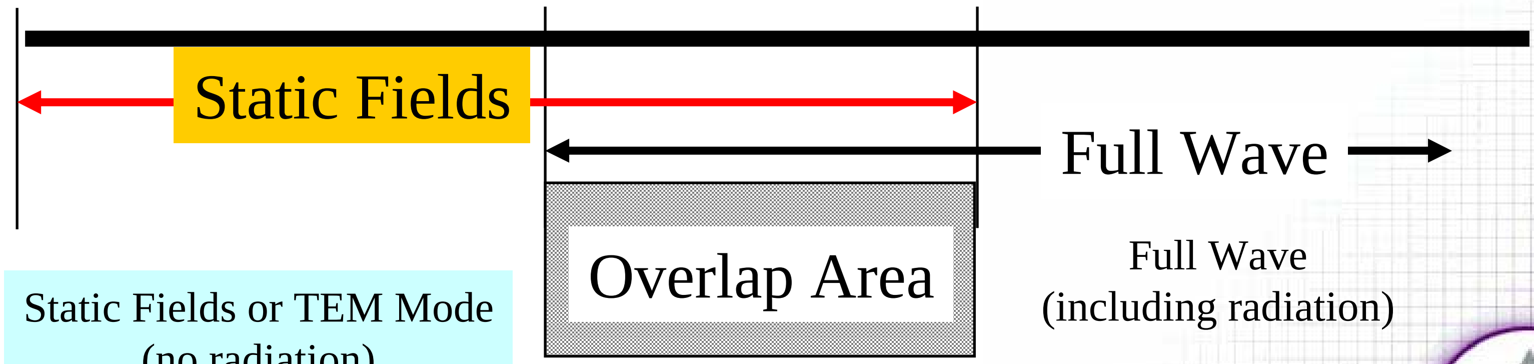




0

1/100λ

1/10λ



Static Fields

Full Wave

Overlap Area

Static Fields or TEM Mode
(no radiation)

Input: V, I
Output: C, L, R (SPICE)

Full Wave
(including radiation)

Input: Modal Waves
Output: s-parameters (or z and y)

One Tenth of λ_g Checking Rule

Wavelength = 30cm@1GHz $\xrightarrow{\div 10}$ **3cm** $\xrightarrow{\div 2}$ **1.5cm**

Wavelength = 3cm@10GHz $\xrightarrow{\div 10}$ **0.3cm** $\xrightarrow{\div 2}$ **0.15cm**

Wavelength = 1.5cm@20GHz $\xrightarrow{\div 10}$ **1.5mm** $\xrightarrow{\div 2}$ **750um**

$$\sqrt{\varepsilon_{eff}} < \sqrt{\varepsilon_{oxide}} \cong \sqrt{4} = 2$$

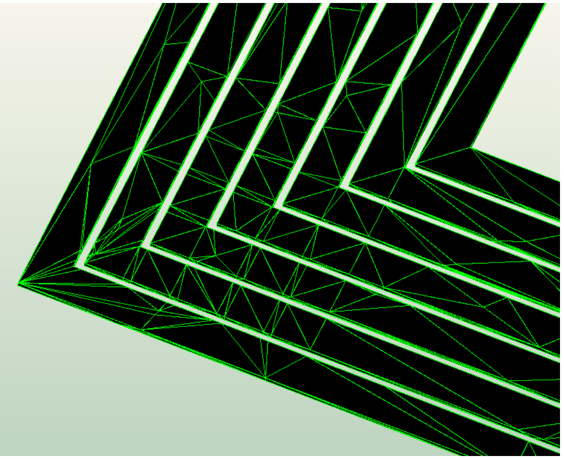
Suppose the size of your spiral inductor is small than 400um, then, theoretically, that spiral inductor could be well-modeled by lump RLC up to 20 GHz.

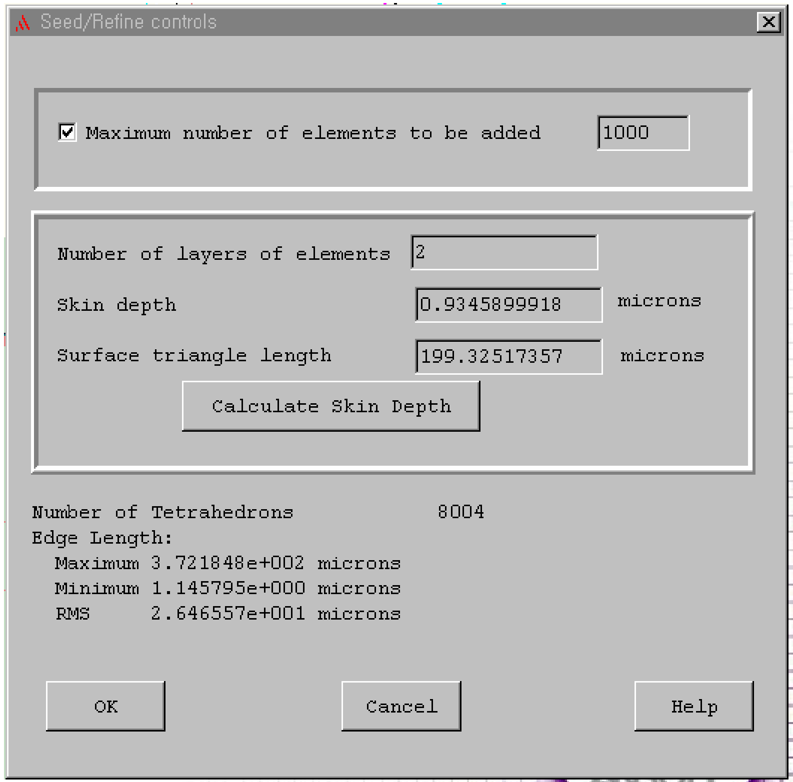
Ansoft HFSS

Spiral Inductor Design – Skin Depth

- Skin Depth
  - The distance δ through which the amplitude of a traveling plane wave decreases by a factor of e^{-1} or 0.386
- $$\delta = \frac{1}{\alpha} = \frac{1}{\sqrt{\pi f \mu \sigma}} \qquad (m)$$
- Skin Depth of Various Materials

