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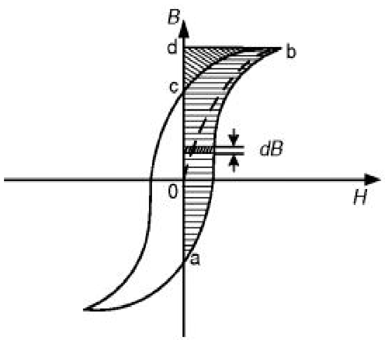
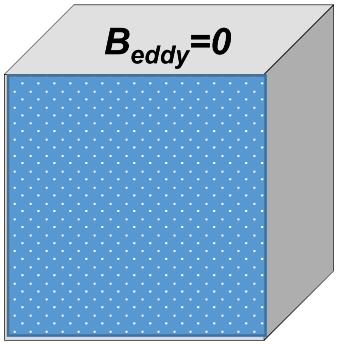
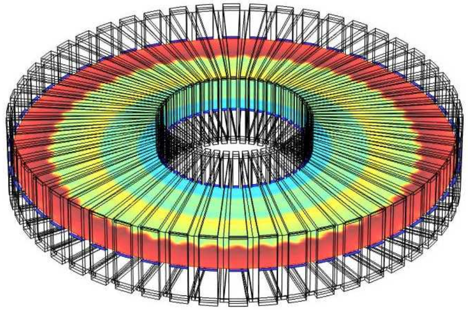
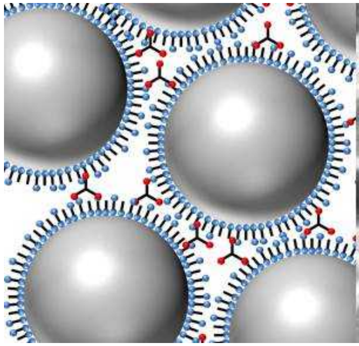
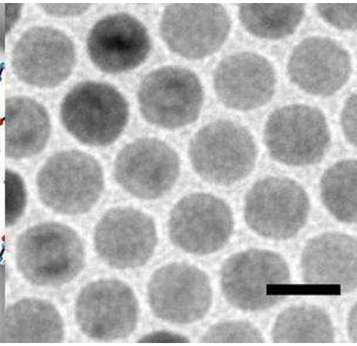




