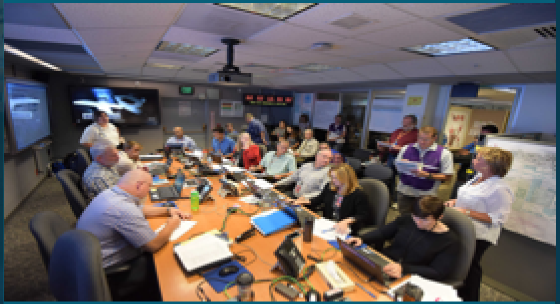
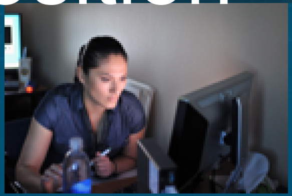
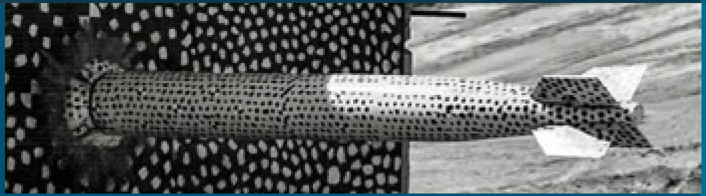
SAND2021-8394C

Sandia National Laboratories

High Resolution, High Conductivity Components by Aerosol Jet Printing and Electrodeposition







Presented By

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U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

UNM CENTER FOR MICRO-ENGINEERED MATERIALS

THE 32ND ANNUAL INTERNATIONAL VIRTUAL SOLID FREEFORM FABRICATION SYMPOSIUM – AN ADDITIVE MANUFACTURING CONFERENCE – 2021

August 2-4, 2021

SAND-XXXX

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Presentation Overview

I. Introduction

- Additive manufacturing of electronics by aerosol jet printing.
- Options for enhancement of conductivity for printed parts.

II. Results:

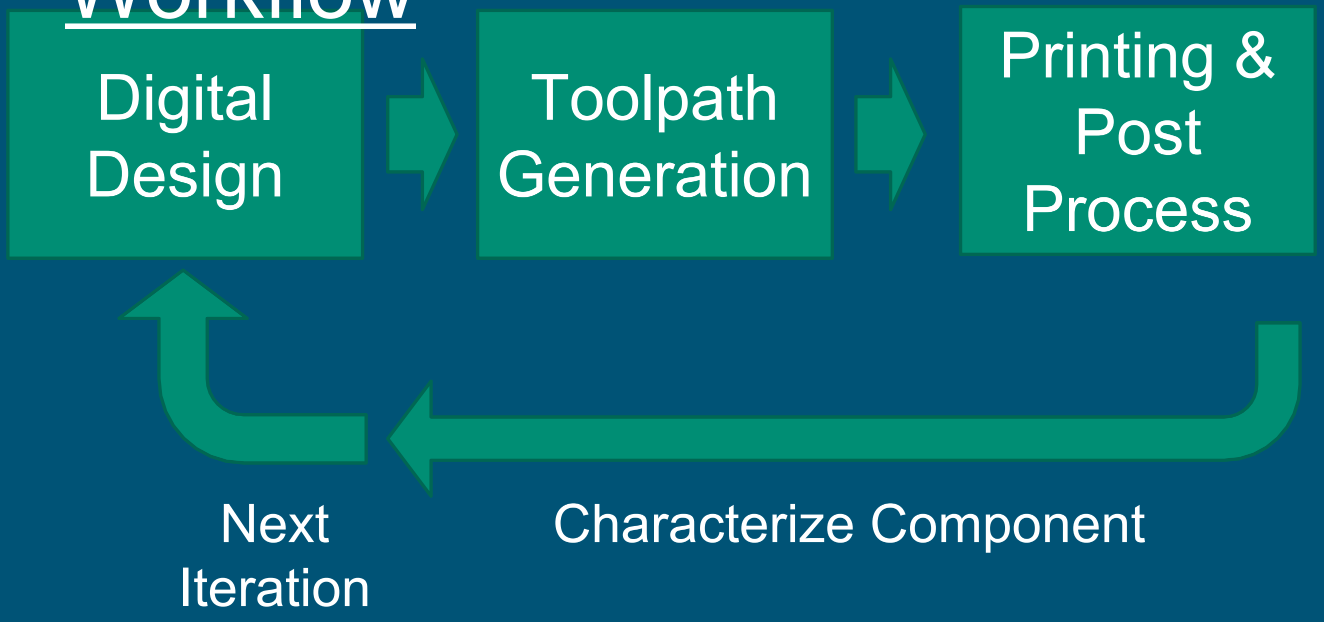
- Printing of planar spiral inductors for transformer applications
- Deposition of Cu by electroless deposition.
- Deposition of Cu by electrodeposition.
- Impedance analysis of printed / inductors.