Material	σ(S/m)	@5GHz
Aluminum	5.8e+7	0.934μm





☑ Maximum number of elements to be added: 1000

Number of layers of elements: 2

Skin depth: 0.9345899918 microns

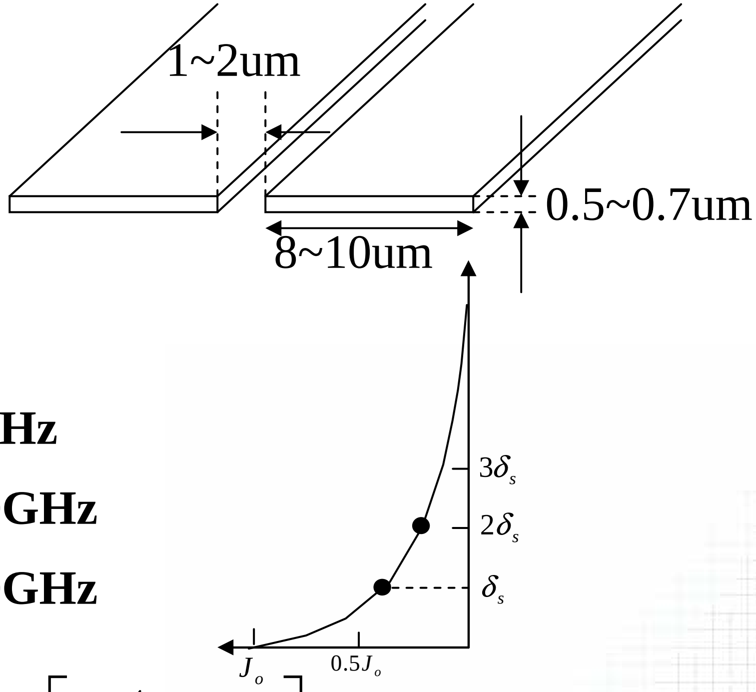
Surface triangle length: 199.32517357 microns

```
Number of Tetrahedrons            8004
Edge Length:
  Maximum 3.721848e+002 microns
  Minimum 1.145795e+000 microns
  RMS     2.646557e+001 microns
```

Skin Depth Calculation

$$\delta_s = \frac{1}{\sqrt{\pi \cdot f \cdot \mu_R \cdot \mu_o \cdot \sigma}}$$

$$\delta_{Cu} = \frac{0.066}{\sqrt{f}}$$ meter



Skin Depth = 2.1um for copper@1GHz

Skin Depth = 0.66um for copper@10GHz

Skin Depth = 0.47um for copper@20GHz

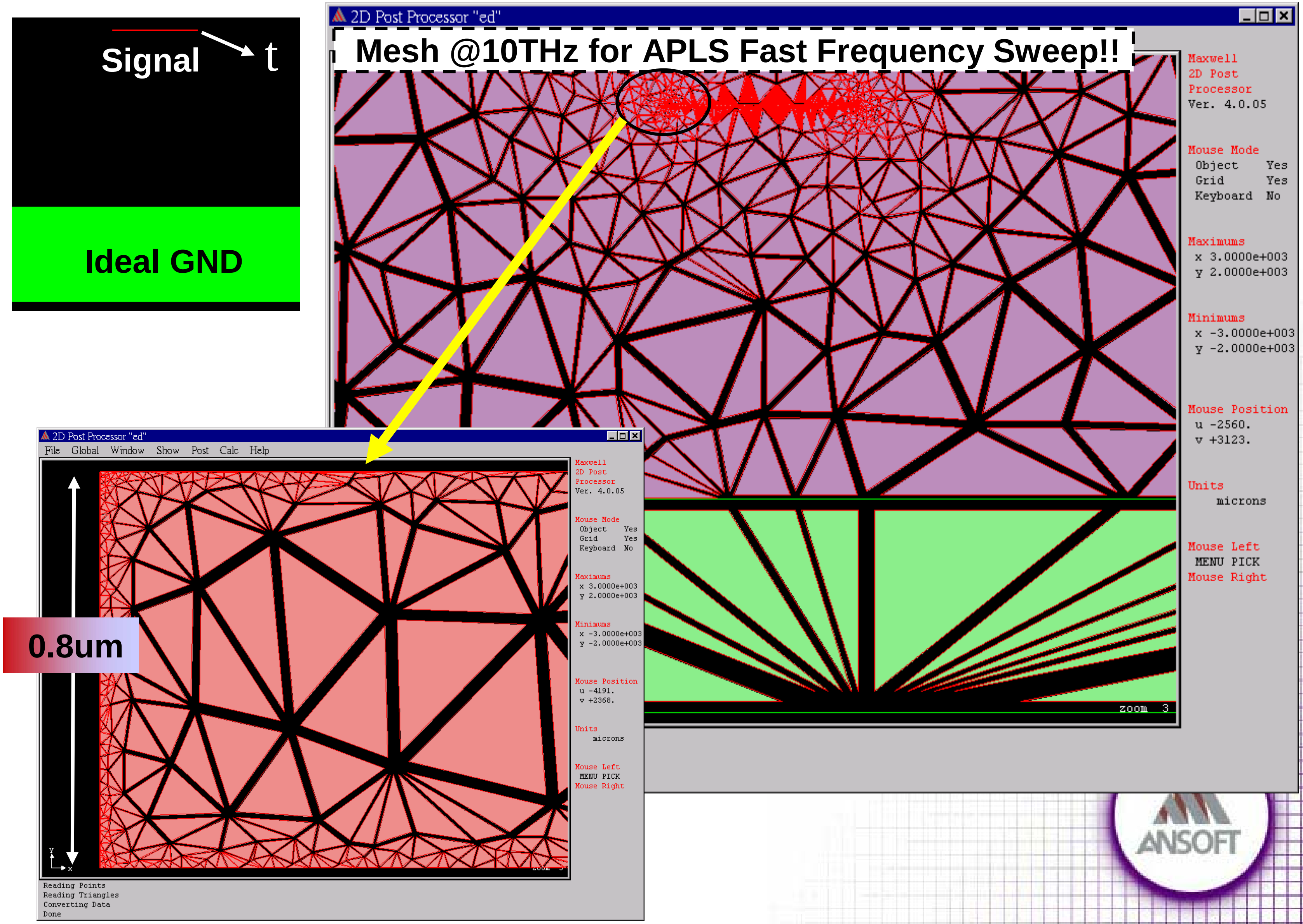
$$\sigma_{Cu} = \frac{1}{1.673}\left[{}^{1}\!/_{\mu\Omega \cdot cm}\right] \quad \sigma_{Al} = \frac{1}{2.65}\left[{}^{1}\!/_{\mu\Omega \cdot cm}\right]$$

$$\sigma_{Cu} : \sigma_{Al} = 1 : 0.63$$

According to the size and thickness of a spiral inductor in IC, it almost can be regarded as low frequency problem. Therefore, Ansoft Spicelink is very helpful in this frequency range.

