

**Additive Manufacturing of Magnetic Components for  
Power Electronics Integration  
(Work in Progress)**



*Presented by*  
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**Outline**

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**I. Introduction: motivation and objectives**

**II. Approach: 3D printing magnetic components**

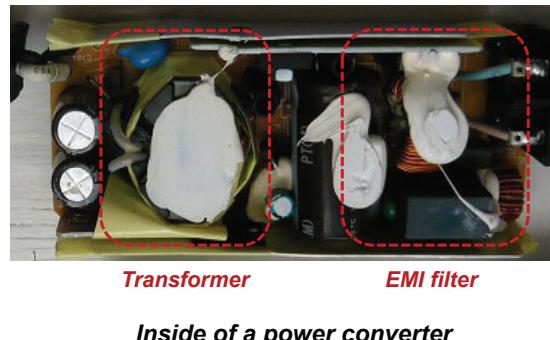
**III. Magnetic materials fabrication**

**IV. Feasibility demonstration of 3D printing  
magmetics**

**V. Summary and future work**

## Magnetic Components in Power Electronics Circuits

- Power electronic circuits require the use of inductors and transformers;
- Magnetic components are usually the largest, heaviest, and expensive components in a circuit.



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## Traditional Fabrication Methods of Magnetic Components

**Magnetic components = Magnetic Core + Winding**

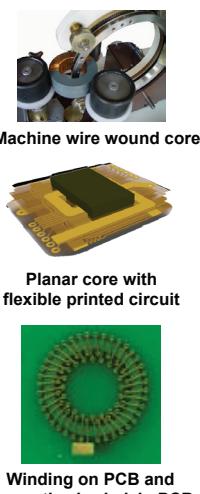
➤ Magnetic Core

Soft ferrite core
Powder core
LTCC tape core
Amorphous laminate core
Nanocrystalline laminate core



➤ Winding

Filament wire
Flexible printed circuit
Winding on PCB

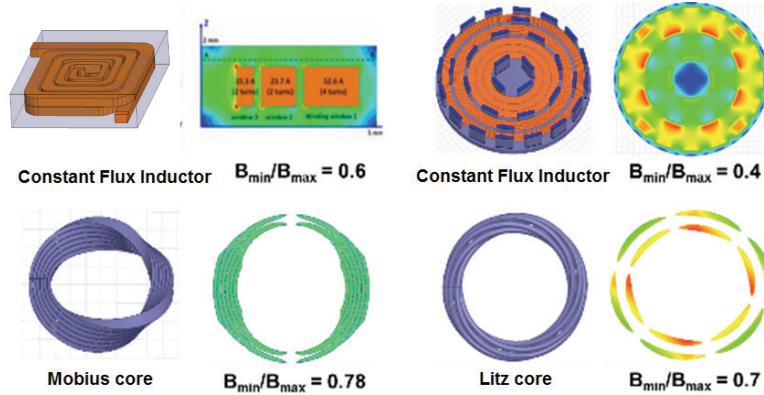


**Core and winding of magnetic components are fabricated separately and required multiple, complex manufacturing processes.**

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## Limitations of Traditional Methods for Fabricating Complex Shaped Components

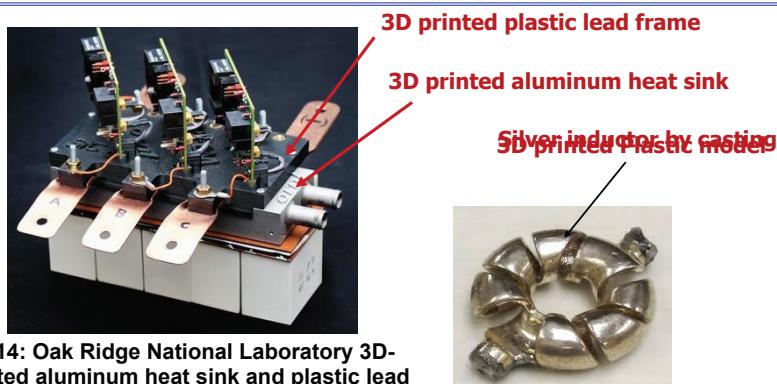
- Magnetic core designs can be optimized to efficiently use magnetic materials and produce more uniform flux density, but are too complex to manufacture with current discrete processes.