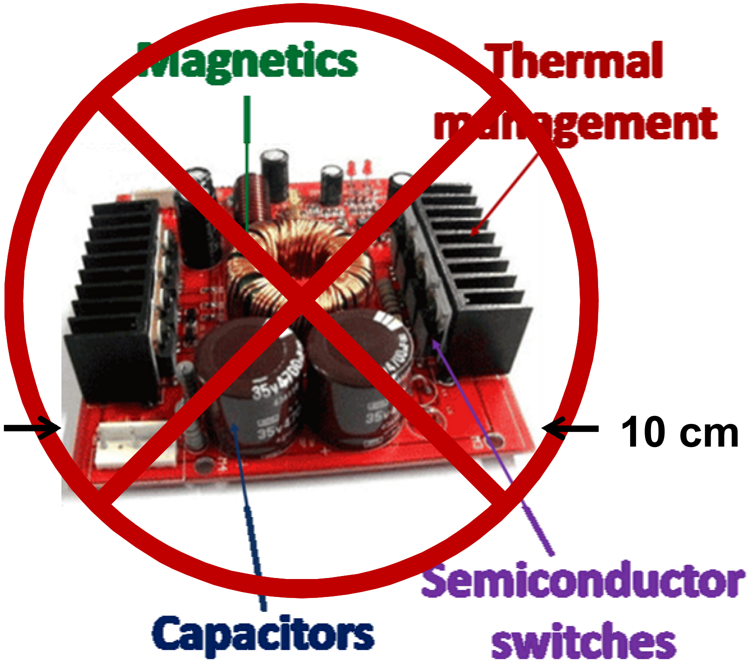




Nanoscale-Enabled Microinductors for Power Electronics

Eric D. Langlois, Dale L. Huber, John D. Watt and Todd Monson

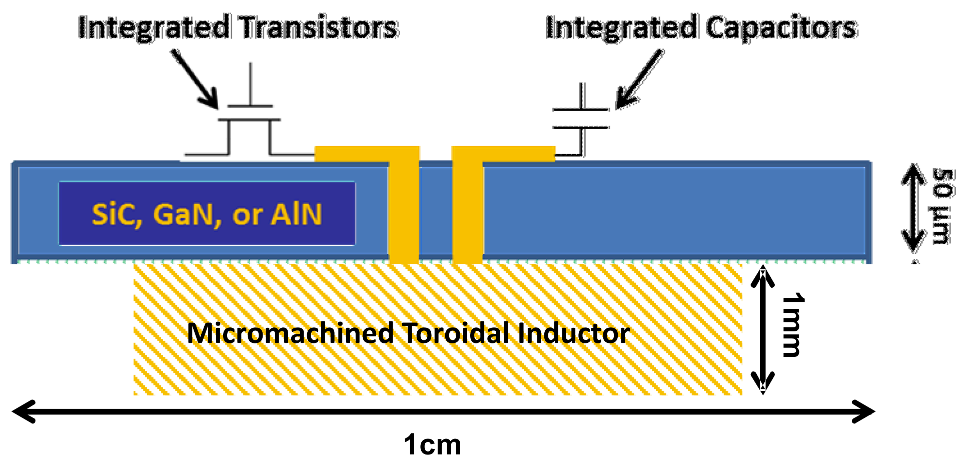
Status Quo and Future State

Status Quo



Discrete components on PCB

Future State



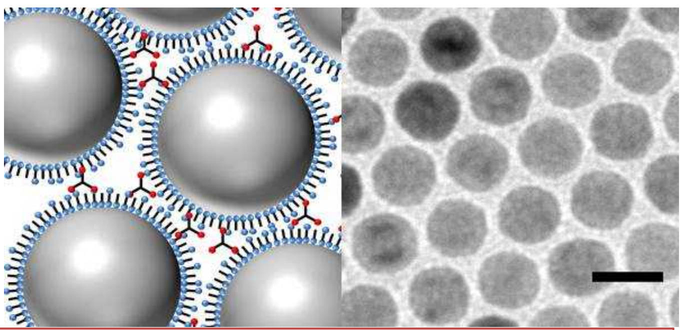
Power Supply on Chip (PSoC)

#1 figure of merit: reduced form factor!

Novel Iron Nanocomposite

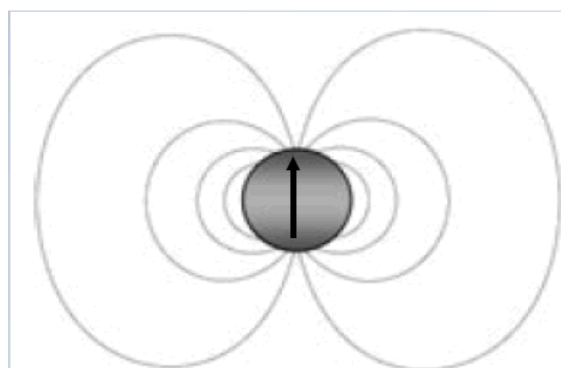
The nanoparticles are directly crosslinked to each other via chemical synthesis using liquid precursors that separate the nanoparticles with nanometer precision.

- Avoid phase separation common with mixing
- avoids strong dipolar interactions that form ferromagnetic domains
- achieves a high packing fraction.

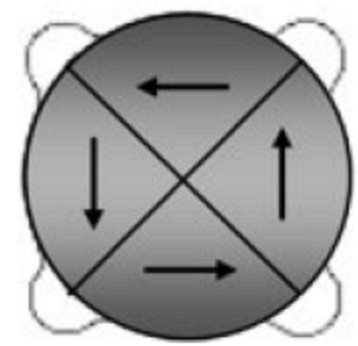


- **Superparamagnetic particles are single domain magnetic particles whose electron spins are aligned into a single giant moment.**
- **Nanocomposite will be designed such that nanoparticles are always above the blocking temperature, T_B.**

Single Domain:
- No energy spent creating domain walls
- No lossy magnetization processes present, i.e., no hysteresis.



Multidomain:
- Energy required to create domain walls
- Domain wall motion creates hystersis.



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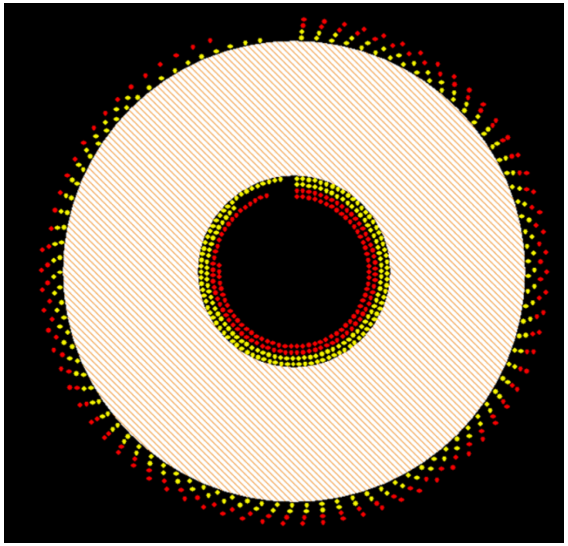
Microinductor Figure of Merit: Energy Density, W

High magnetic saturation!