Skin Effect Simulation with Ansoft SI2D

t = 0.8 & 1.5um for IC Application



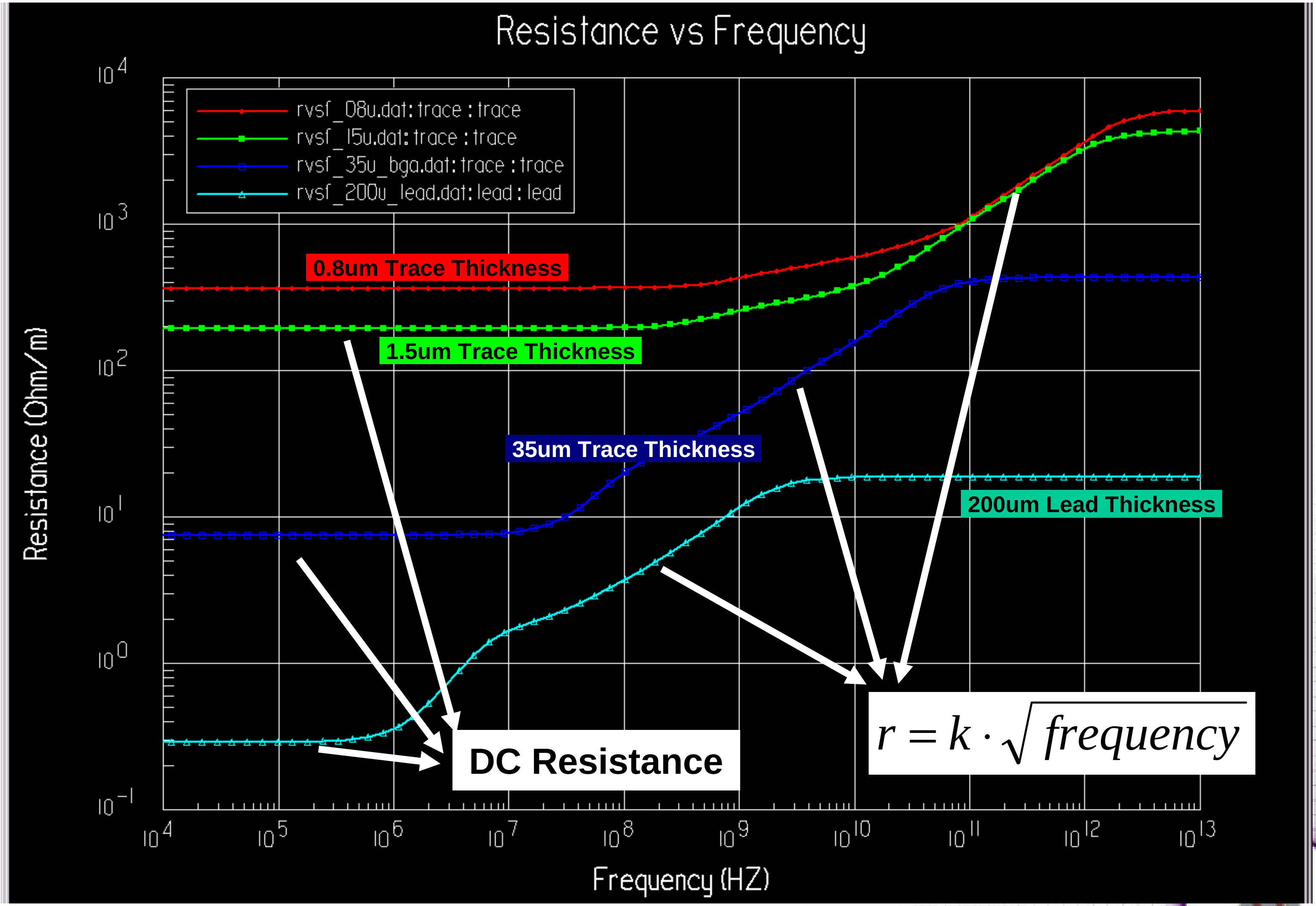
Mesh @10THz for APLS Fast Frequency Sweep!!

```
Maxwell
2D Post
Processor
Ver. 4.0.05

Mouse Mode
 Object    Yes
 Grid      Yes
 Keyboard  No

Maximums
 x 3.0000e+003
 y 2.0000e+003

Minimums
 x -3.0000e+003
 y -2.0000e+003

Mouse Position
 u -2560.
 v +3123.

Units
    microns

Mouse Left
 MENU PICK
Mouse Right
```

```
Maxwell
2D Post
Processor
Ver. 4.0.05

Mouse Mode
 Object    Yes
 Grid      Yes
 Keyboard  No

Maximums
 x 3.0000e+003
 y 2.0000e+003

Minimums
 x -3.0000e+003
 y -2.0000e+003

Mouse Position
 u -4191.
 v +2368.

Units
    microns

Mouse Left
 MENU PICK
Mouse Right
```

```
Reading Points
Reading Triangles
Converting Data
Done
```