However, the above novel structures can be easily fabricated by 3D printing of plastic materials.

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## 3D Printing in Power Electronics R&D



2014: Oak Ridge National Laboratory 3D-printed aluminum heat sink and plastic lead frame for a 10-kW power inverter [1]

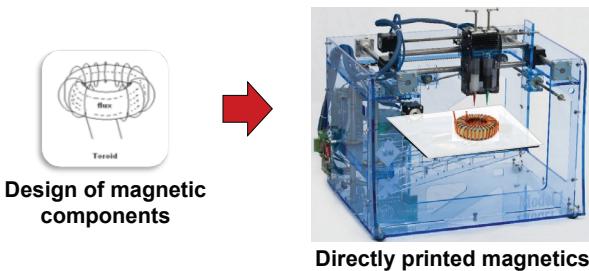
2015: Stanford University:  
A sterling silver inductor was made from a 3D-printed plastic model [2]

[1] Chinthavali, M.; Ayers, C.; Campbell, S.; Wiles, R.; Ozpineci, B., "A 10-kW SiC inverter with a novel printed metal power module with integrated cooling using additive manufacturing," in *Wide Bandgap Power Devices and Applications (WiPDA), 2014 IEEE Workshop on*, vol. no., pp.48-54, 13-15 Oct. 2014

[2] Wei Liang; Raymond, L.; Rivas, J., "3-D-Printed Air-Core Inductors for High-Frequency Power Converters," in *Power Electronics, IEEE Transactions on*, vol.31, no.1, pp.52-64, Jan. 2016

## Potential Benefits of 3D Printing in PE

- Rapid prototyping → design to fabrication in hours;
- Unlimited geometries → if it can be designed, it can be printed;
- Ease of embedding → directly manufacturing onto partially fabricated structures.



**3D printing (rapid-prototyping or mass-production) has great potential to advance power electronics integration.**

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## Objectives

- ❑ Investigate 3D printing processes and equipment for additive manufacturing of magnetics;
- ❑ Formulate and characterize magnetic pastes for 3D printing;
- ❑ Demonstrate the feasibility of 3D printing magnetic components;
- ❑ Characterize the properties of 3D printed magnetics.

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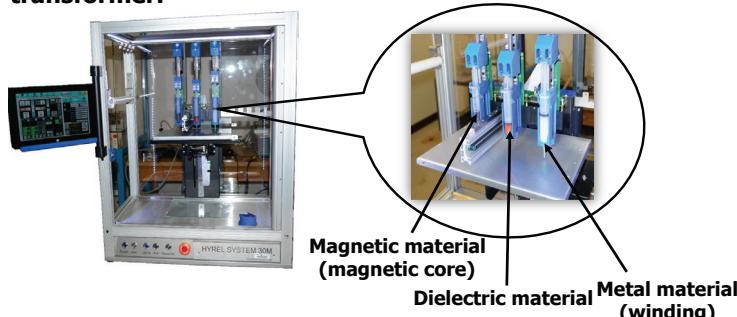
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## Approach: Paste Extrusion 3D Printer

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- Selected a multi-extruder paste extrusion 3D printer to make a hybrid material system, such as inductor/transformer.



**Hyrel system 30M multi-extruder paste extrusion 3D printer**

Possible to print paste or colloidal form of metal, ceramic or magnetic powders in organic oligomers, binders, and solvents.

