SENTINEL
ic technologies

www.sentinel-ic.com

MAGNETO

A Front to Back Process Variation Aware SPICE Based Design System For Arbitrary EM Devices and Shapes

James Victory, Juan Cordovez, and Derek Shaeffer

Outline

1 Introduction to Magneto

2 Specific EM Solutions and Model Architecture

3 Tool Verification

4 Process Variation and Statistical Modeling

5 PDK Integration and Visualization Demos

Outline

1 Introduction to Magneto

2 Specific EM Solutions and Model Architecture

3 Tool Verification

4 Process Variation and Statistical Modeling

5 PDK Integration and Visualization Demos

Motivation for Magneto

Overcome Limitations of Commercial Passive Design Tools

- Standard Foundry-supplied models
  - Offer a limited set of device geometries, within restricted device topologies
  - Quality of the modeling often in doubt
  - Typically only inductors supported

- Advanced Inductor Synthesis Tools
  - Good models, but limited to specific topologies
  - Lumped-element models are static and usually require ‘curve-fitting’, fitting errors can compromise model accuracy
  - Often disconnected with Technology Model Library

Technology Model Library
- Where the device SPICE models live......
- MOSFETs, BJTs, Varactors, Resistors, etc.
- Corner, Local and Global Statistical Models

- Electromagnetic Solvers
  - Excellent model accuracy for S-parameter models, however, can pose problems for some simulator analyses
  - Flexible spice-element models rarely available
  - Exploring the ‘design space’ is very time consuming
  - Disconnect with technology model library
  - Disconnects in PDK integration, particularly in back-end design & physical verification

What is Magneto?

SENTINEL
ic technologies

A Fast and Powerful Quasi-Static EM Modeling Tool that covers…

- Self and mutual inductance based on the Neumann method
- Skin and proximity effects through robust ladder networks and coupled eddy-current loops
- Self and mutual capacitance through Poisson’s formulation
- Distributed substrate conductance and capacitance
- Top-side substrate contacts captured
- Ground Shields and backside ground planes supported
- Metal fill supported
- Arbitrary Devices and Shapes

And Generates Physically-Based SPICE models with…

- Full integration with technology model libraries
- Process variation captured and available for corner and statistical modeling
- Temperature dependence of material properties

Seamlessly Integrated in Your PDK…

- On the fly functionality enhancement for arbitrary PDK libraries or devices
- Flexible, non-intrusive integration without requirements for custom cells or 3rd party libraries
- Powerful visualization and optimization interfaces

Outline

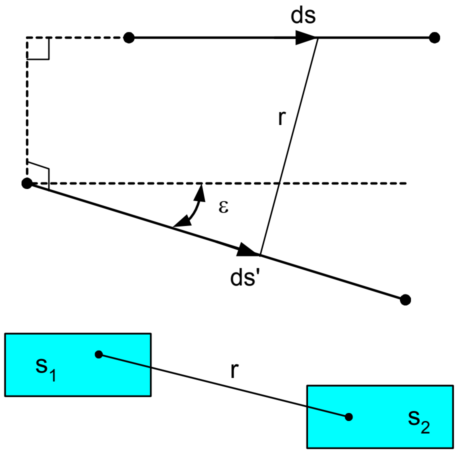
1. Introduction to Magneto
2. **Specific EM Solutions and Model Architecture**
3. Tool Verification
4. Process Variation and Statistical Modeling
5. PDK Integration and Visualization Demos

Magneto Inductance Solution

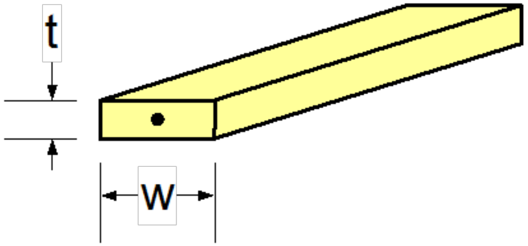
Neumann Formulation for Mutual Inductance

- ☐ Gives the mutual inductance of a pair of current filaments
- ☐ Closed-form solutions for many configurations have been provided by Grover
  - Parallel filaments of same length
  - Parallel filaments of different lengths
  - Filaments in any arbitrary orientation
- ☐ Solutions can be extended to finite cross-sections for parallel segments using Geometric Mean Distance (GMD)

$$M = \frac{\mu}{4\pi} \iint \frac{\cos\varepsilon}{r} \cdot ds ds'$$



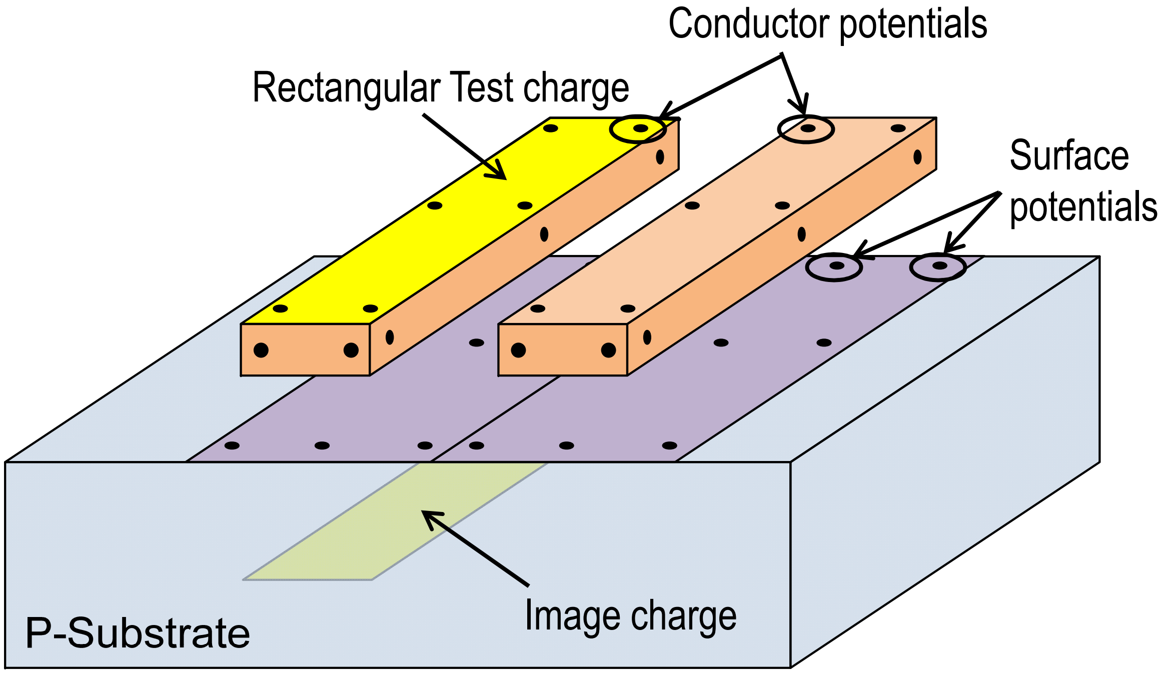
Grover-Greenhouse Formulation for Self-Inductance



$$L_s(l,w,t) = 2\times10^{-7}\cdot l \cdot \left[\ln\left(\frac{2l}{w+t}\right) + 0.5 + \frac{w+t}{3l} \right]$$

Magneto Capacitance Solution

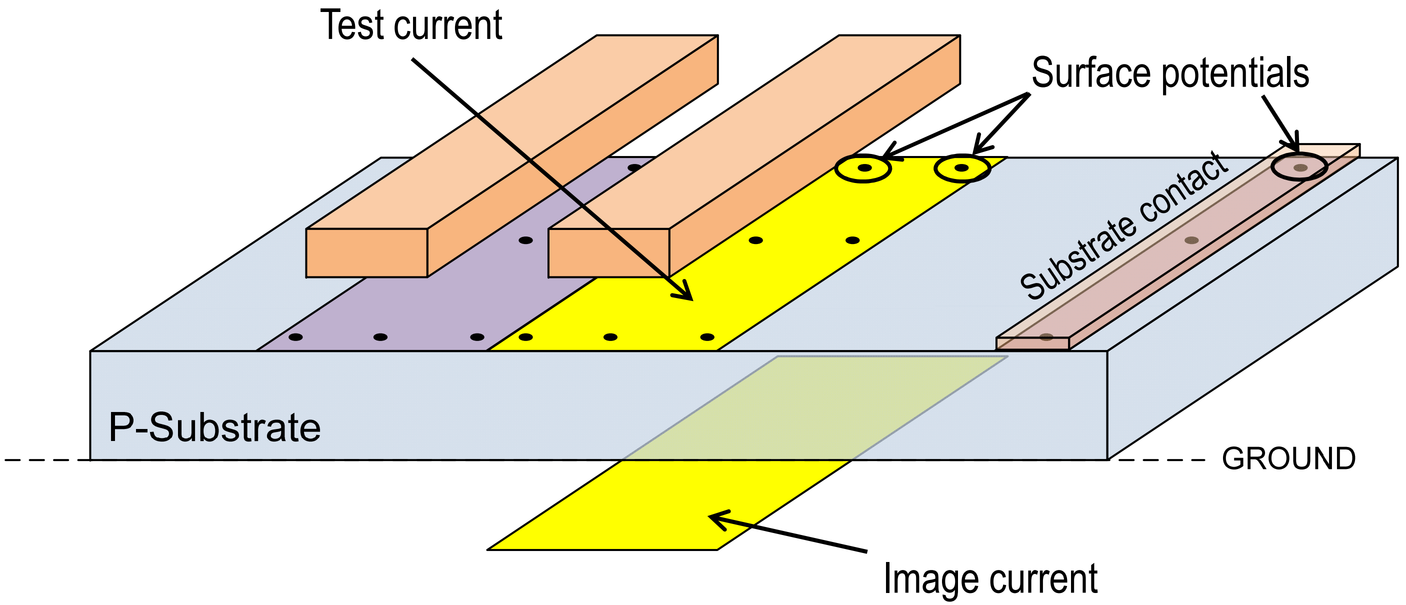
- Closed form Poisson's equation solution via Green's function defines potential and charge distribution
- Charge definitions κ: Area of each conductor substrate surface and conductor edges line charges
- Method of images accounts for substrate charge across oxide-silicon dielectric boundary
- Potentials definitions φ: Points located on conductor and substrate surface patches
- Potential vector is related to charge vector by a "Coefficients of Potential Matrix": P
- Geometric summation matrices for charge (X_Q) and potential (X_V) capture full distributed network



$$\begin{tikzcd}
 & \varphi = \mathbf{P}\boldsymbol{\kappa} \arrow[dd] & \\
\varphi = \mathbf{X}_V \mathbf{v} \arrow[dr] & & \mathbf{q} = \mathbf{X}_Q \boldsymbol{\kappa} \arrow[dl] \\
 & \mathbf{q} = \mathbf{C}\mathbf{v} \arrow[d] & \\
 & \boxed{\mathbf{C} = \mathbf{X}_Q \mathbf{P}^{+} \mathbf{X}_V} &
\end{tikzcd}$$