Core Material	M_{sat} (T)
Iron	2.15
Nanocomposite	2.04
SiFe alloy	1.87
Metglas	1.60



Nanocomposite Core Energy Density

- W_c (Nanocomposite) 20% > W_c (SiFe alloy)
- W_c (Nanocomposite) 60% > W_c (Metglas)
  - greater inductance
  - greater energy storage (B ~ M_{sat})
  - 60% higher switching currents
  - fewer coil turns needed
    - reduces overall size
    - reduces winding resistance
- reduced flux leakage and EMI

$$Core\ Energy\ Density, W_c = \frac{B^2}{2\mu_r\mu_0}$$

Preliminary Macroscale Modeling (Ansoft)

- 60% reduction core size
- 40 AWG wiring

Estimated Reductions through Micromachining

- 90% reduction in length
- 6% reduction in area

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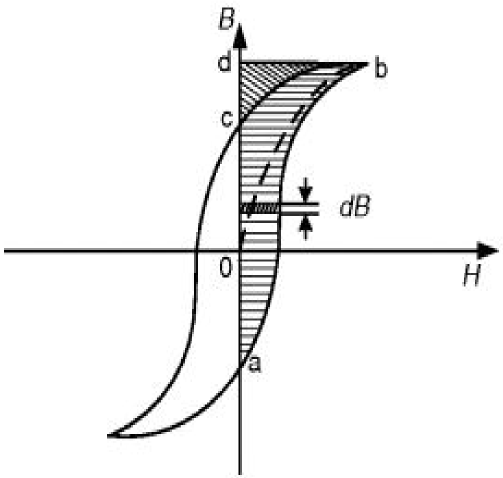
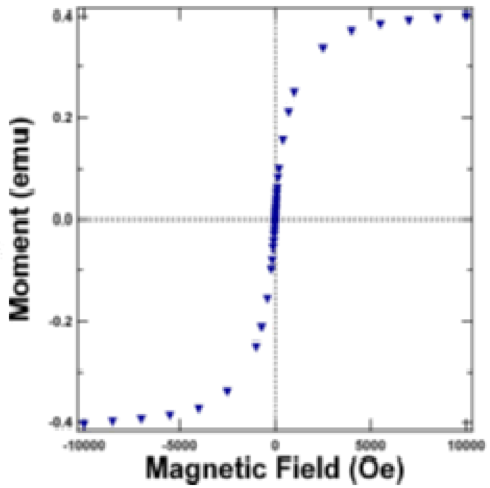
Core Loss





$$\frac{P_{hys}}{V} = \oint H(t)dB$$

Zero core hysteresis!

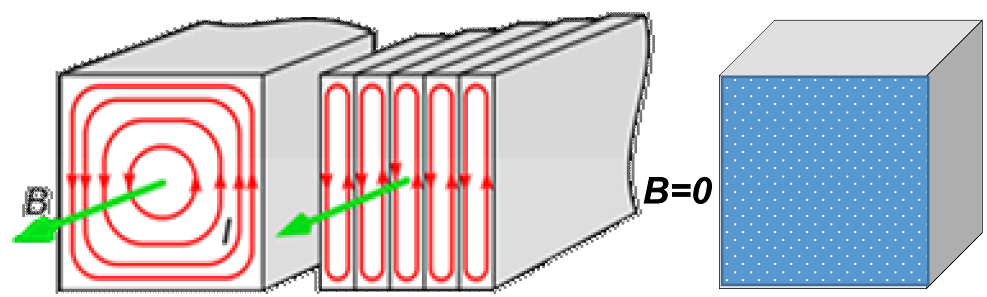
H_c = 1E3 A/m for Metglas

Hysteresis is zero for superparamagnetic particles by definition.

$$\frac{P_{eddy}}{V} = \frac{\omega B^2 A}{48\boldsymbol{\rho}}$$

□ $\boldsymbol{\rho} = \infty; \frac{\boldsymbol{P_{eddy}}}{\boldsymbol{V}} = \mathbf{0}$

Zero eddy currents!



Core loss, P_v = 100's of kW/m^3 @ 0.5 MHz for ferrites

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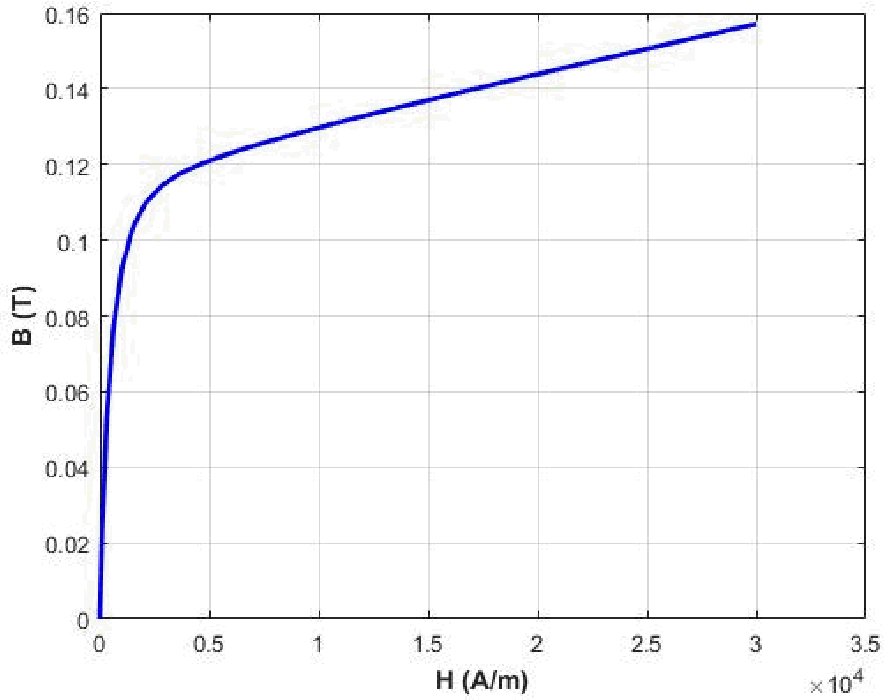
Modeled Toroidal Microinductor