III. Conclusions and Future Work

Motivation: Additive Manufacturing of Electronic Parts

- **Traditional Electronics Manufacturing:**
  - Mass Production.
  - Low cost per unit, but high up-front cost.
  - High cost for design modification and geometric complexity.
- **Additive Manufacturing / 3D printing**
  - Low-volume production.
  - Rapid prototyping.
- Techniques available for AM:
  - Syringe printing (200-500 μm resolution).
  - Inkjet printing (50-100 μm resolution).
  - Aerosol jet printing (10-50 μm resolution).
- While Aerosol Jet Printing can produce high resolution parts, the conductivity of the printed parts needs to be improved in order to minimize losses.

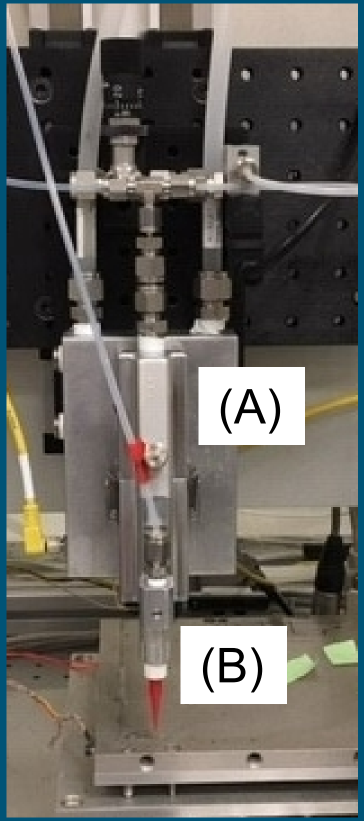
Additive Manufacturing Workflow



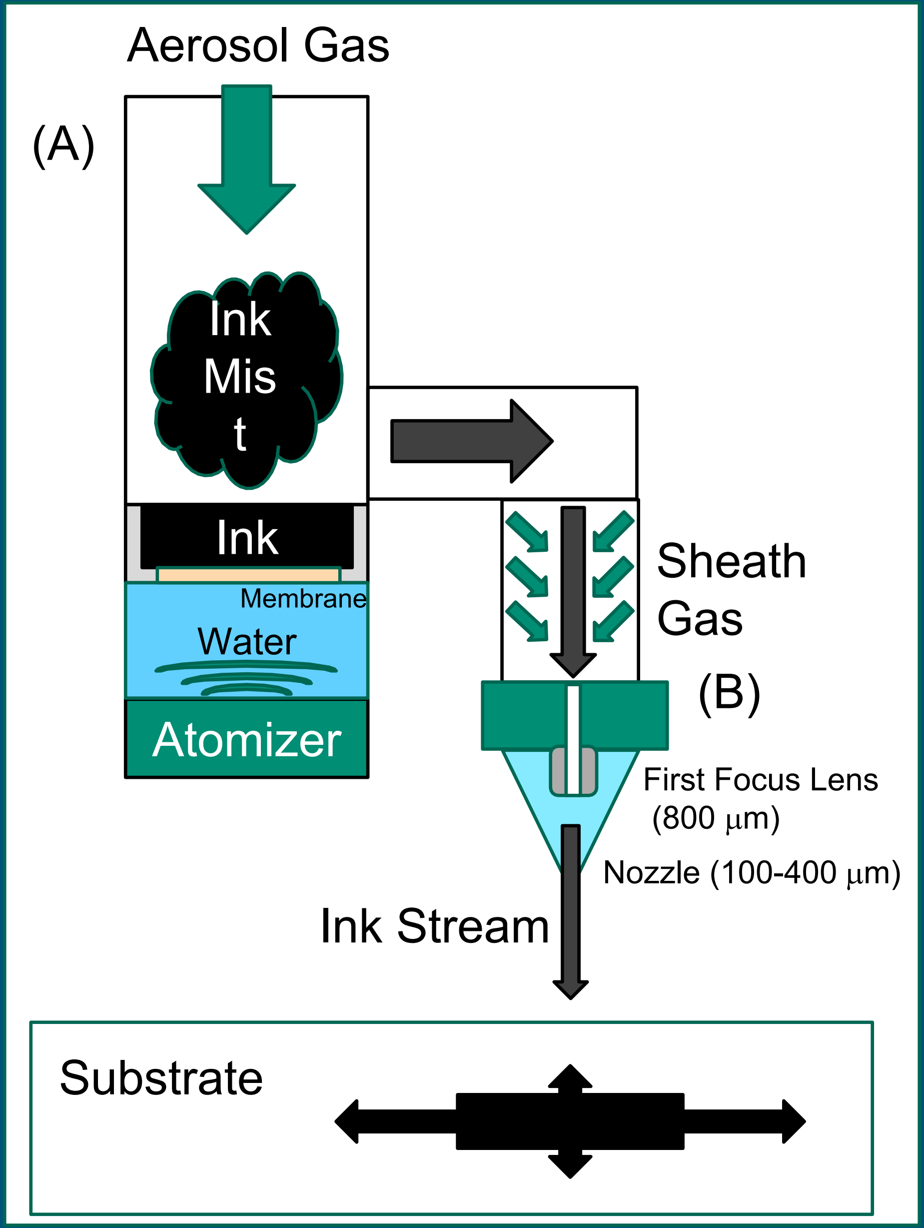
Aerosol Jet Printing (AJP) – IDS "Nanojet" Printer