Magneto Substrate Solution

- ☐ Substrate conductance matrix solved analogous to capacitance solution: Replace Q with I, C with G
- ☐ Solve Green's function for a semi-infinite uniform bulk conductor
- ☐ Image currents account for the floating or grounded back-side connection
- ☐ Surface substrate contact supported for arbitrary shapes and distances



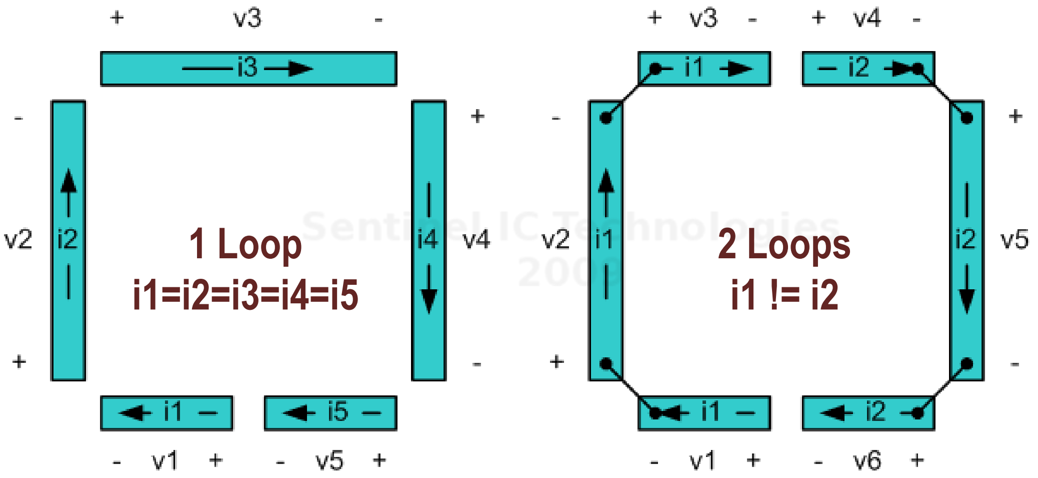
$$\boldsymbol{\varphi} = \mathbf{P}_{sub}\mathbf{i}$$

$$\downarrow$$

$$G = \mathbf{X}_I \mathbf{P}_{sub}{}^{+} \mathbf{X}_V$$

Generalization for Arbitrary EM devices: The Loop Concept

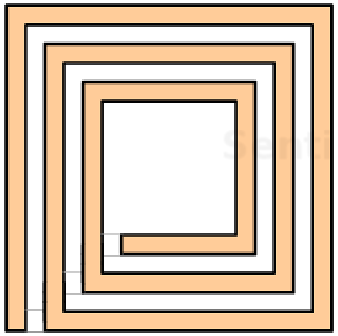
- ❑ **Component segments connected through *metal* are collected into *loop***
- ❑ **Loops have 2 ports where 1 port can be shared between loops**
- ❑ **Each loop treated for:**
  - ▪ **INTRA-loop self-coupling between *segments* and…**
  - ▪ **INTER-loop coupling**



1 Loop
i1=i2=i3=i4=i5

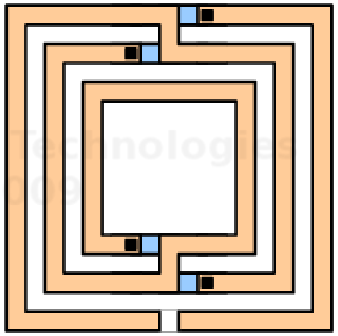
2 Loops
i1 != i2

Basic Spiral Inductor



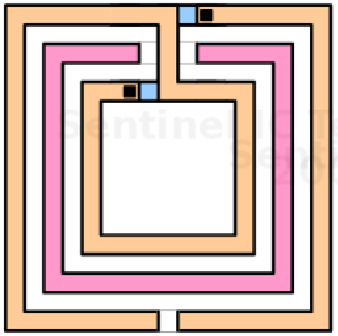
1 Loop

Symmetric Spiral



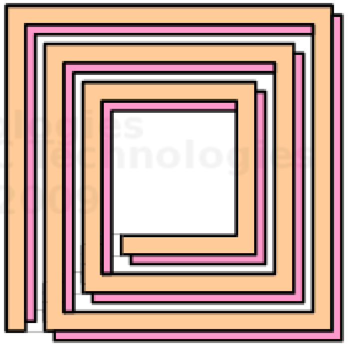
2 Loops (Virtual CT)
3 Loops (Drawn CT)

Symmetric Transformer



4 Loops (Virtual CTs)

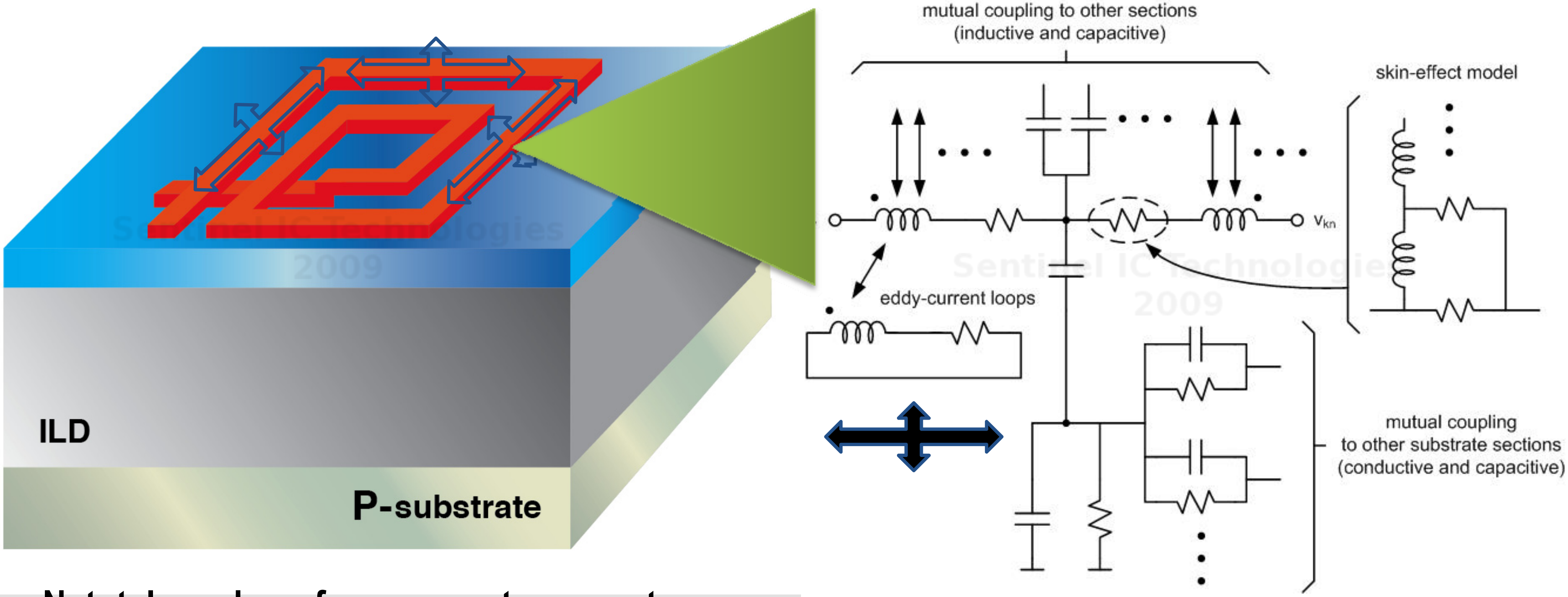
Finlay Transformer



2 Loops

Magneto Model Generation

- Each loop segment evaluated for L, R, C, G and mutual coupling to all other component segments
- Nth order matrix generated to give highly accurate distributed network
- Segments collected together in Loops, forming large L, R,C, G matrices.
- Matrix reduction to user specified model order provides compact subcircuits that accurately capture desired design space

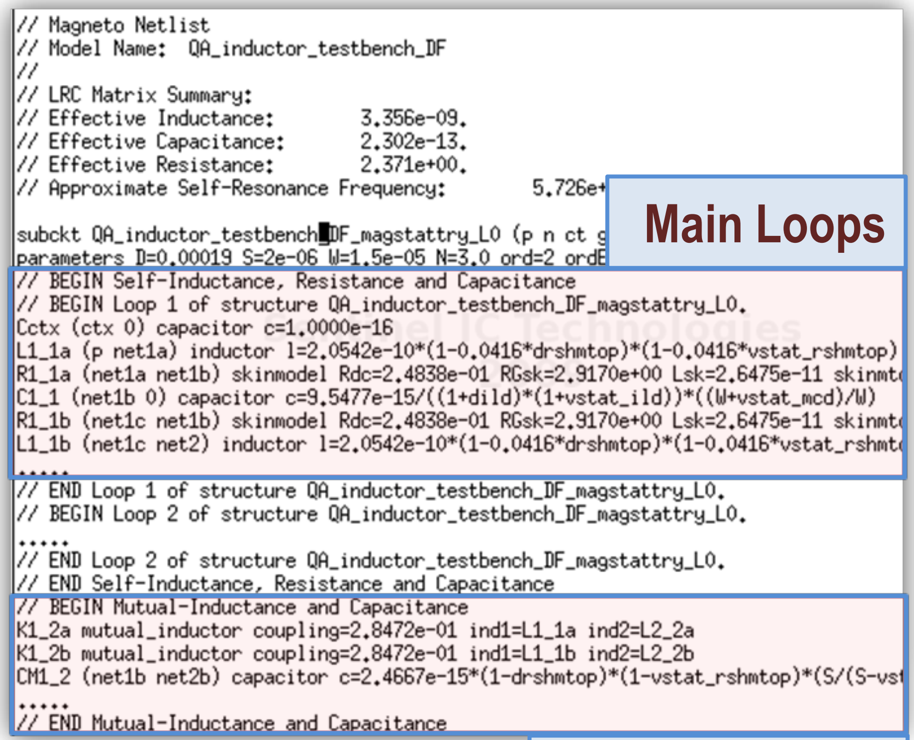


N=total number of component segments

Example Model Netlist

Models dynamically generated in quasi-real time depending on:

- Device topology and geometry
- Model order and proximity definition



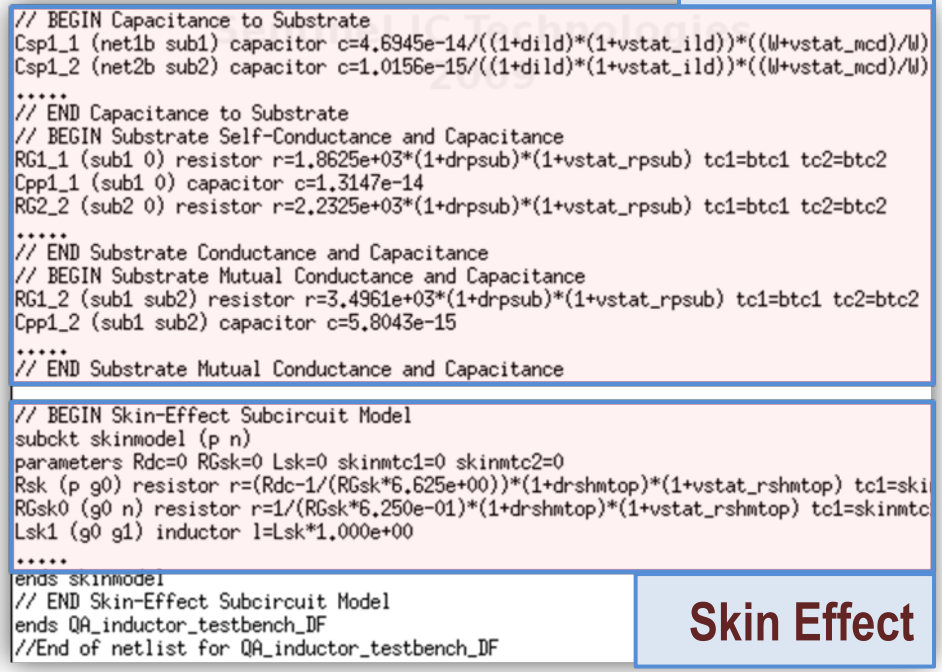
```
// Magneto Netlist
// Model Name:  QA_inductor_testbench_DF
//
// LRC Matrix Summary:
// Effective Inductance:        3.356e-09.
// Effective Capacitance:       2.302e-13.
// Effective Resistance:        2.371e+00.
// Approximate Self-Resonance Frequency:       5.726e+

subckt QA_inductor_testbench_DF_magstattry_L0 (p n ct g
parameters D=0.00019 S=2e-06 W=1.5e-05 N=3.0 ord=2 ordE
// BEGIN Self-Inductance, Resistance and Capacitance
// BEGIN Loop 1 of structure QA_inductor_testbench_DF_magstattry_L0.
Cctx (ctx 0) capacitor c=1.0000e-16
L1_1a (p net1a) inductor l=2.0542e-10*(1-0.0416*drshmtop)*(1-0.0416*vstat_rshmtop)
R1_1a (net1a net1b) skinmodel Rdc=2.4838e-01 RGsk=2.9170e+00 Lsk=2.6475e-11 skinmt
C1_1 (net1b 0) capacitor c=9.5477e-15/((1+dild)*(1+vstat_ild))*((W+vstat_mcd)/W)
R1_1b (net1c net1b) skinmodel Rdc=2.4838e-01 RGsk=2.9170e+00 Lsk=2.6475e-11 skinmt
L1_1b (net1c net2) inductor l=2.0542e-10*(1-0.0416*drshmtop)*(1-0.0416*vstat_rshmt
.....
// END Loop 1 of structure QA_inductor_testbench_DF_magstattry_L0.
// BEGIN Loop 2 of structure QA_inductor_testbench_DF_magstattry_L0.
.....
// END Loop 2 of structure QA_inductor_testbench_DF_magstattry_L0.
// END Self-Inductance, Resistance and Capacitance
// BEGIN Mutual-Inductance and Capacitance
K1_2a mutual_inductor coupling=2.8472e-01 ind1=L1_1a ind2=L2_2a
K1_2b mutual_inductor coupling=2.8472e-01 ind1=L1_1b ind2=L2_2b
CM1_2 (net1b net2b) capacitor c=2.4667e-15*(1-drshmtop)*(1-vstat_rshmtop)*(S/(S-vst
.....
// END Mutual-Inductance and Capacitance
```

Main Loops

Mutual L and C

Substrate



```
// BEGIN Capacitance to Substrate
Csp1_1 (net1b sub1) capacitor c=4.6945e-14/((1+dild)*(1+vstat_ild))*((W+vstat_mcd)/W)
Csp1_2 (net2b sub2) capacitor c=1.0156e-15/((1+dild)*(1+vstat_ild))*((W+vstat_mcd)/W)
.....
// END Capacitance to Substrate
// BEGIN Substrate Self-Conductance and Capacitance
RG1_1 (sub1 0) resistor r=1.8625e+03*(1+drpsub)*(1+vstat_rpsub) tc1=btc1 tc2=btc2
Cpp1_1 (sub1 0) capacitor c=1.3147e-14
RG2_2 (sub2 0) resistor r=2.2325e+03*(1+drpsub)*(1+vstat_rpsub) tc1=btc1 tc2=btc2
.....
// END Substrate Conductance and Capacitance
// BEGIN Substrate Mutual Conductance and Capacitance
RG1_2 (sub1 sub2) resistor r=3.4961e+03*(1+drpsub)*(1+vstat_rpsub) tc1=btc1 tc2=btc2
Cpp1_2 (sub1 sub2) capacitor c=5.8043e-15
.....
// END Substrate Mutual Conductance and Capacitance

// BEGIN Skin-Effect Subcircuit Model
subckt skinmodel (p n)
parameters Rdc=0 RGsk=0 Lsk=0 skinmtc1=0 skinmtc2=0
Rsk (p g0) resistor r=(Rdc-1/(RGsk*6.625e+00))*(1+drshmtop)*(1+vstat_rshmtop) tc1=ski
RGsk0 (g0 n) resistor r=1/(RGsk*6.250e-01)*(1+drshmtop)*(1+vstat_rshmtop) tc1=skinmtc
Lsk1 (g0 g1) inductor l=Lsk*1.000e+00
.....
ends skinmodel
// END Skin-Effect Subcircuit Model
ends QA_inductor_testbench_DF
//End of netlist for QA_inductor_testbench_DF
```

Skin Effect

*** Proximity Not Shown**

Magneto Technology File

Sample Magneto Input Technology File

```
% Substrate definitions
tech.SUBS_THICK=750e-6;          % Substrate thickness
tech.SUBS_ER=3.99;               % Substrate effective relative dielectric constant
tech.SUBS_BULK_ER=11.9;          % Substrate bulk layer effective relative dielectric constant
tech.SUBS_CONDUCTIVITY=5.33;     % Substrate conductivity in S/m

% Resistor temperature coefficients (metal resistance)
tech.TCR1=3.42e-3;               % Metal resistor temperature coefficient tc1
tech.TCR2=-1.117e-7;             % Metal resistor temperature coefficient tc2
tech.TCSR1=5.0e-4;               % Substrate resistance temperature coefficient tc2
tech.TCSR2=1.0e-6;               % Substrate resistance temperature coefficient tc1

% Metal Layer definitions
tech.M1=6;                                            % M1 layer: enumerated constant
tech.LAYER_NAME{tech.M1}='M1';                        % M1 layer: layer name
tech.LAYER_HEIGHT(tech.M1)=1.10e-6 + tech.SUBS_THICK; % M1 layer: layer height above ground
tech.LAYER_THICK(tech.M1)=0.53e-6;                    % M1 layer: layer thickness
tech.LAYER_COND(tech.M1)=2.42e7;                      % M1 layer: conductivity (S/m)
```

☐ Technology file may be defined independently OR work directly from the technology definitions available in parasitic extraction verification packages

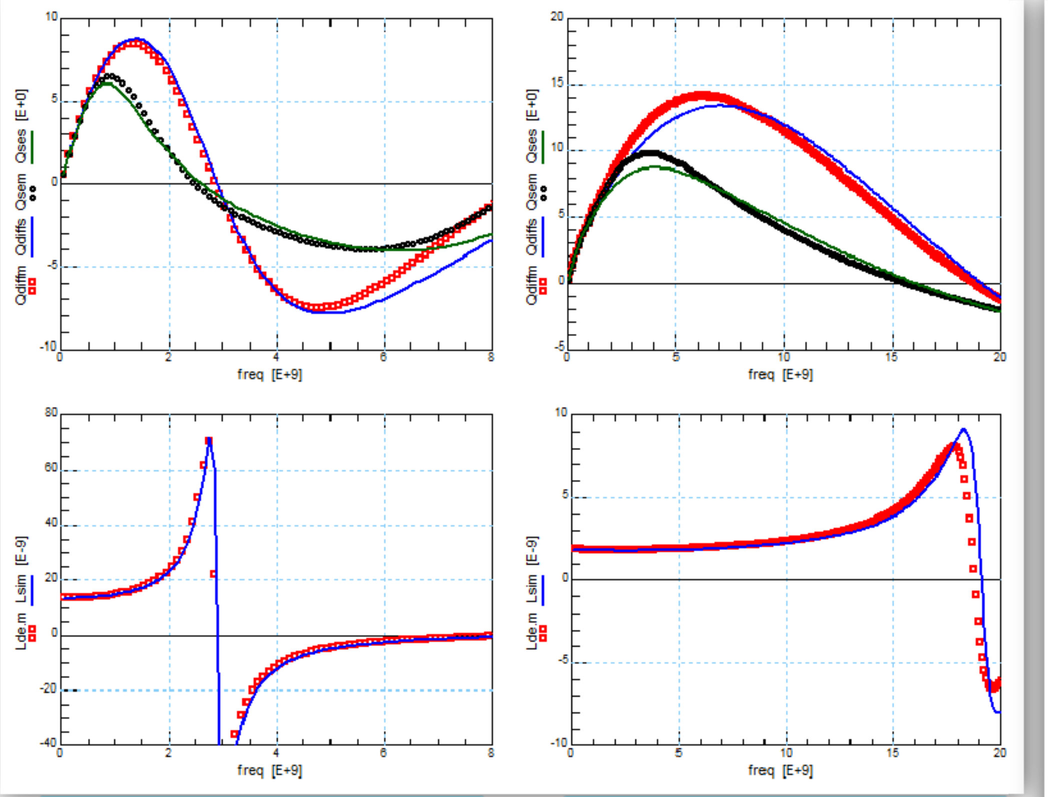
☐ Flexible support for wafer thinning and diverse packaging compounds