Skin Depth Simulation with Ansoft SI2D



0.8um Trace Thickness

1.5um Trace Thickness

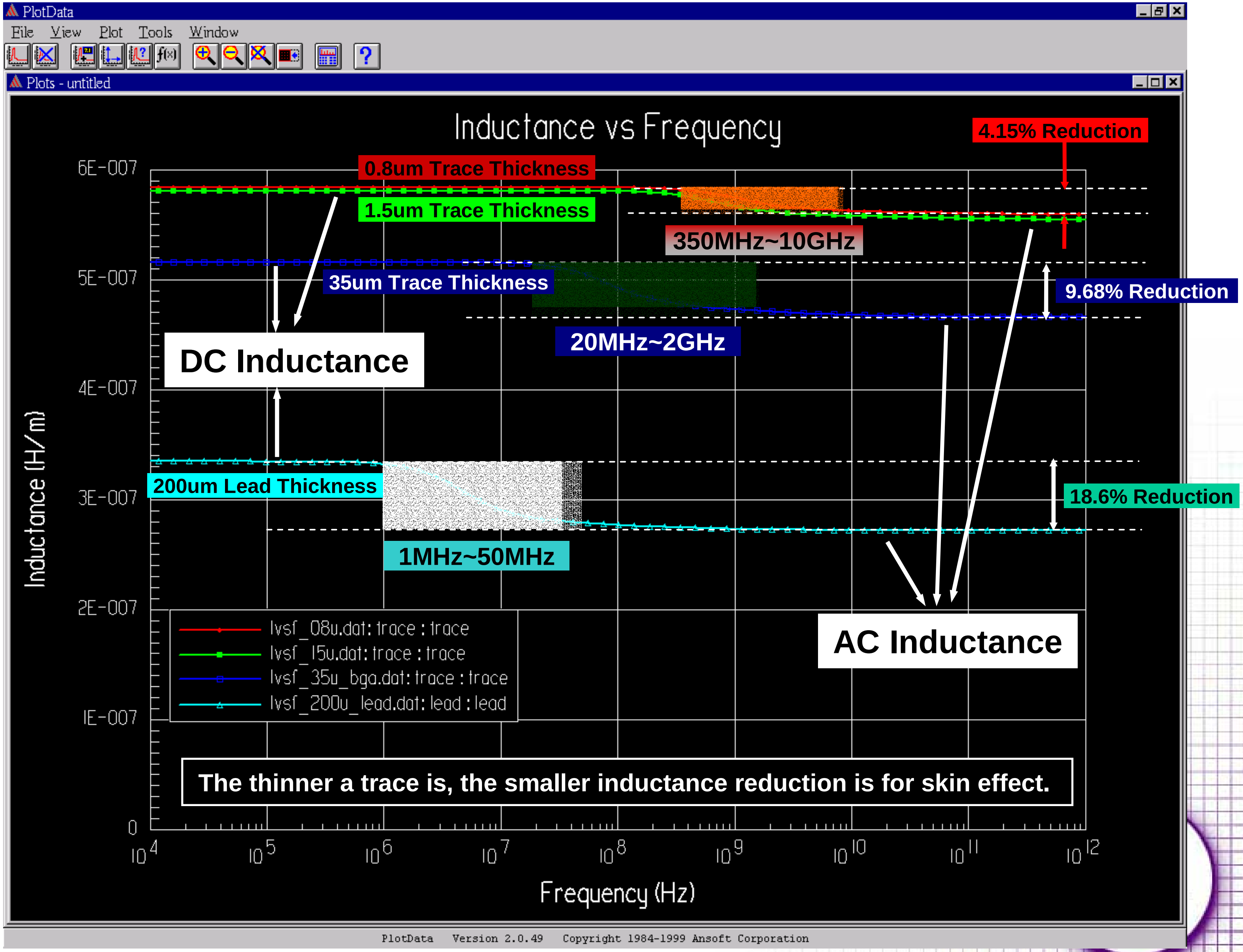
35um Trace Thickness

200um Lead Thickness

DC Resistance

$$r = k \cdot \sqrt{frequency}$$

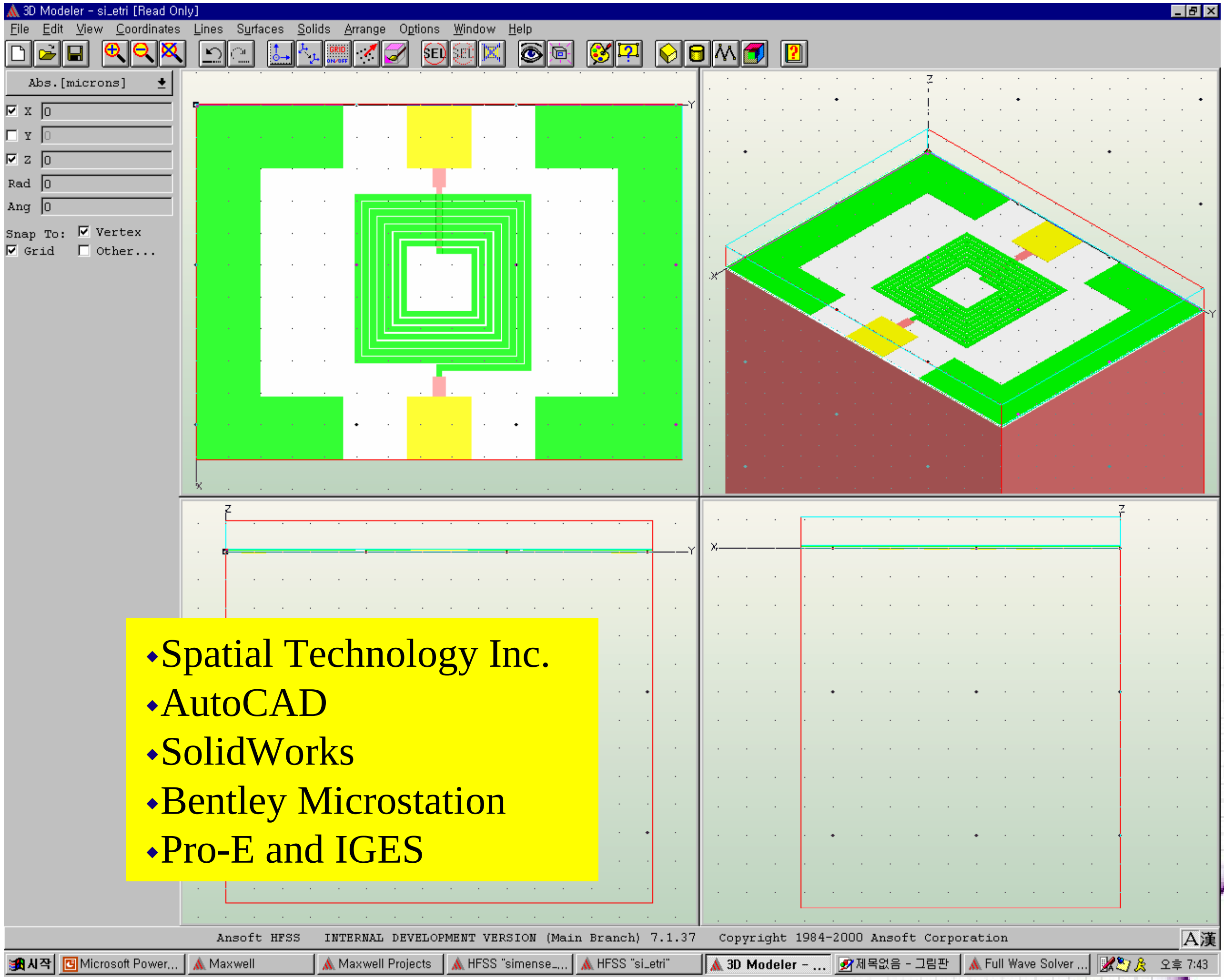
Skin Depth Simulation with Ansoft SI2D



The thinner a trace is, the smaller inductance reduction is for skin effect.