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### Development of a Low Temperature Curable Magnetic Paste

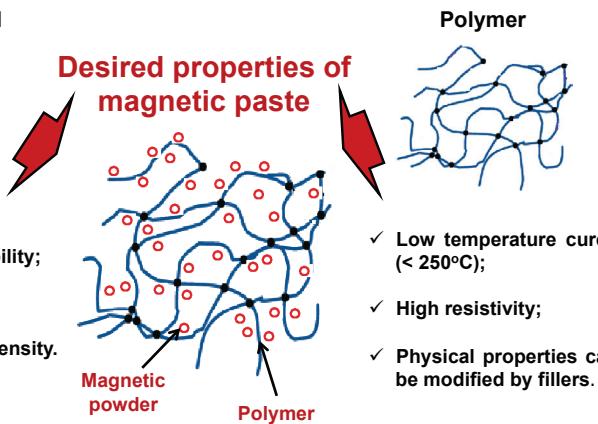
- A paste material with desired magnetic properties, which can be shaped at low temperatures of less than 250°C.

Soft magnetic material



#### Desired properties of magnetic paste

- ✓ High relative permeability;
- ✓ Low coercivity;
- ✓ High saturation flux density.

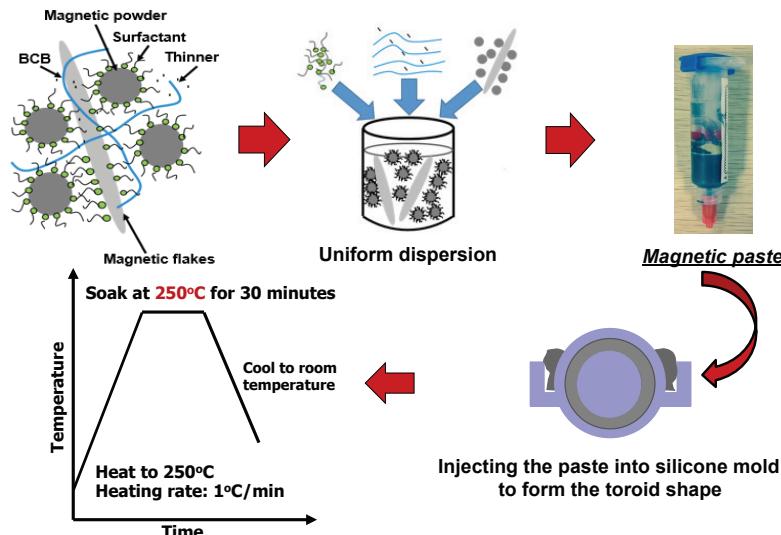


- ✓ Low temperature cured (< 250°C);
- ✓ High resistivity;
- ✓ Physical properties can be modified by fillers.

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## Fabrication of Low Temperature Curable Powder-Based Magnetic Paste

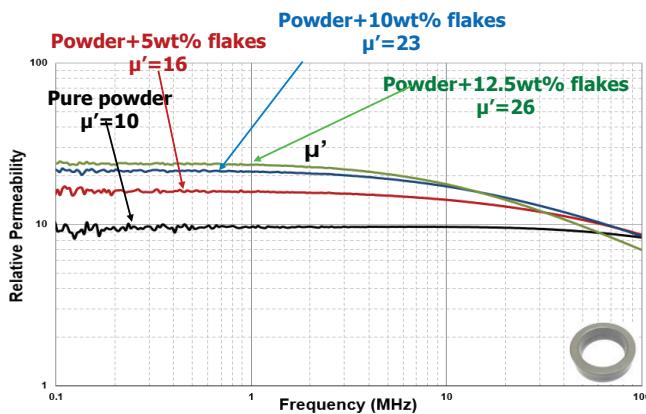
- A low-temperature ( $<250^{\circ}\text{C}$ ) curable magnetic paste



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## Relative Permeability Measurements

- Measured relative permeability dispersion spectra of toroid cores with different formulations.