Outline

Magneto Model Verification

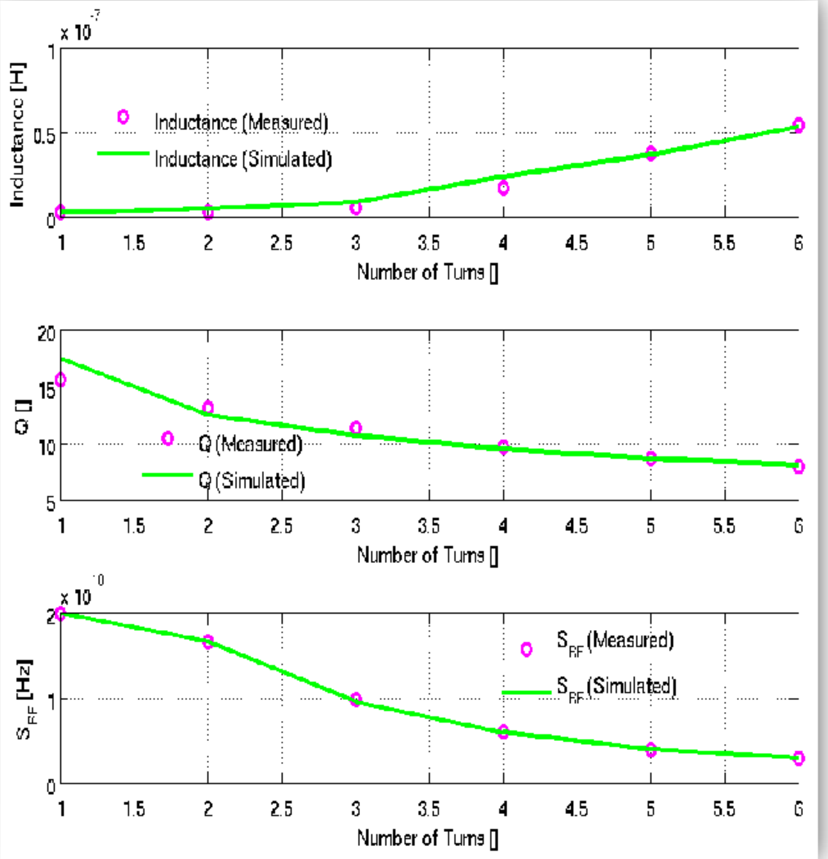
Asymmetric and Differential Q, L over Frequency

Qpk, L, SRF over Turns

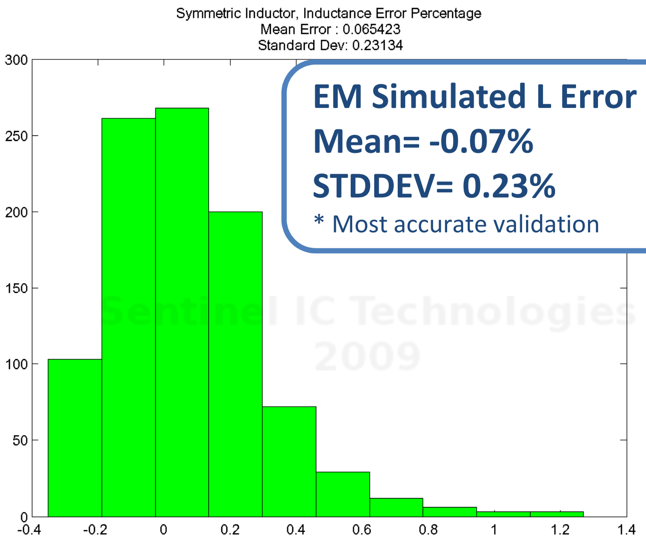


Large 16nH, 6 turn

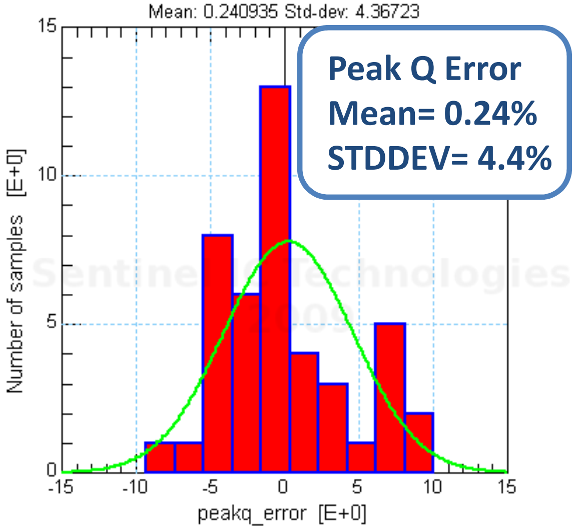
Small 2nH, 2 turn



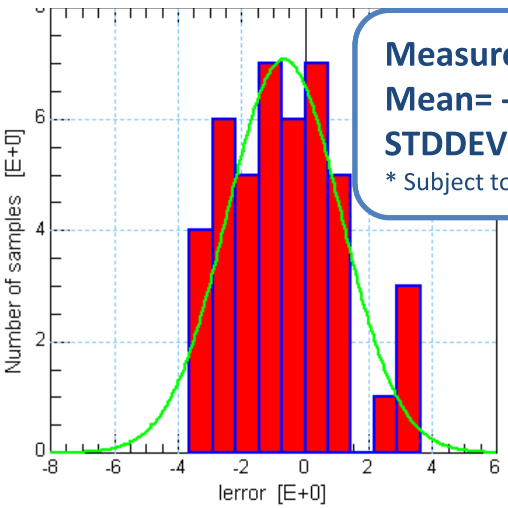
Extensive Inductor FOM Verification



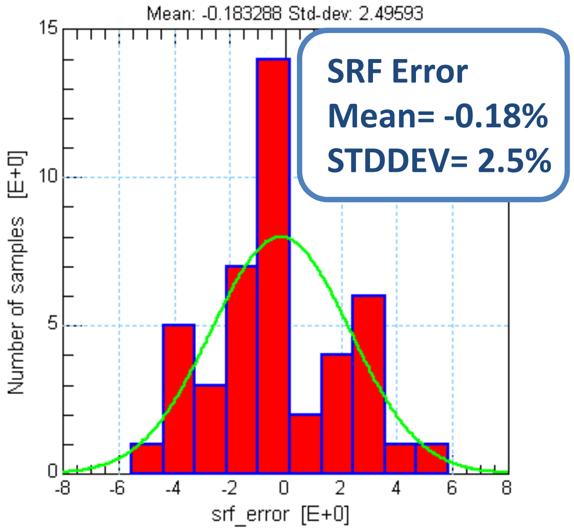
EM Simulated L Error
Mean= -0.07%
STDDEV= 0.23%
* Most accurate validation



Peak Q Error
Mean= 0.24%
STDDEV= 4.4%



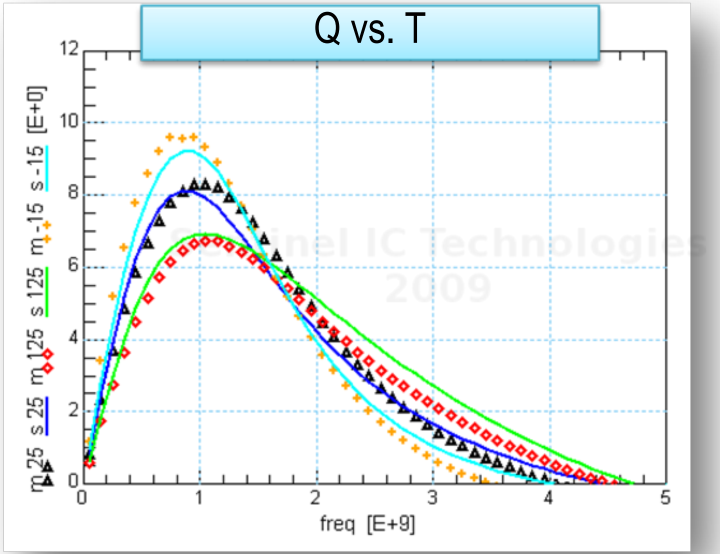
Measured L Error
Mean= -0.7%
STDDEV= 1.8%
* Subject to de-embedding errors