Project Goal: Next Generation Buck Converter w/ Reduced Foot Print
COMSOL Multiphysics 5.2a will be used to design next gen microinductor

Inductor Performance Specifications	
Parameter	**Value**
Current	1-5 Amps
L_{in}	500 nH
L_{out}	2 μH
Switching Frequency	1-10 Mhz



1st gen batch nancomposite BH data used for model

COMSOL Multiphysics

- **Customized materials property parameters**
- **Complex geometries**
- **Parametric optimization**
- **Frequency domain simulation**
- **Combined electromagnetic (EM) and thermomechanical (TM) multiphysics modeling possible**
- **New physics incorporation via customized equations**

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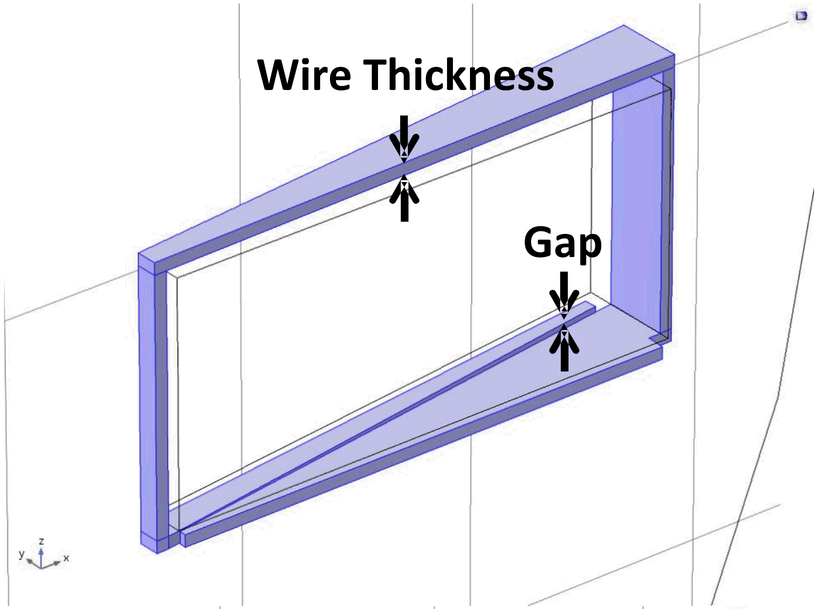
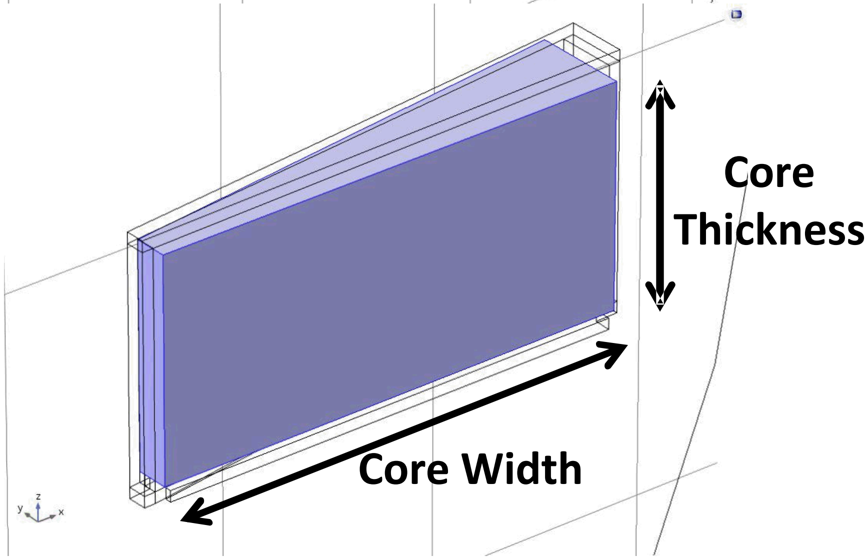
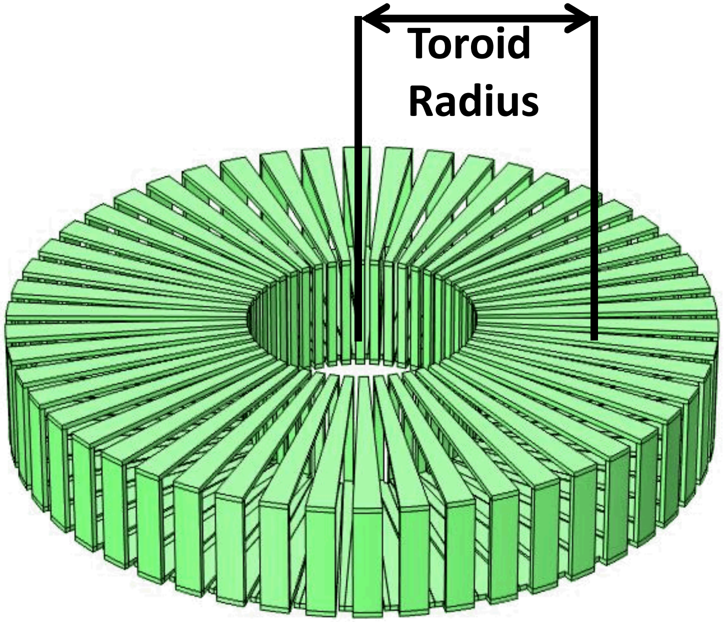
Fully Parameterized Geometry