PlotData Version 2.0.49 Copyright 1984-1999 Ansoft Corporation

Spiral Inductor Design – Imported 3D Model



Abs.[microns]

☑ X 0

☐ Y 0

☑ Z 0

Rad 0

Ang 0

Snap To: ☑ Vertex

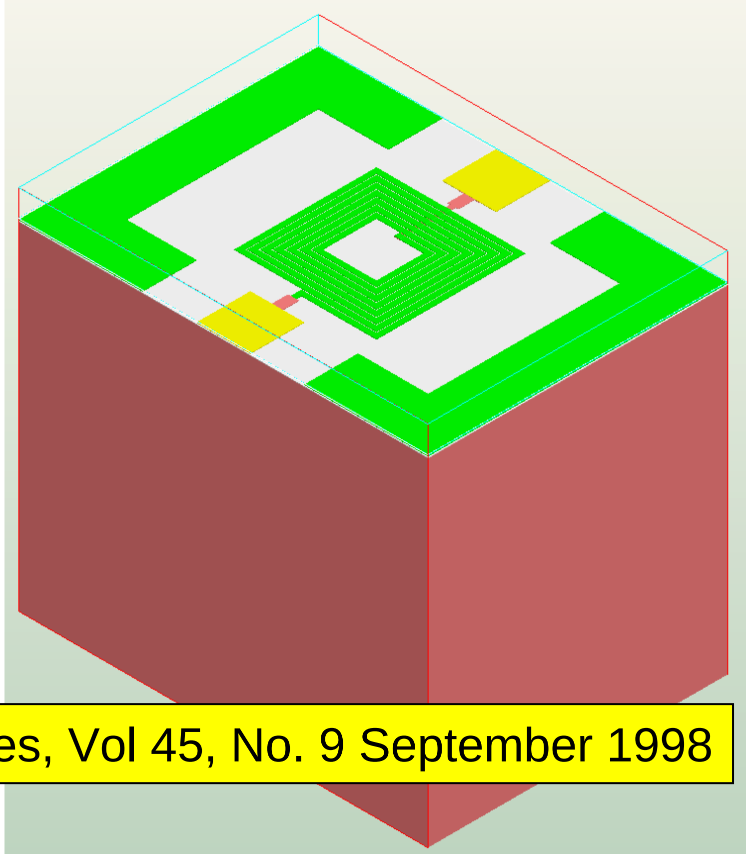
☑ Grid ☐ Other...

Ansoft HFSS INTERNAL DEVELOPMENT VERSION (Main Branch) 7.1.37 Copyright 1984-2000 Ansoft Corporation

- Spatial Technology Inc.
- AutoCAD
- SolidWorks
- Bentley Microstation
- Pro-E and IGES

Spiral Inductor Design – Create a Model in 3D Modeler

- Outer Dimension : 276um
- Metal Thickness : 1.1um
- Metal Width : 10um(8-30)
- Turn spacing : 2um(2-10)
- Number of Turns : 8
- Oxide Thickness : 1.2um
- Silicon Substrate height : 625um

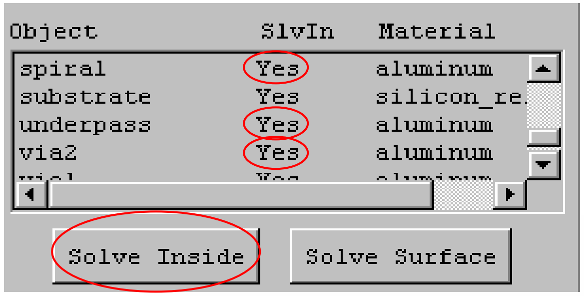


- IEEE Transaction on Electron Devices, Vol 45, No. 9 September 1998

Spiral Inductor Design – Setup Material

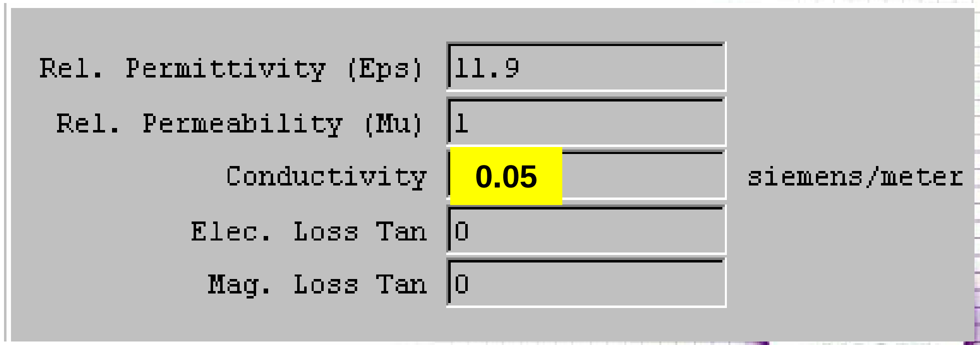
- Silicon Dioxide
  - Lossless Dielectric
  - $\varepsilon_r = 4$

- Metalization : Aluminum
  - Good Conductor
  - Conductivity : 3.8e+007 S/m
  - Solve Metal Inside Option
  - Skin Depth mesh is required