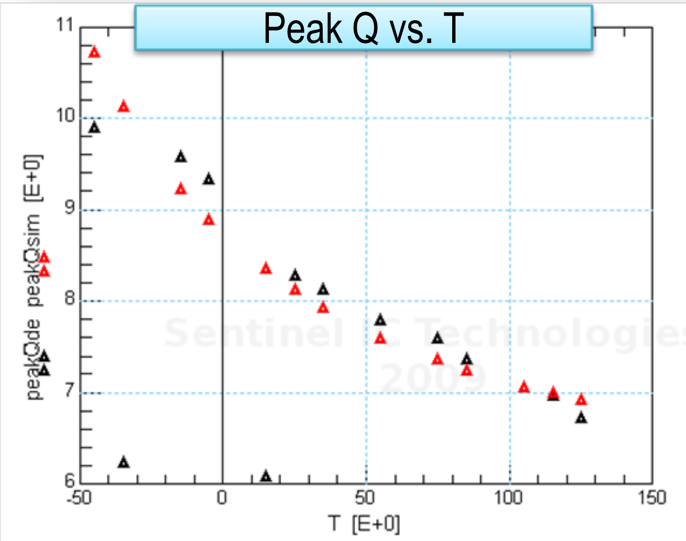


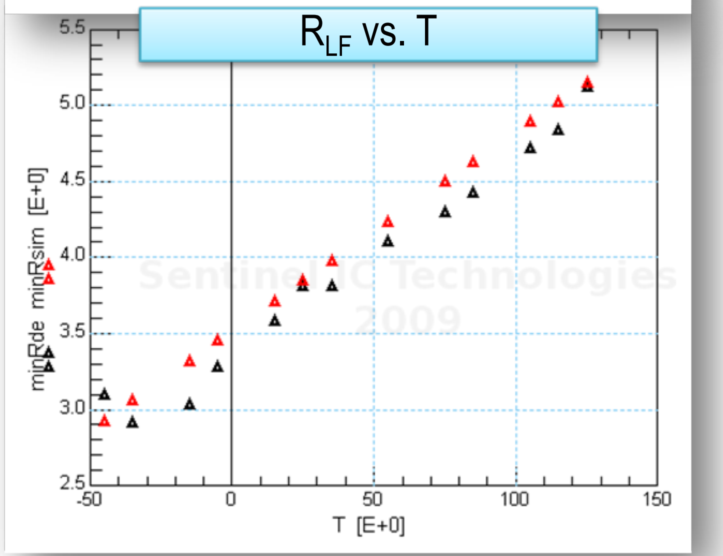
SRF Error
Mean= -0.18%
STDDEV= 2.5%

Magneto Temperature Model Validation

- RF validation performed over temperature
- Metal resistance TCs validated with low frequency resistance and Q
- Substrate resistance TCs extracted and validated with Q roll-off at high frequency

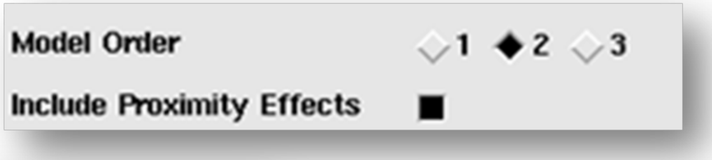

Q vs. T


Peak Q vs. T


R_{LF} vs. T

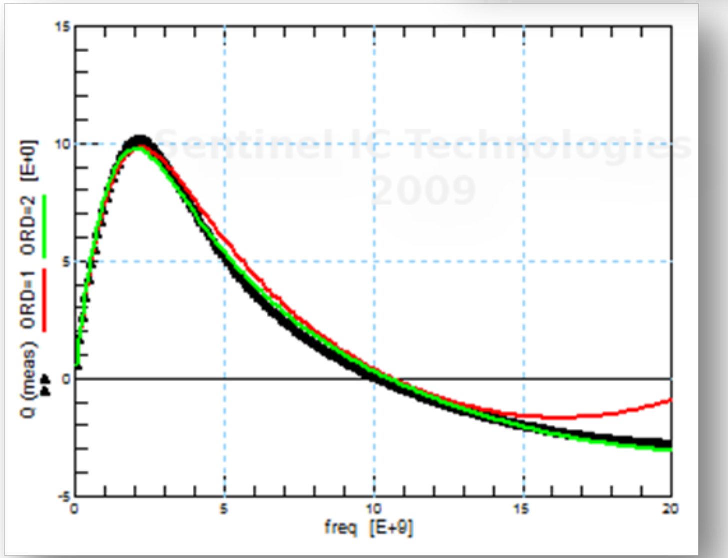
Flexible Model Order Definition

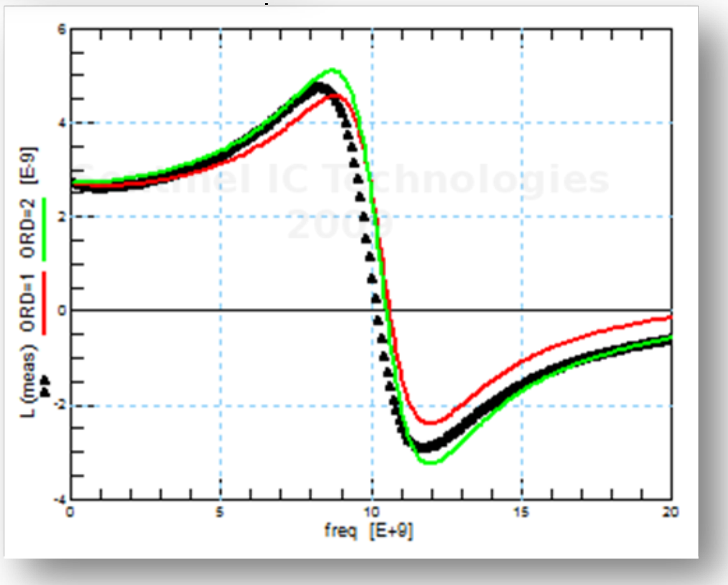
- ☐ **Model Order determines number of distributed networks**
  - Higher Model Order provides more broadband accuracy
- ☐ **Proximity Switch turns on or off proximity effects**
  - Trade-off accuracy for model complexity



Model Order ◇ 1 ◆ 2 ◇ 3

Include Proximity Effects ■





Outline

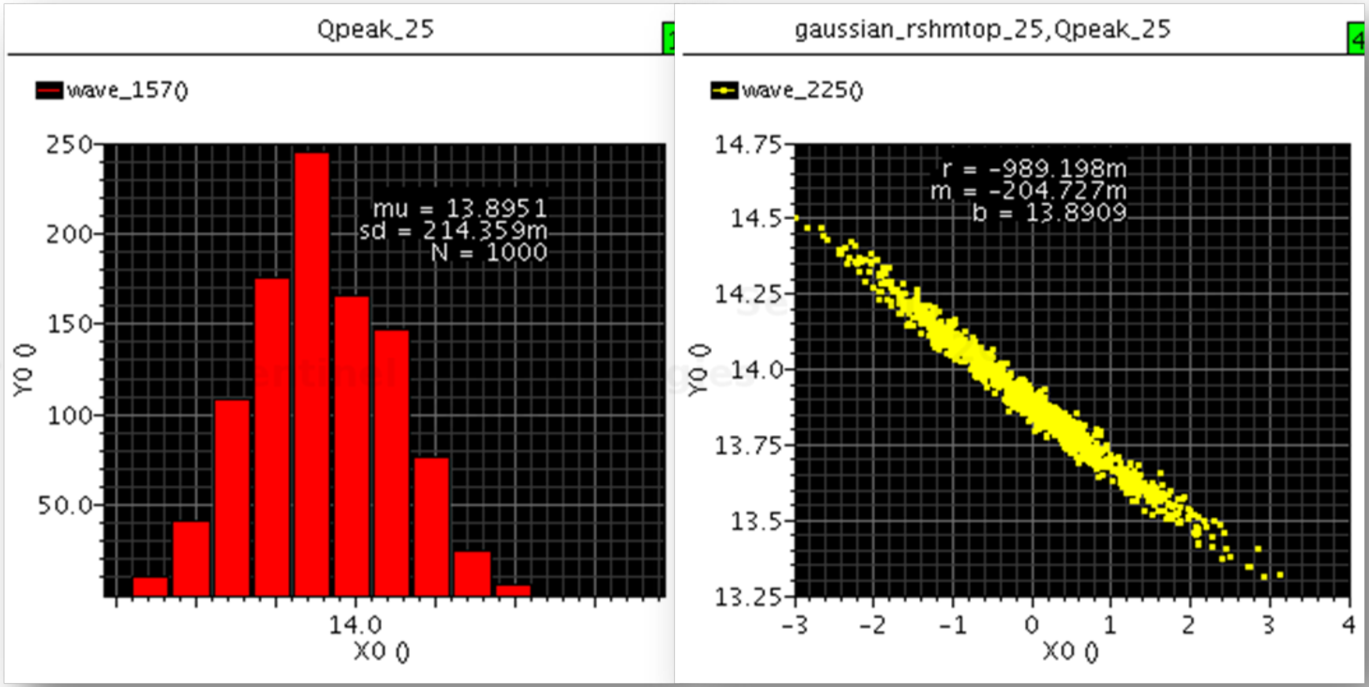
1	Introduction to Magneto
2	Specific EM Solutions and Model Architecture
3	Tool Verification
4	**Process Variation and Statistical Modeling**
5	PDK Integration and Visualization Demos

Magneto: Process Variation Aware!

Magneto advances the state of the art:

- First time “EM” tool with full access to process parameters and technology specifications
- Tight integration of EM model files with technology model library
- Enables sensitivity and yield analysis for RF circuit performance including EM device process variation AND correlation with other BEOL devices (example: MiM)

Magneto Process Parameters
ILD Thickness
Metal Thickness/Sheet Resistance
Via Resistance
Metal CD
Substrate Resistivity



Process Variation Case Study

Mutual Capacitance Variation: M_h and M_{CD}

Physical Process Parameters

M_h: Metal Thickness

M_{CD}: Metal Critical Dimension

Implement through FPV

M_h and M_{CD} available from:

- **Inline** (direct physical measurement)
- **PCM** (derived from electrical measurement)
- **Example: Mh derived from ρsh**

Simplified physical equations:

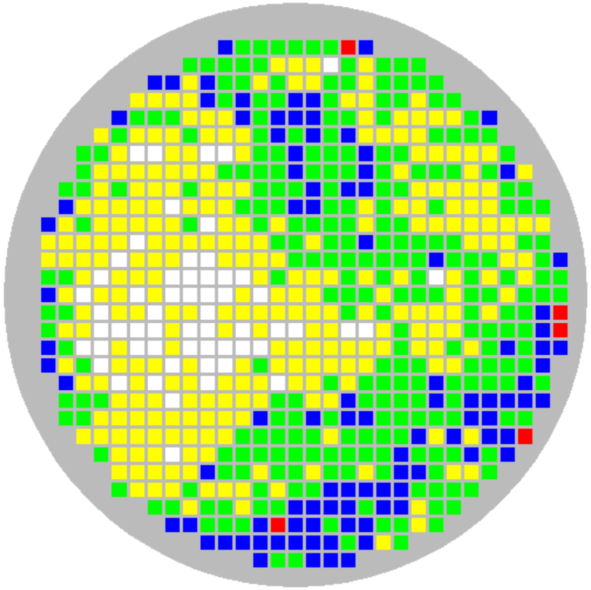
$$CM = \frac{\varepsilon}{S} \cdot M_h$$ (mutual capacitance/length)

$$S = S_{dr} - M_{CD}$$ (metal spacing = drawn – MCD)

$$CM_{value} = CM_{nom} \cdot \left(1 + \frac{dM_h}{M_{hnom}}\right) \cdot \left(\frac{S_{dr}}{S_{dr} - M_{CD}}\right)$$

$$\rho_{sh} = \frac{\rho}{M_h} \Longrightarrow \frac{dM_h}{M_h} = -\frac{d\rho_{sh}}{\rho_{sh}}$$

$$\boxed{CM_{value} = CM_{nom} \cdot \left(1 - \frac{d\rho_{sh}}{\rho_{sh}}\right) \cdot \left(\frac{S_{dr}}{S_{dr} - M_{CD}}\right)}$$



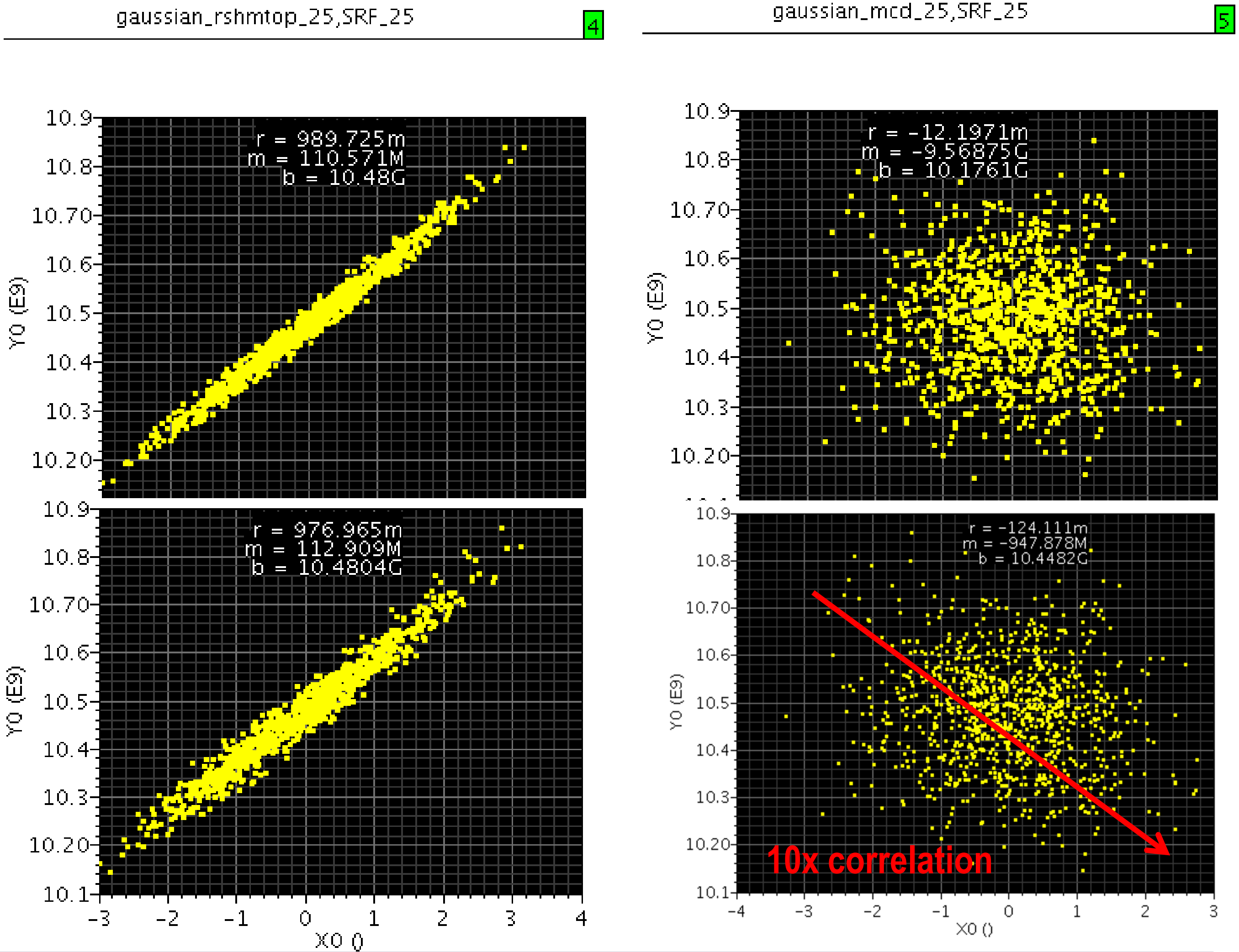
**Approximation: ignores conductivity variation, CD effects on measurements

Process Parameter Case Study

Mutual Capacitance Variation: Mh or MCD?

Process 1
180nm RFCMOS

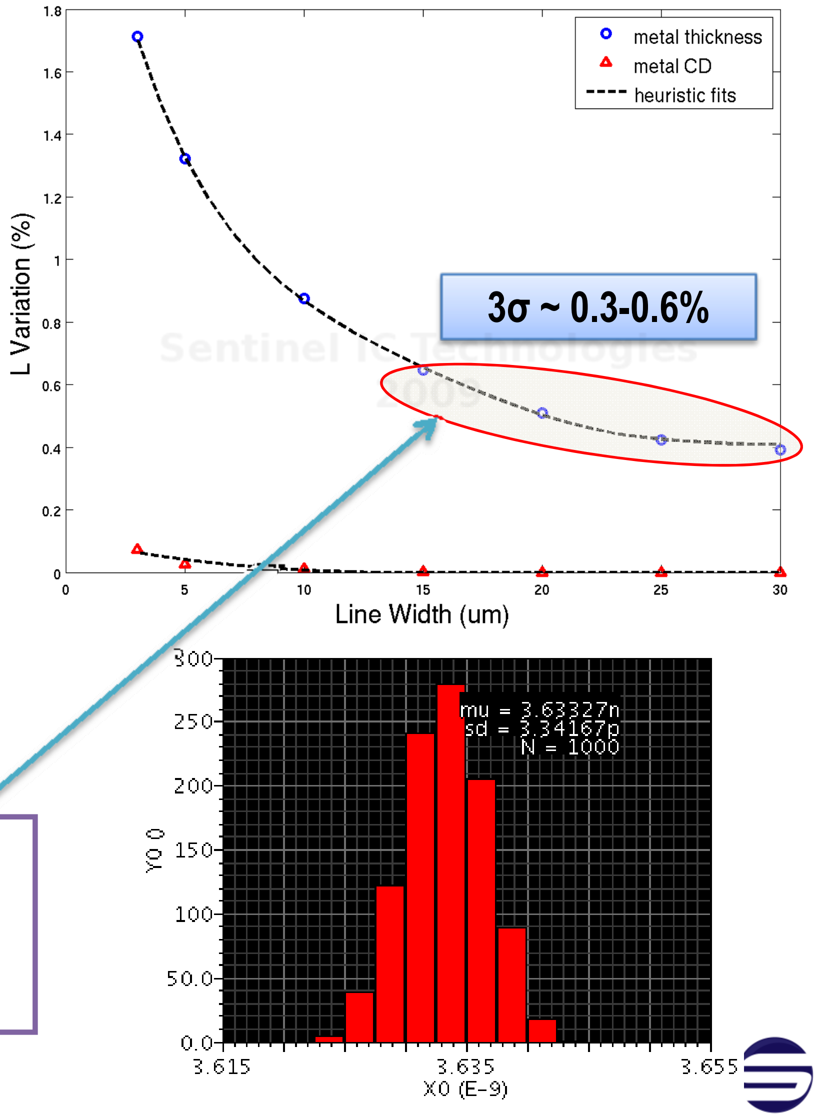
Process 2
Increase MCD 3X
Decrease Spacing 2X



Conclusion: OK to Ignore MCD Variation for Typical Technologies

Inductance Variation

- ☐ Simple incorporation not apparent due to L_{self} log dependence of width, height and length of conductor.
- ☐ Magneto serves as highly accurate “TCAD” tool
  - Vary physical process parameters metal thickness and CD
  - Observe simulated inductance variation
- ☐ Simulation confirms:
  - Variation due to metal CD negligible
- ☐ Simple heuristic fits constructed and applied to model components



3σ ~ 0.3-0.6%

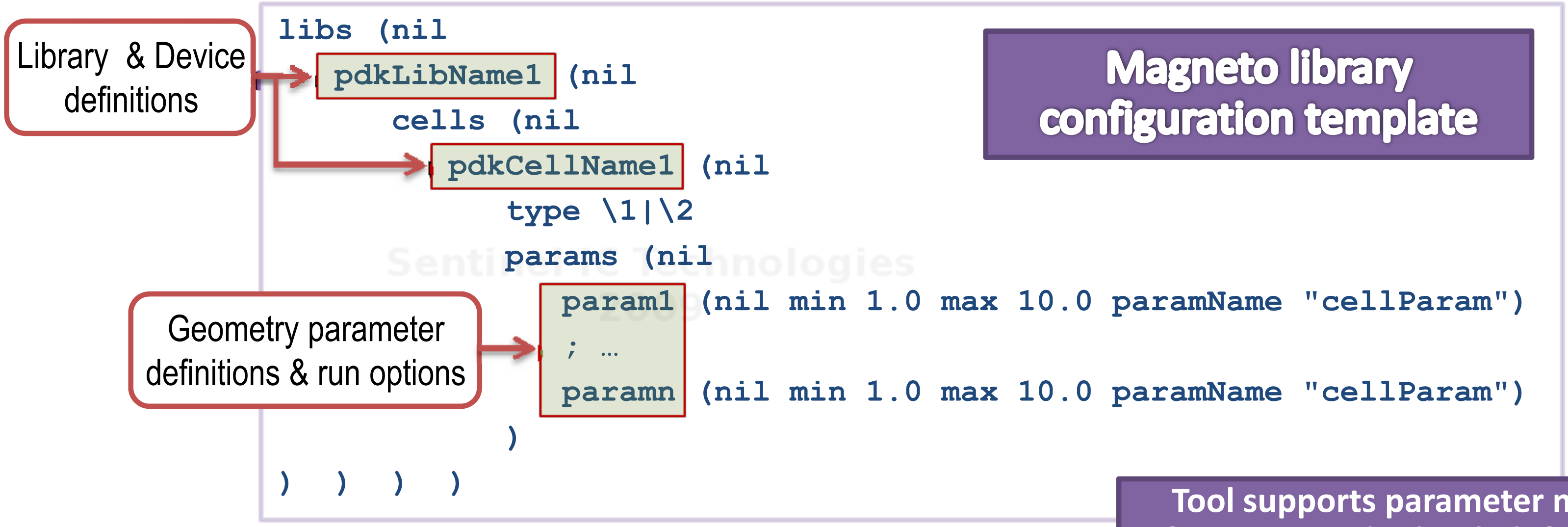
mu = 3.63327n
sd = 3.34167p
N = 1000

- ☐ Typical VCO Inductor has 0.3-0.6% 3σ variation
- ☐ Not uncommon to see foundry models with empirical 1-5% directly leading to Over Design

