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

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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

- **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

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

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
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2. **Specific EM Solutions and Model Architecture**
3. Tool Verification
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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)

Grover-Greenhouse Formulation for Self-Inductance

\[
L_s(l, w, t) = 2 \times 10^{-7} \cdot l \cdot \left[ \ln\left( \frac{2l}{w+t} \right) + 0.5 + \frac{w+t}{3l} \right]
\]
Magneto Capacitance Solution

- Closed form Poisson’s equation solution via Green’s function defines potential and charge distribution
- Charge definitions $\kappa$: 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 $\phi$: 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

\[
\phi = P \kappa
\]
\[
\phi = X_V v \quad q = X_Q \kappa
\]
\[
q = C v
\]
\[
C = X_Q P^+ X_V
\]
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

\[
\begin{align*}
\varphi &= \mathbf{P}_{sub} \mathbf{i} \\
G &= X_f P_{sub}^+ X_V
\end{align*}
\]
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

Generalization for Arbitrary EM devices: The Loop Concept

- 1 Loop
- 2 Loops (Virtual CT)
- 3 Loops (Drawn CT)
- 4 Loops (Virtual CTs)
- 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
Models dynamically generated in quasi-real time depending on:

- Device topology and geometry
- Model order and proximity definition

Example Model Netlist

```text
// Magneto Netlist
// Model Name: QA_inductor_testbench_JF
//
// LRC Matrix Summary:
// Effective Inductance: 3.358e-09.
// Effective Capacitance: 2.02e-15.
// Effective Resistance: 2.97e-09.
// Approximate Self-Resonance Frequency: 5.72e6

subckt QA_inductor_testbench_JF_magnatraty_L0 (p n ct g)
parameters Bn=0.00019 S2=4.056 U=1.5e-05 N=3.0 or=2 onde
BEGIN Self-Inductance, Resistance and Capacitance
// BEGIN Loop 1 of structure QA_inductor_testbench_JF_magnatraty_L0.
C0 (ct cxt 0) capacitor c=1.0000e-15
L1 (p n) inductance i=2.647e-10*(1-0.0416*d-rshatop)*(1-0.0416*vstat_rshatop)
R1 (n netib) skinnodel Rdc=2.483e-01 Rgs=2.917e+00 Lsk=2.647e-11 skinm
c1 (netib 0) capacitor c=5.947e-15*(1+0.01*)(1+vstat_rshatop)*vstat(mod)/u
R1 (n netib) skinnodel Rdc=2.483e-01 Rgs=2.917e+00 Lsk=2.647e-11 skinm
L1 (n netib) skinnodel Rdc=2.483e-01 Rgs=2.917e+00 Lsk=2.647e-11 skinm
// END Loop 1 of structure QA_inductor_testbench_JF_magnatraty_L0.
// BEGIN Loop 2 of structure QA_inductor_testbench_JF_magnatraty_L0.
// END Self-Inductance, Resistance and Capacitance

BEGIN Mutual-Inductance and Capacitance
K1 (p) mutual_inductor coupling=2.647e-10 ind=1 L1 (p n) ind=2 L2 2a
K1 (p) mutual_inductor coupling=2.647e-10 ind=1 L1 (p n) ind=2 L2 2a
CML (n net2b) capacitor c=2.466e-15*(1+vstat_rshatop)*(3/3 vstat)
// END Mutual-Inductance and Capacitance
```

---

**Substrate**

- CAPACITANCE TO SUBSTRATE
  - Csp1 (n m) capacitor c=4.694e-14*(1+0.01*)(1+vstat_rshatop)*vstat(mod)/u
  - Csp1 (n m) capacitor c=1.000e-15*(1+0.01*)(1+vstat_rshatop)*vstat(mod)/u

**Skin Effect**

- BEGIN Skin-Effect Subcircuit Model
  - subckt skinmodel (p n)
  - parameters Rd=0 Rgs=0 Lsk=0 skinm=10 skinm=20
  - Rs (p g) resistor r=(Rdc=1*Rgs=6.25e+00)*(1+vstat_rshatop)*vstat_rshatop tc=3
  - Gs (p g) resistor r=1/Rgs=6.25e-01*(1+vstat_rshatop)*vstat_rshatop tc=3
  - Lsk (p g) inductor l=Lsk=1.000e+00