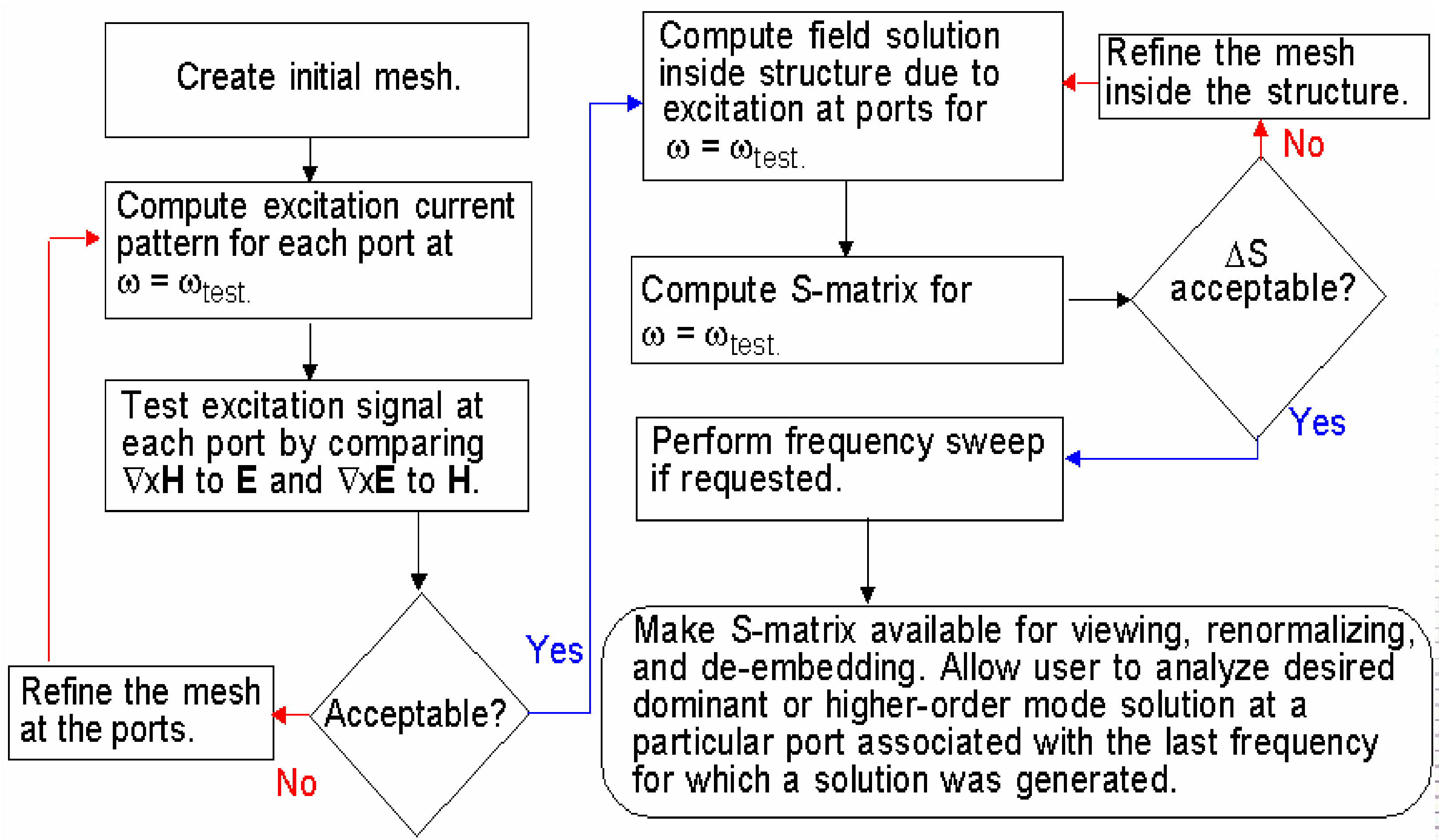
Object	SlvIn	Material
spiral	Yes	aluminum
substrate	Yes	silicon_re
underpass	Yes	aluminum
via2	Yes	aluminum

- Silicon Substrate
  - Lossy Dielectric
  - $\varepsilon_r = 11.9$
  - R=4-6Ω·Cm(Rsistivity)
    2k Ω·Cm(Rsistivity)
  - Conductivity
    $\sigma=1/R = 20$ S/m
    $1/R = 0.05$ S/m



Rel. Permittivity (Eps): 11.9
Rel. Permeability (Mu): 1
Conductivity: 0.05 siemens/meter
Elec. Loss Tan: 0
Mag. Loss Tan: 0

Spiral Inductor Design – Adaptive Solution



Create initial mesh.

Compute excitation current pattern for each port at $\omega = \omega_{test}$.

Test excitation signal at each port by comparing $\nabla \times \mathbf{H}$ to $\mathbf{E}$ and $\nabla \times \mathbf{E}$ to $\mathbf{H}$.

Acceptable?

No

Refine the mesh at the ports.

Yes

Compute field solution inside structure due to excitation at ports for $\omega = \omega_{test}$.

Compute S-matrix for $\omega = \omega_{test}$.

ΔS acceptable?

No

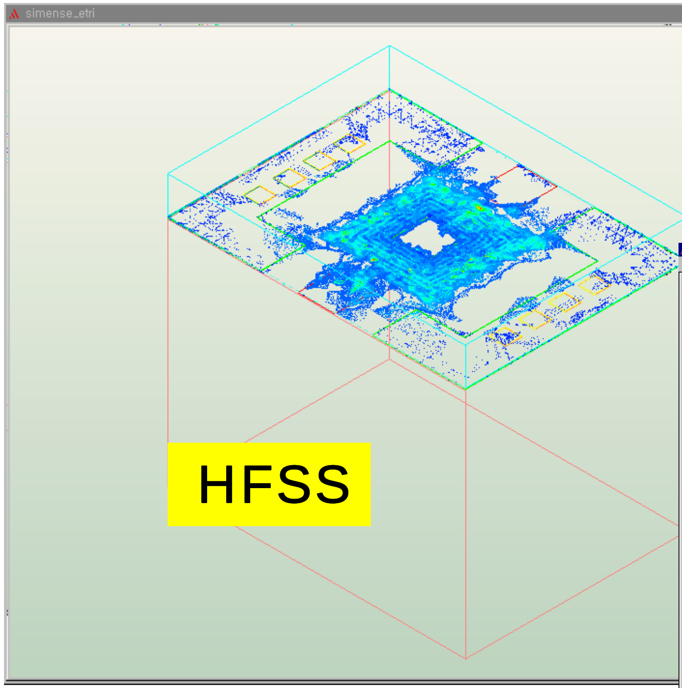
Refine the mesh inside the structure.