Outline

Flexible Integration into Cadence®

- ☐ Magneto functionality enhancement may be added to any library element, on-the-fly & non intrusively
- ☐ Magneto automation handles all interactions between Cadence views including:
  - Seamless synthesis of passive models based on CDF definitions
  - Feedback of key device figures of merit into CDFs
  - Inclusion of models into simulator(s) path definitions
  - Robust routine execution definitions & revision control methodology
- ☐ Support for multiple simulators including generic spice syntax acceptable to Spectre® and ADS®



Library & Device definitions

Geometry parameter definitions & run options

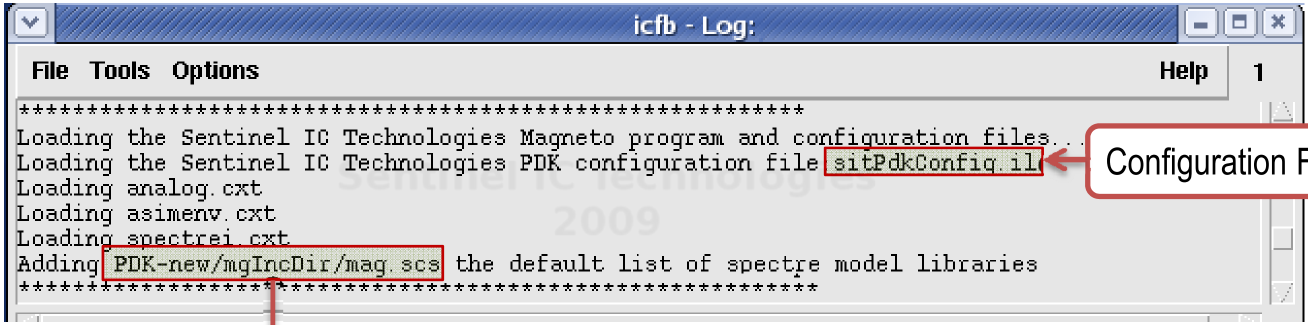
```
libs (nil
  pdkLibName1 (nil
      cells (nil
        pdkCellName1 (nil
            type \1|\2
            params (nil
              param1 (nil min 1.0 max 10.0 paramName "cellParam")
              ; …
              paramn (nil min 1.0 max 10.0 paramName "cellParam")
            )
) ) ) )
```

Magneto library configuration template

Tool supports parameter mapping, factoring, and other helpful utilities

Flexible Integration into Cadence® (2)

Sample Magneto ICFB Load View



```
*********************************************************
Loading the Sentinel IC Technologies Magneto program and configuration files...
Loading the Sentinel IC Technologies PDK configuration file sitPdkConfig.il
Loading analog.cxt
Loading asimenv.cxt
Loading spectrei.cxt
Adding PDK-new/mgIncDir/mag.scs the default list of spectre model libraries
**********************************************************
```

Configuration File

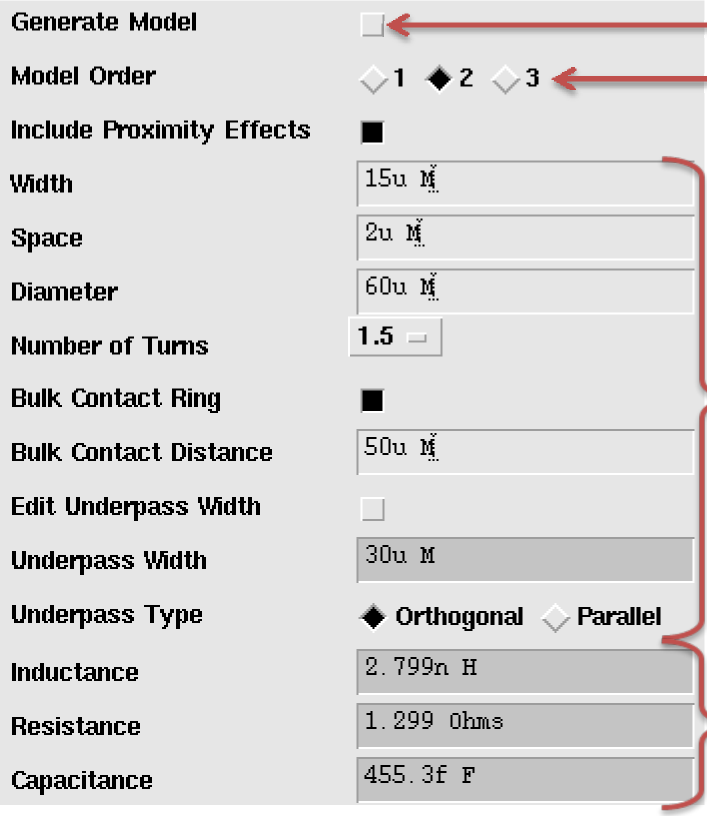
Sample Magneto Spectre Device Include File

```
*********************************************************************
* Sentinel IC Technologies, Inc. Magneto Subckt Include File        *
*********************************************************************
include “lib_cellName_basicSpiral_L0.scs”
include “lib_cellName_symmetricSpiral_L1.scs”
include “lib_cellName_symmetricTransformer_L2.scs”
include “lib_cellName_finlayTransformer_L3.scs”
```

Synthesized Models

Magneto Inductor Device Example

Sample Device CDF



Generate Model	☐
Model Order	○ 1 ● 2 ○ 3
Include Proximity Effects	■
Width	15u M
Space	2u M
Diameter	60u M
Number of Turns	1.5
Bulk Contact Ring	■
Bulk Contact Distance	50u M
Edit Underpass Width	☐
Underpass Width	30u M
Underpass Type	● Orthogonal ○ Parallel
Inductance	2.799n H
Resistance	1.299 Ohms
Capacitance	455.3f F