2 μH Inductor Geometry	
Parameter	**Value**
Gap	50 μm
Toroid Radius	2.2 mm
Core Thickness	1 mm
Core Width	2.1 mm
Wire Thickness	50 μm
Number of Turns, N	50



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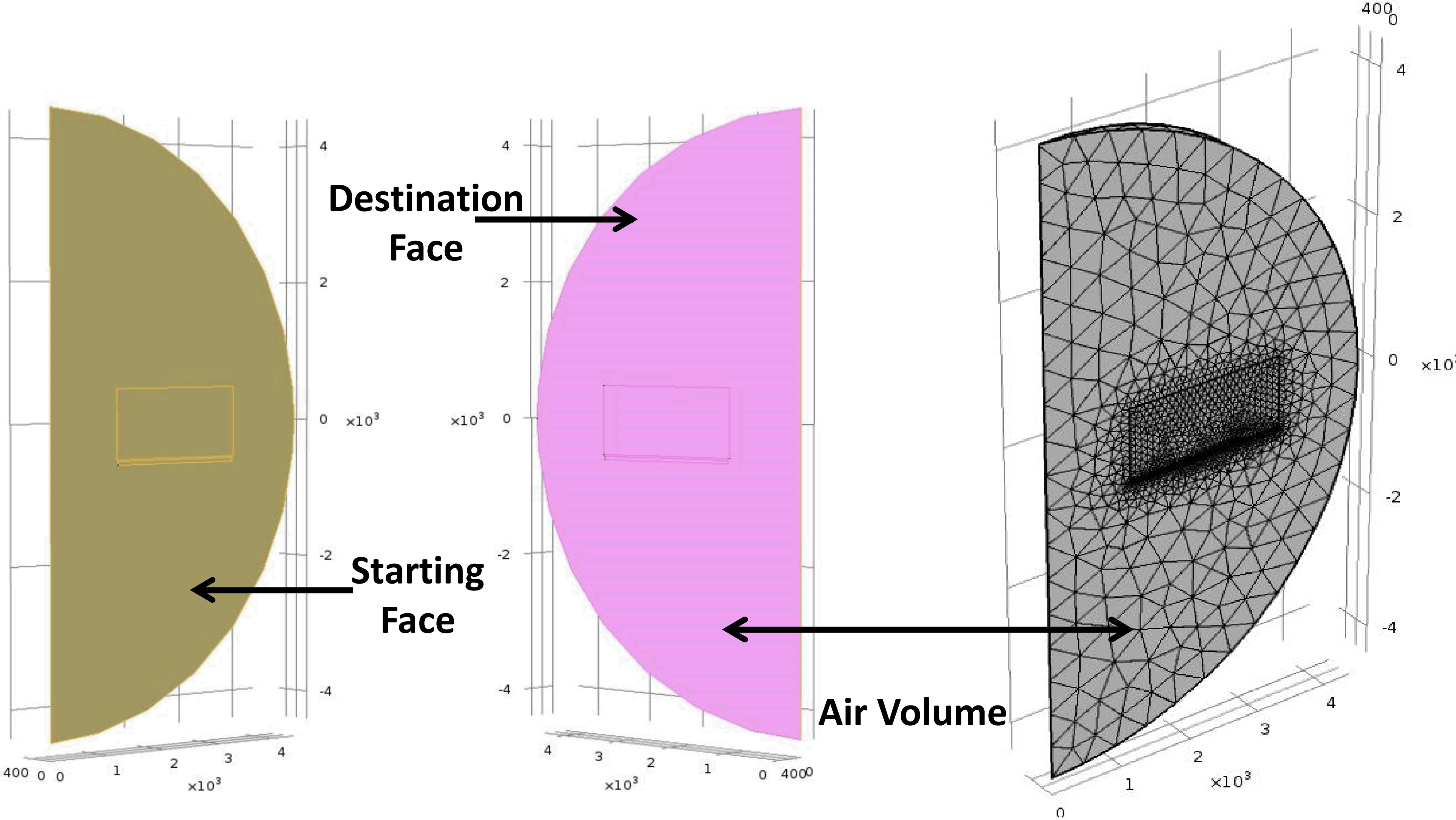
Periodic Boundary Conditions and Mesh



Exploits rotational symmetry by modeling single coil turn and scaling by number of turns.