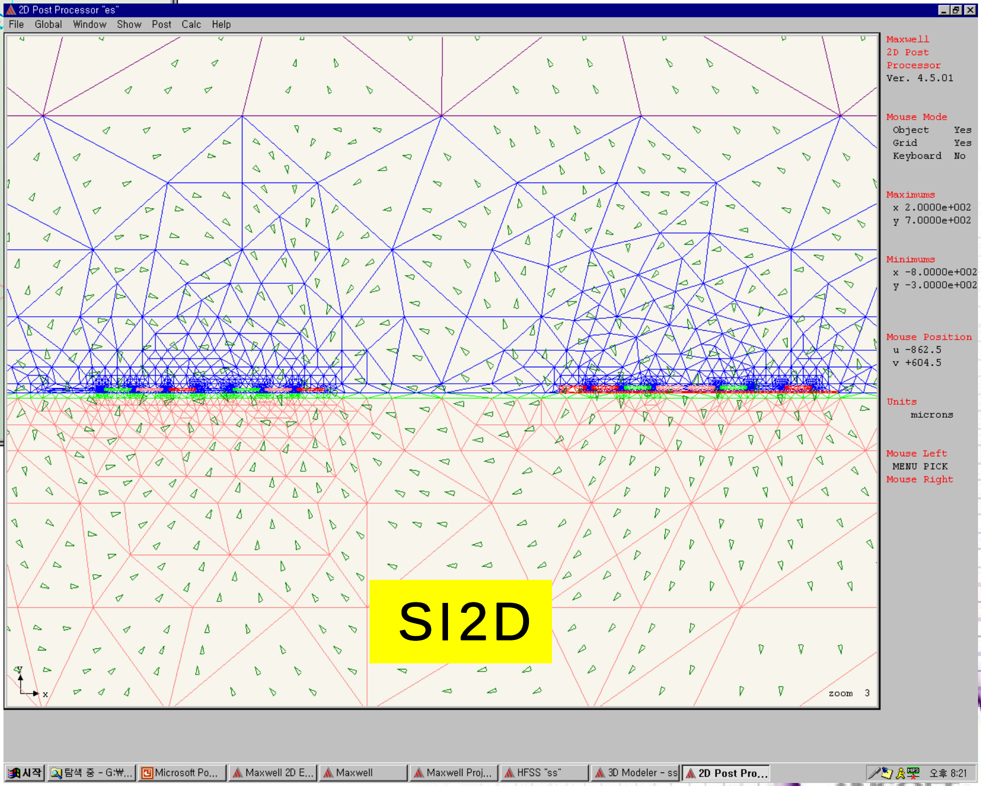
Yes

Perform frequency sweep if requested.

Make S-matrix available for viewing, renormalizing, and de-embedding. Allow user to analyze desired dominant or higher-order mode solution at a particular port associated with the last frequency for which a solution was generated.

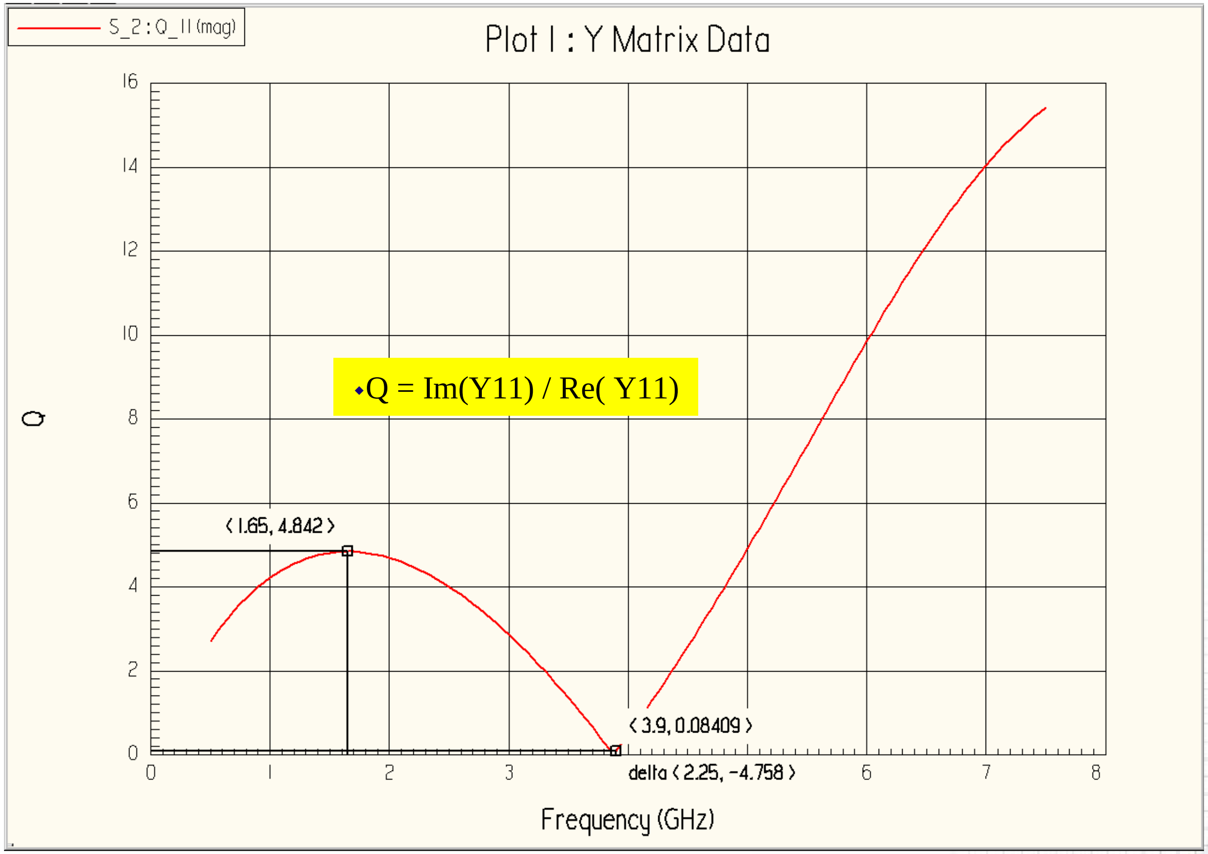
Spiral Inductor Design – Post-Processing (field plots)





```
Maxwell
2D Post
Processor
Ver. 4.5.01

Mouse Mode
 Object    Yes
 Grid      Yes
 Keyboard  No

Maximums
 x 2.0000e+002
 y 7.0000e+002

Minimums
 x -8.0000e+002
 y -3.0000e+002

Mouse Position
 u -862.5
 v +604.5

Units
    microns

Mouse Left
 MENU PICK
Mouse Right
```

Spiral Inductor Design – Post-Processing (Quality factor)

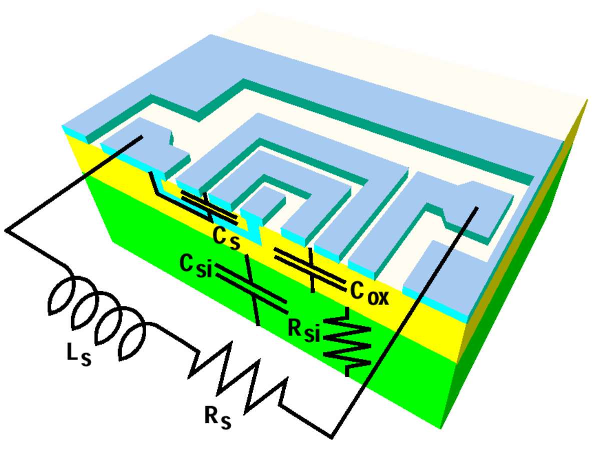


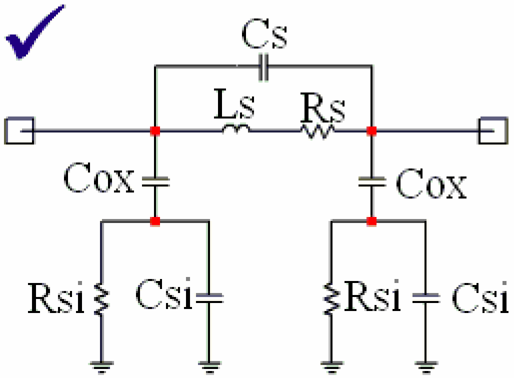
- Q = Im(Y11) / Re(Y11)

The maximum Q of the inductor is 4.842 at 1.65GHz. The resonant frequency is 3.9GHz.