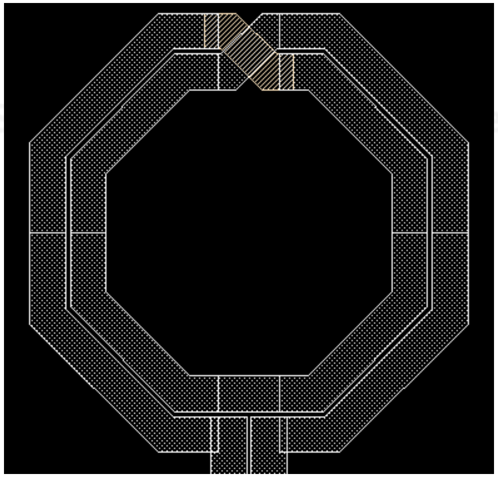
Model Generation Switch

User Selectable Model Precision vs. Simulation Speed Trade Off

Physical Parameters for Model Generation

Up-to-date Figures of Merit

Sample Scalable Layout



Demo # 1:
Performance Exploration & Optimization

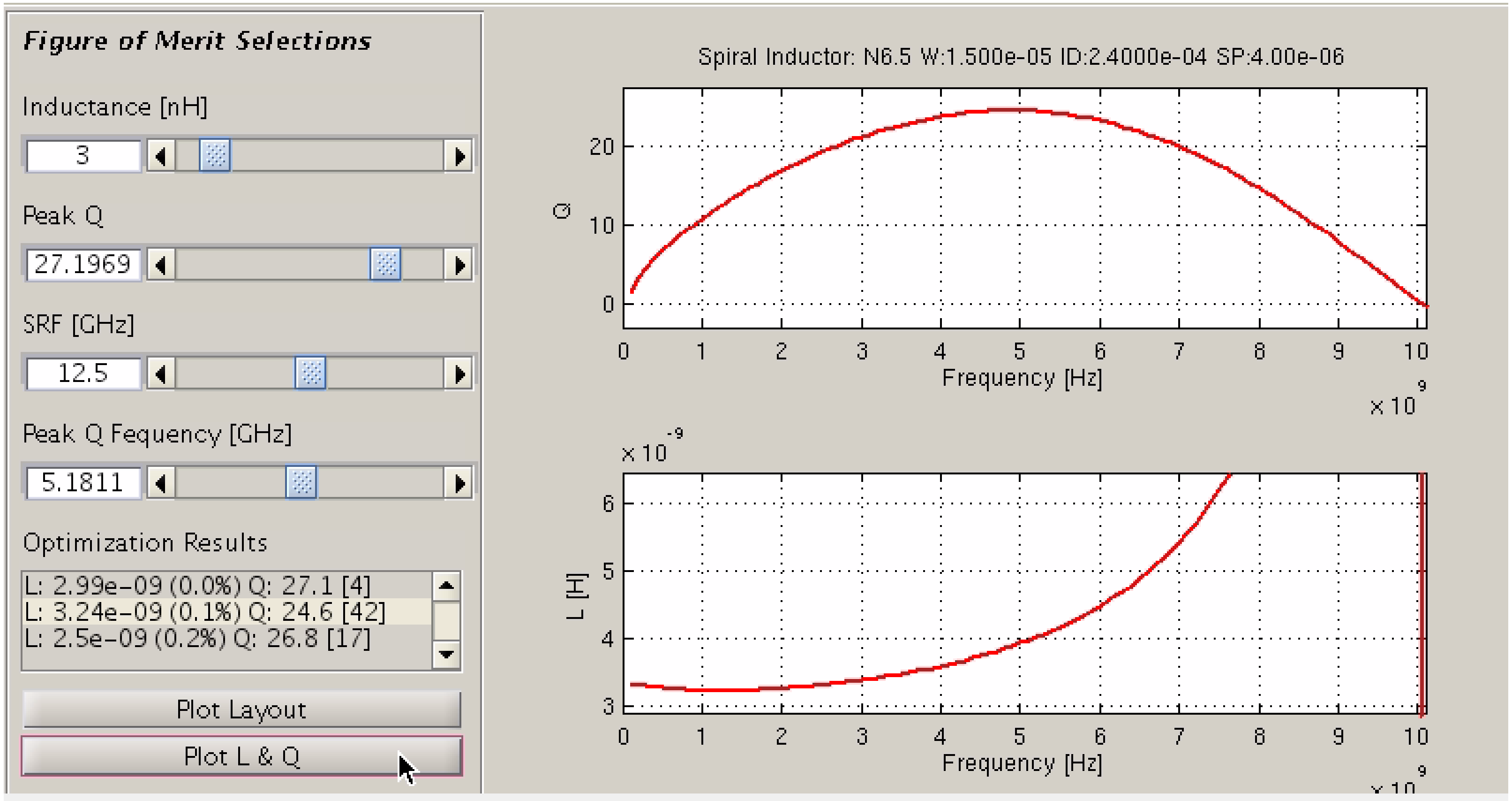


Figure of Merit Selections

Inductance [nH]: 3

Peak Q: 27.1969

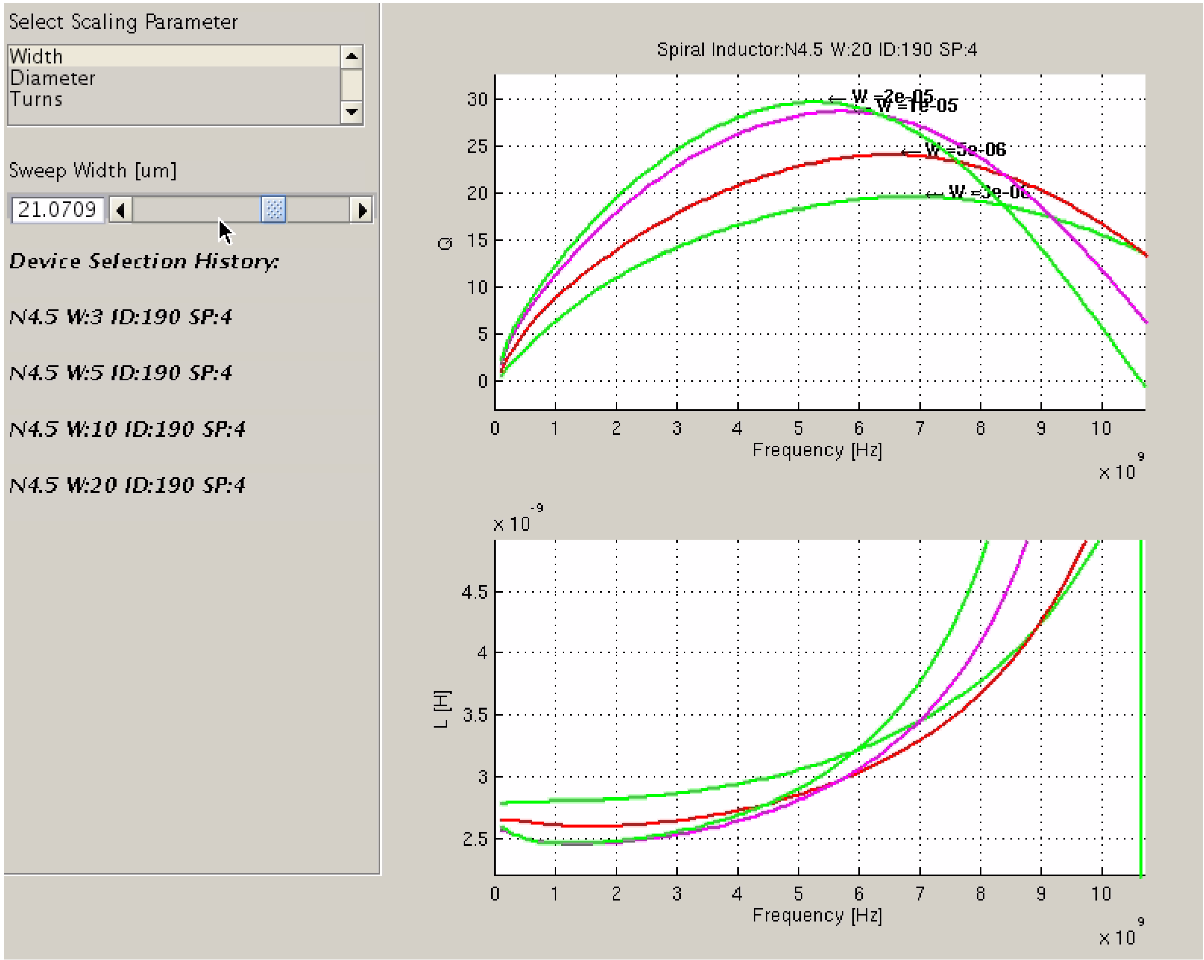
SRF [GHz]: 12.5

Peak Q Fequency [GHz]: 5.1811

Optimization Results

L: 2.99e−09 (0.0%) Q: 27.1 [4]
L: 3.24e−09 (0.1%) Q: 24.6 [42]
L: 2.5e−09 (0.2%) Q: 26.8 [17]

Demo # 2:
Inductor Design Space Visualization



Select Scaling Parameter

- Width
- Diameter
- Turns

Sweep Width [um]: 21.0709

Device Selection History:

N4.5 W:3 ID:190 SP:4

N4.5 W:5 ID:190 SP:4

N4.5 W:10 ID:190 SP:4

N4.5 W:20 ID:190 SP:4

Summary

Magneto

A Front to Back Process Variation Aware SPICE Based Design System For Arbitrary EM Devices and Shapes

- ☐ Comprehensive Treatment of EM effects
- ☐ Generated SPICE Models: Accurate and Flexible
- ☐ EM Device Process Variation and Correlation Captured
- ☐ Adaptive, Seamless PDK Integration and Design Interfaces

Acknowledgements

Thank You

GRACE Semiconductor

Silicon, Test Structure Generation and Measurements

Plamen Kolev

Test Structure Generation

References

1. Derek K. Shaeffer, “Monolithic Inductor and Transformer Modeling for Dummies”, 2007 RFIC Workshop, June 2007
2. S. Bantas, “Rapid On-Chip Electromagnetic Extraction and Compact Modeling with Guaranteed Passivity”, MOS-AK Workshop, September 2009
3. H.M. Greenhouse, “Design of Planar Rectangular Microelectronic Inductors”, *IEEE Transactions on Parts, Hybrids and Packaging*, vol. PHP-10, no. 2, June 1974, pp. 101-109.
4. Frederick W. Grover, *Inductance Calculations*, D. Van Nostrand Co., New York: 1946.
5. Simon Ramo, John R. Whinnery and Theodore van Duzer, *Fields and Waves in Communication Electronics*, John Wiley & Sons, Inc., New York: 1965.
6. Albert E. Ruehli, “Equivalent Circuit Models for Three-Dimensional Multiconductor Systems,” *IEEE Transactions on Microwave Theory and Techniques*, vol. MTT-22, no. 3, March 1974, pp. 216-221.
7. Albert E. Ruehli and Pierce A. Brennan, “Efficient Capacitance Calculations for Three-Dimensional Multiconductor Systems,” *IEEE Transactions on Microwave Theory and Techniques*, vol. MTT-21, no. 2, February 1973, pp. 76-82.
8. S. S. Mohan, et al., “Simple Accurate Expressions for Planar Spiral Inductances,” *IEEE Journal of Solid-State Circuits*, vol. 34, no. 10, October 1999, pp. 1419-1424.
9. Ali M. Niknejad and Robert G. Meyer, “Analysis, Design and Optimization of Spiral Inductors and Transformers for Si RF IC’s,” *IEEE Journal of Solid-State Circuits*, vol. 33, no. 10, October 1998, pp. 1470-1481.
10. Ali M. Niknejad, Ranjit Gharpurey, and Robert G. Meyer, “Numerically Stable Green Function for Modeling and Analysis of Substrate Coupling in Integrated Circuits,” *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems*, vol. 17, no. 4, April 1998, pp. 305-315.
11. Jue-Hsien Chern, et al., “Multilevel Metal Capacitance Models for CAD Design Synthesis Systems,” *IEEE Electron Device Letters*, vol. 13, no. 1, January 1992, pp. 32-34.

References (cont.)

10. William B. Kuhn and Noureddin M. Ibrahim, “Analysis of Current Crowding Effects in Multiturn Spiral Inductors,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 49, no. 1, January 2001, pp. 31-38.
11. Kirk B. Ashby, et al., “High Q Inductors for Wireless Applications in a Complementary Silicon Bipolar Process,” *IEEE Journal of Solid-State Circuits*, vol. 31, no. 1, January 1996, pp. 4-9.
12. Yu Cao, et al., “Frequency-Independent Equivalent-Circuit Model for On-Chip Spiral Inductors,” *IEEE Journal of Solid-State Circuits*, vol. 38, no. 3, March 2003, pp. 419-426.
13. C. Patrick Yue and S. Simon Wong, “On-Chip Spiral Inductors with Patterned Ground Shields for Si-Based RF IC’s,” *IEEE Journal of Solid-State Circuits*, vol. 33, no. 5, May 1998, pp. 743-752.
14. John R. Long, “Monolithic Transformers for Silicon RF IC Design,” *IEEE Journal of Solid-State Circuits*, vol. 35, no. 9, September 2000, pp. 1368-1382.

SENTINEL

ic technologies

Thank you

For additional information please visit us at

www.sentinel-ic.com