- reduces number of meshing elements needed
- reduces computation time
- easier to scale features
- easier to model realistic microfabricated inductor features

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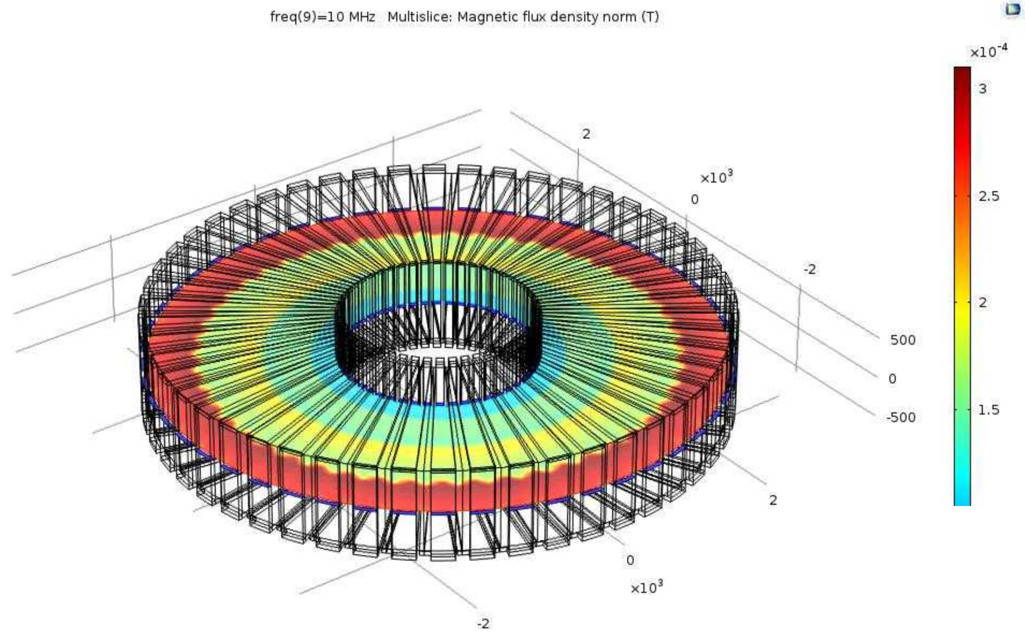
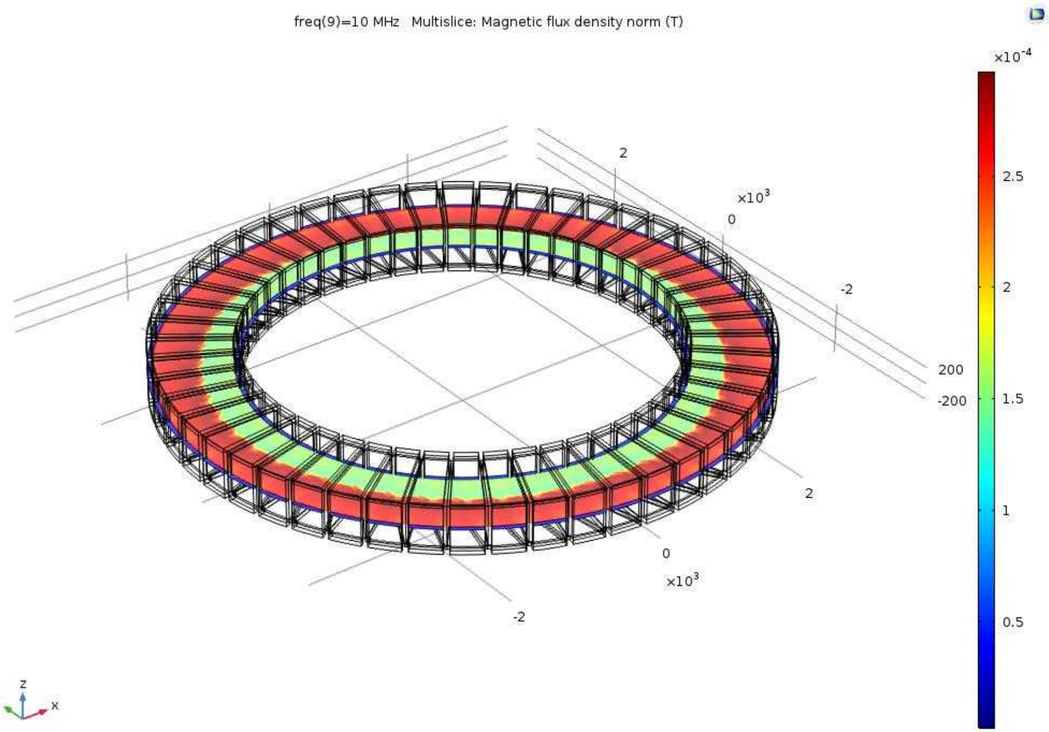
2μH and 500nH Microinductors