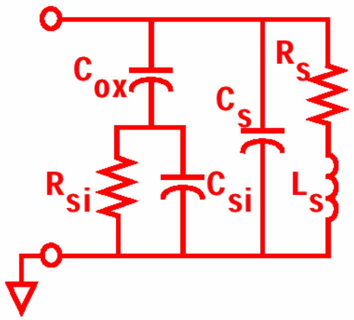
Spiral Inductor modeling - equivalent circuit model based on 3D EM

Model Description



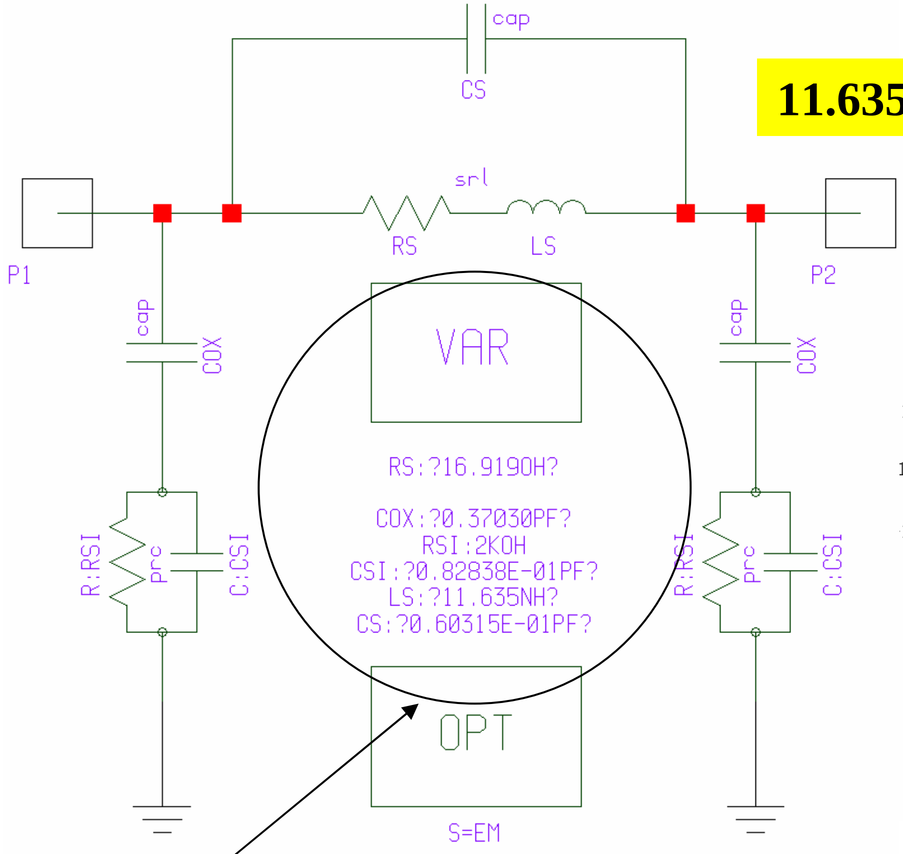


Model Description

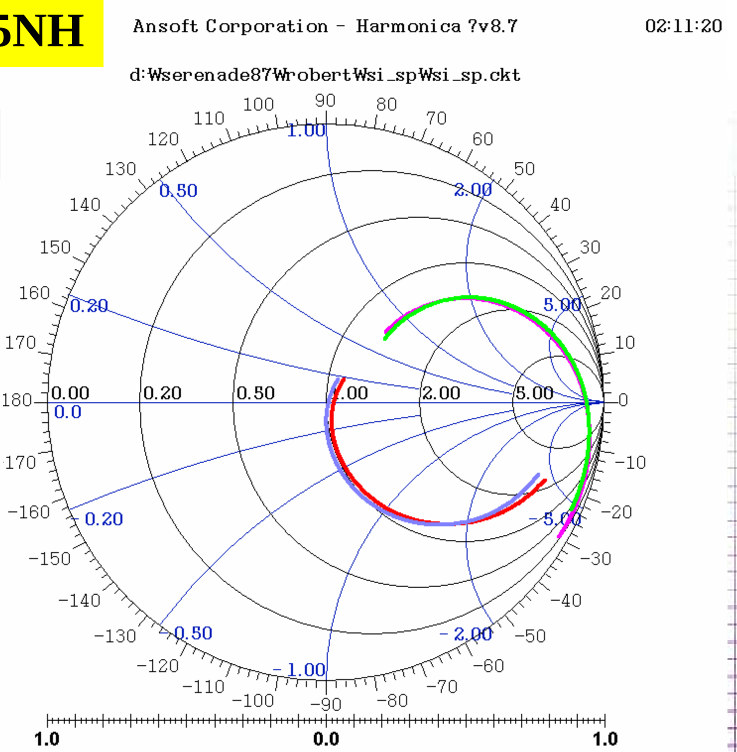
Physical Model of Inductor on Silicon		Effects
	L_s: Greenhouse Method	Mutual Couplings
	$R_s = \frac{\rho \cdot l}{w \cdot \delta \cdot (1 - e^{-t/\delta})}$	Eddy Current
	$C_s = n \cdot w^2 \cdot \frac{\varepsilon_{ox}}{t_{ox\ M1\text{-}M2}}$	Feed-Through Capacitance
	$C_{ox} = \frac{1}{2} \cdot l \cdot w \cdot \frac{\varepsilon_{ox}}{t_{ox}}$	Oxide Capacitance
	$C_{si} = \frac{1}{2} \cdot l \cdot w \cdot C_{Sub}$	Si Substrate Capacitance
	$R_{si} = \frac{2}{l \cdot w \cdot G_{Sub}}$	Si Substrate Ohmic Loss

- Silicon RFIC Spiral Inductor

Spiral Inductor modeling - equivalent circuit model based on 3D EM



11.635NH



Equivalent circuit parameter values determined by optimizing to fit EM simulation

Summary

EM Simulation is well suited for a variety of modeling activities including:

- Electrical/Thermal modeling of HBT
- Passive Component (i.e. spiral inductor) design and modeling
- HF Package Models
- Interconnect and substrate coupling analysis