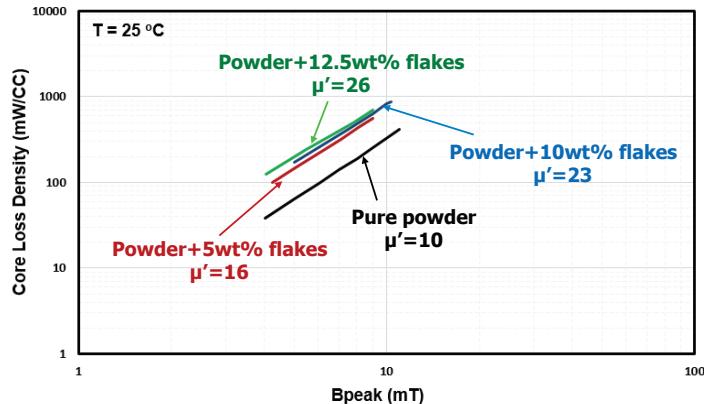


Magnetic paste formulations were designed and fabricated to give a core relative permeability ranging from 10 to 26.

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## Core-Loss Density Measurements

- Core-loss density plots measured at 1 MHz of the various cores at room temperature.

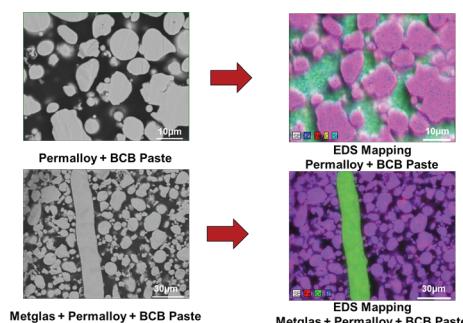


Relative permeability and core-loss density of the soft magnetic composite can be adjusted by varying the paste formulation.

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## Microstructure Characterization of Composite Cores

- Cross-sectional SEM image and EDS mapping of the toroid cores with and without Metglas flakes were characterized.



- The magnetic particles/flakes seem to be completely insulated by the polymer;
- The average DC resistivity of the core is about  $13.8 \Omega\cdot\text{cm}$ , which is  $10^6$  times higher than the metal.

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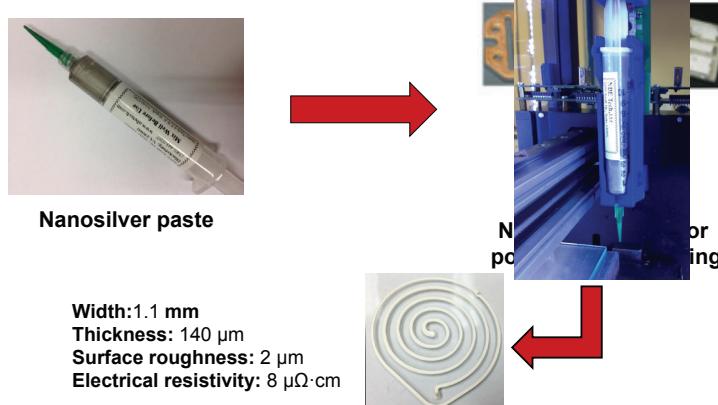
## Candidate Metal Materials for the Winding

### ➤ Characteristics of candidate metal pastes or ink materials

Material	Ease of processing	Single layer print thickness	Resistivity
Nano-silver ink (AgCite™)	✓ Low temperature sintering (~250°C)	✗ < 10 µm	✓ $2.8 \times 10^{-6}$
Nano-copper Ink (Gwent group)	✗ Special laser curing		✓ $9 \times 10^{-6}$
Graphene Ink (Northwestern University)	✗ high-intensity pulsed xenon lamp		✗ $\sim 10^{-3}$
Silver flake polymer paste (DuPont CB028)	✗ UV curing	<20µm	✗ $\sim 10^{-3}$
Voxel8 Silver paste (Voxel8, Inc.)	✓ Room temperature drying	Not available	✓ $5 \times 10^{-6}$
Nanosilver paste (NBE Technologies, LLC.)	✓ Low temperature sintering (<250°C)	>100µm	✓ $5 \times 10^{-6}$
Copper-tin paste ORMET circuits,inc	✓ Low temperature curing (<210°C)	✗ <50µm	✓ $5 \times 10^{-6}$
Copper paste Northwestern University	✗ (>600°C)	✗ <50µm	Not available
Gallium-indium Slurry North Carolina State University	✓ Room temperature drying	Not available	✗ $\sim 10^{-3}$

## Evaluation of Nanosilver Paste for 3D Printing

### ➤ A low-temperature (<250°C) sinterable nanosilver paste



❖ Nanosilver paste can achieve a crack-free single layer thicker than 100 µm and has potential to form bulk crack-free parts.