2 μH Inductor Model Results	
Frequency	10 MHz
Applied Current	1 A
Inductance	2 μH
AC Coil Resistance	2.1 Ω
Core Thickness	1 mm
Inner/Outer Diameter	2.3/6.5 mm



500 nH Inductor Model Results	
Frequency	10 MHz
Applied Current	1 A
Inductance	500 nH
AC Coil Resistance	2.9 Ω
Core Thickness	0.5 mm
Inner/Outer Diameter	5.1/6.9 mm

Conclusions and Future Work

- **Novel Sandia developed iron nanocomposite core material can provide a significant leap over existing core materials in terms of reducing form factor, increasing energy density, and reducing core loss in future power inductors.**
- **Finite element modeling using COMSOL Multiphysics commercial software is an ideal tool for designing microinductors.**

➢ **Optimization of batch nancore material.**

➢ **Determination of what core loss does exist as a function of frequency.**

➢ **Design optimization of microinductor using COMSOL as batch material improves and its performance is better characterized.**

➢ **Development of microfabrication flow around this new material.**

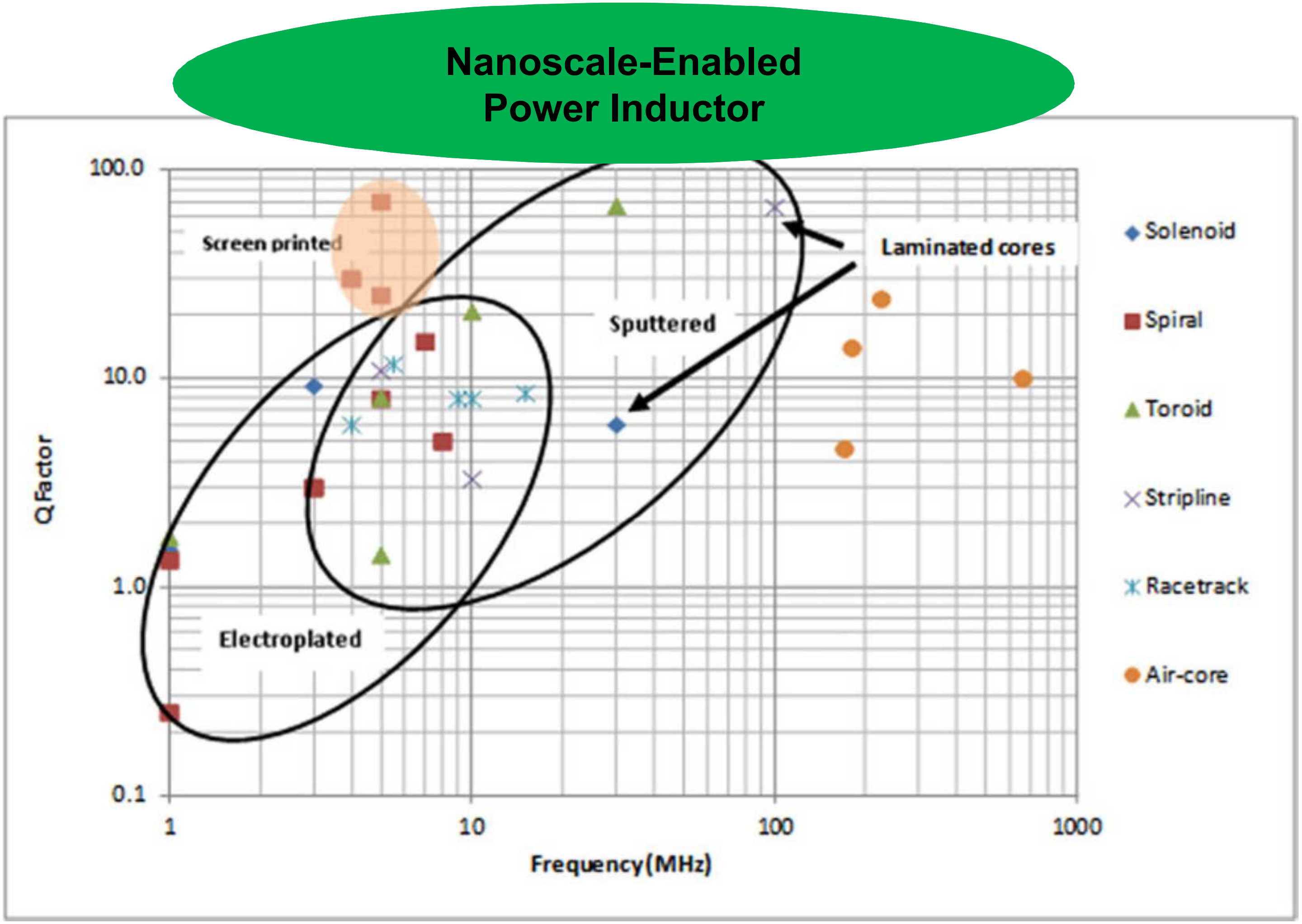
➢ **Development of photomask layout for creating nanoscale-enabled microinductors.**

Thank You!