ENDS SKINMODEL

**Mutual L and C**

- BEGIN Mutual-Inductance and Capacitance
  - K1 (n m) mutual_inductor coupling=2.647e-10 ind=1 L1 (n m) ind=2 L2 2a
  - K1 (n m) mutual_inductor coupling=2.647e-10 ind=1 L1 (n m) ind=2 L2 2a
  - CML (n net2b) capacitor c=2.466e-15*(1+vstat_rshatop)*(3/3 vstat)

END Mutual-Inductance and Capacitance
```
% Substrate definitions
tech.SUBS_THICK=750e-6;
tech.SUBS_ER=3.99;
tech.SUBS_BULK_ER=11.9;
tech.SUBS_CONDUCTIVITY=5.33;

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

% Metal Layer definitions
tech.M1=6;
tech.LAYER_NAME{tech.M1}='M1';
tech.LAYER_HEIGHT(tech.M1)=1.10e-6 + tech.SUBS_THICK;
tech.LAYER_THICK(tech.M1)=0.53e-6;
tech.LAYER_COND(tech.M1)=2.42e7;

% Substrate thickness
% Substrate effective relative dielectric constant
% Substrate bulk layer effective relative dielectric constant
% Substrate conductivity in S/m
% Metal resistor temperature coefficient tc1
% Metal resistor temperature coefficient tc2
% Substrate resistance temperature coefficient tc2
% Substrate resistance temperature coefficient tc1

- 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
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*

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

**Peak Q Error**
- Mean = 0.24%
- STDDEV = 4.4%

**SRF Error**
- Mean = -0.18%
- STDDEV = 2.5%
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
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
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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

**Simplified physical equations:**

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

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

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

\[ \rho_{sh} = \frac{\rho}{M_h} \implies \frac{dM_h}{M_h} = -\frac{d\rho_{sh}}{\rho_{sh}} \]

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

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

- $M_h$ and $M_{CD}$ available from:
  - Inline (direct physical measurement)
  - PCM (derived from electrical measurement)
  - Example: $M_h$ derived from $psh$
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

- 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
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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 (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")
      )
    )
  )
)
```

Tool supports parameter mapping, factoring, and other helpful utilities
Flexible Integration into Cadence® (2)

Sample Magneto ICFB Load View

Sample Magneto Spectre Device Include File

```plaintext
include "lib_cellName_basicSpiral_L0.scs"
include "lib_cellName_symmetricSpiral_L1.scs"
include "lib_cellName_symmetricTransformer_L2.scs"
include "lib_cellName_finlayTransformer_L3.scs"
```

Configuration File

Synthesized Models
# Magneto Inductor Device Example

## Sample Device CDF

<table>
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<th>Value</th>
</tr>
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<tr>
<td>Generate Model</td>
<td></td>
</tr>
<tr>
<td>Model Order</td>
<td>1</td>
</tr>
<tr>
<td>Include Proximity Effects</td>
<td></td>
</tr>
<tr>
<td>Width</td>
<td>15 μM</td>
</tr>
<tr>
<td>Space</td>
<td>2 μM</td>
</tr>
<tr>
<td>Diameter</td>
<td>60 μM</td>
</tr>
<tr>
<td>Number of Turns</td>
<td>1.5</td>
</tr>
<tr>
<td>Bulk Contact Ring</td>
<td></td>
</tr>
<tr>
<td>Bulk Contact Distance</td>
<td>50 μM</td>
</tr>
<tr>
<td>Edit Underpass Width</td>
<td></td>
</tr>
<tr>
<td>Underpass Width</td>
<td>30 μM</td>
</tr>
<tr>
<td>Underpass Type</td>
<td>Orthogonal, Parallel</td>
</tr>
<tr>
<td>Inductance</td>
<td>2.799nH</td>
</tr>
<tr>
<td>Resistance</td>
<td>1.299Ω</td>
</tr>
<tr>
<td>Capacitance</td>
<td>455.3fF</td>
</tr>
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## Model Generation Switch

- **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 Frequency [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]

Graphs showing frequency vs. Q and L vs. frequency.
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

Graphs:
- Spiral Inductor N4.5 W:20 ID:190 SP:4
  - Frequency [Hz] vs. L [H]
  - Frequency [Hz] vs. W [um]
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
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Test Structure Generation
References