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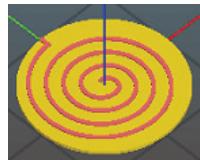
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## Structure Designs of Magnetic Components for feasibility demonstration

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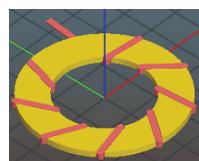
### 1. Simple shape



- Diameter of planar core: 20 mm;
- Thickness of planar core: 0.4 mm;
- Winding width: 0.8 mm;
- Winding thickness: 0.2 mm;
- Relative permeability of used Poly-Mag paste: 10;
- Inductance (calculation result): 155nH

This shape is designed for testing the basic capability of the 3D printer for processing multi-materials.

### 2. Complex shape

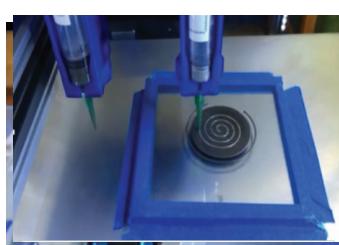


- Out diameter of toroid core: 20 mm;
- Inner diameter of toroid core: 12 mm;
- Thickness of toroid core: 0.6 mm;
- Winding width: 0.8 mm;
- Winding thickness: 0.2 mm;
- Relative permeability of used Poly-Mag paste: 10;
- Inductance (calculation result): 120nH

This shape is designed for testing the printer's line and layer resolutions.

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## Feasibility Demonstration of 3D Printing Magnetics



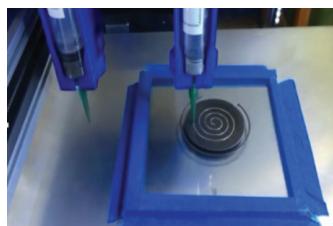
Measured inductance: 179 nH



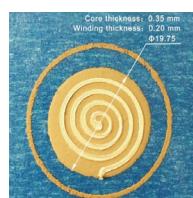
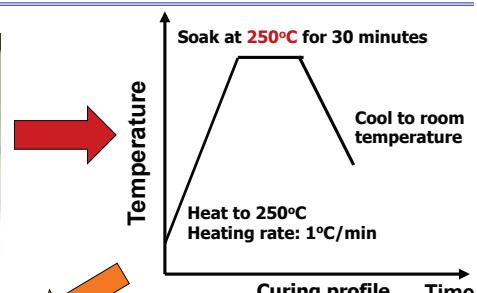
Measured inductance: 110 nH

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## Feasibility Demonstration of 3D Printing Magnetics



Measured inductance: 179 nH



Measured inductance: 110 nH

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## Summary and Future Work

- ✓ Completed an evaluation of 3D printing processes and equipment for additive manufacturing of magnetics;
- ✓ Prepared several formulations of low temperature curable soft magnetic pastes and characterized their magnetic properties and microstructures;
- ✓ Investigated the effects of printer parameters and material viscosity on print quality;
- ✓ Demonstrated the feasibility of 3D printing magnetic components.
  
- ❑ Improve printing quality (line and thickness resolutions) by adjusting motion parameters, temperature profiles, and nozzle sizes;
- ❑ Design and fabricate magnetic components with complex structure;
- ❑ Characterize magnetic properties of the magnetic components.

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## Thank you for your attention!

### Acknowledgements:

- ✓ Industrial Members of HDI Mini-consortium of CPES for financial support of Yasmine Yan
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## Questions or Comments?

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