Acknowledgements:

- John Watt and Dale Huber for providing nanocomposite magnetometery data generated by a QuantumDesign Versalab™ vibrating sample magnetometer.
- This project was supported by Laboratory Directed Research and Development (LDRD) Project Number 200184 and Laboratory Directed Research and Development (LDRD) Project Number 200203.

Microinductor Figure of Merit: Q_{max}

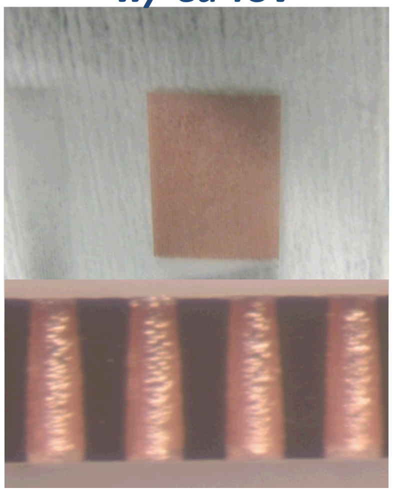


Lower loss, i.e., higher Q needed!

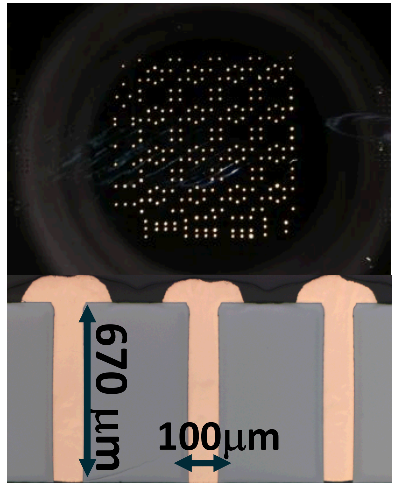
* Cian ÓMathúna, N. Wang, S. Kulkarni, and S. Roy, "Review of Integrated Magnetics for Power Supply on Chip (PwrSoC)," IEEE Transactions on Power Electronics, vol. 27, pp. 4799-4816, 2012.

Electroplated Metal Micromachining

Photo-defined Glass w/ Cu TSV



DRIE Si w/ Cu TSV

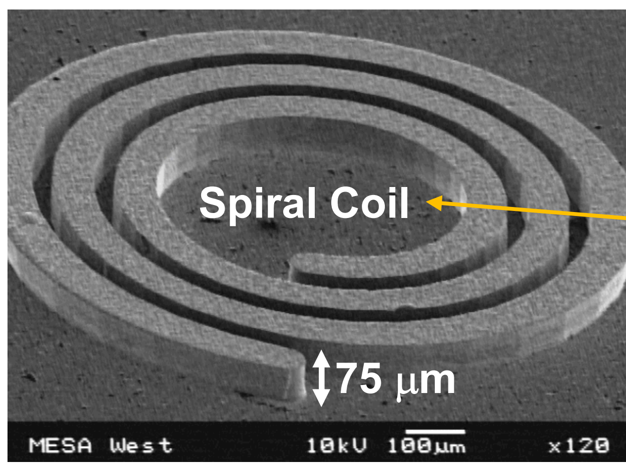


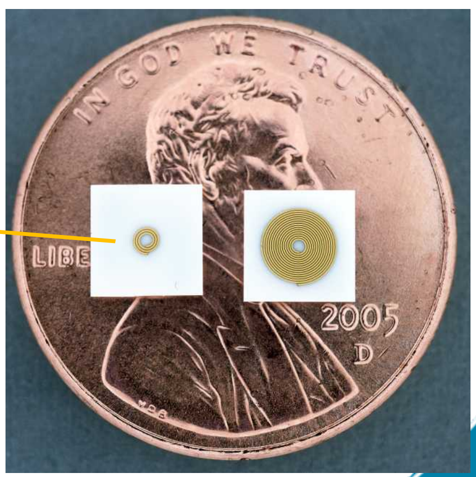
Benefits

- µm to mm size copper features
- 10:1 aspect ratios
- Multilayered electroforming possible
- Flexible choice in substrate materials (glass, silicon, PCB, alumina, sapphire, etc.)

Skin Depth

- $\delta = \frac{1}{\sqrt{\pi f \mu \sigma}}$
- δ=37µm (10MHZ) to 117 µm (1MHz)
- Wire thickness < δ





How compatible is the nanocomposite with existing micromachining techniques and what advanced fabrication challenges need to be solved ?