Principle of Operation:

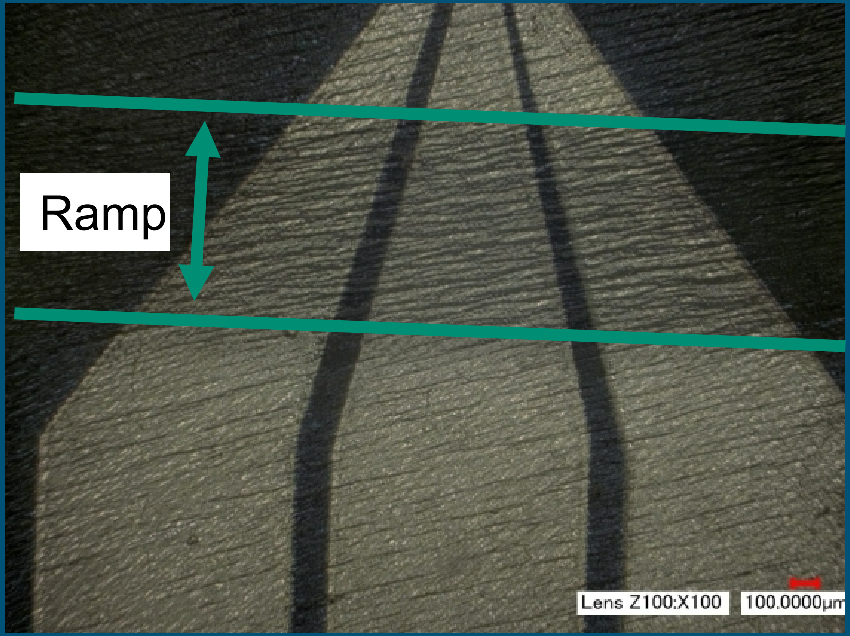
- Low viscosity (<50 cps) ink is atomized by ultrasonic atomizer into an **ink mist**.
- Mist is driven to the nozzle by **aerosol gas.**
- **Sheath Gas** and **Aerodynamic Focusing Lenses** are used to focus the ink stream.
- Ink is dispensed through the nozzle onto a heated substrate where it solidifies.
- Why AJP?
  - High Precision: Can print lines as small as 10-50 μm.
  - Versatility: Supports a wide range of materials– metals, insulators, magnetic materials.
  - Flexible Stand Off Distance: Can support printing on curved and stepped surfaces with stand-off distance of 1-5 mm.

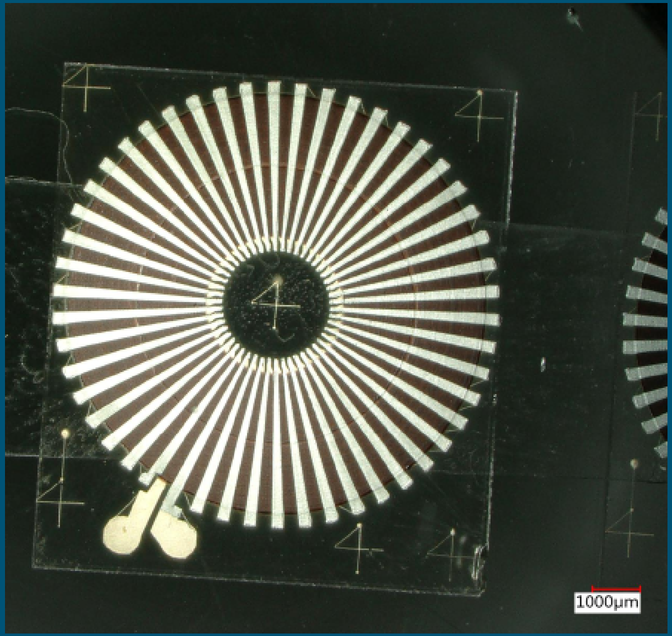


Nanojet Print Head



Examples of AJP Capability





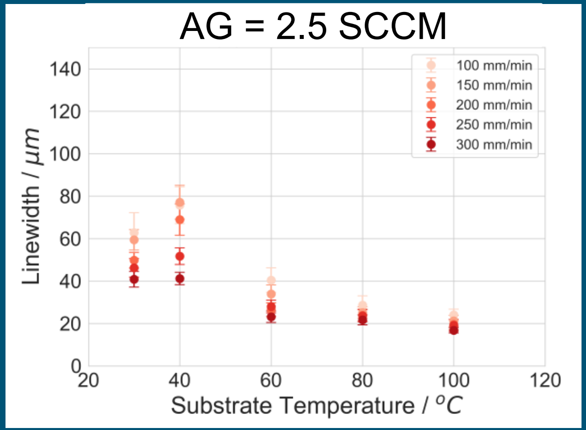
Non-Contact Printing: Printing of interconnects across a 500 μm tall ramp.

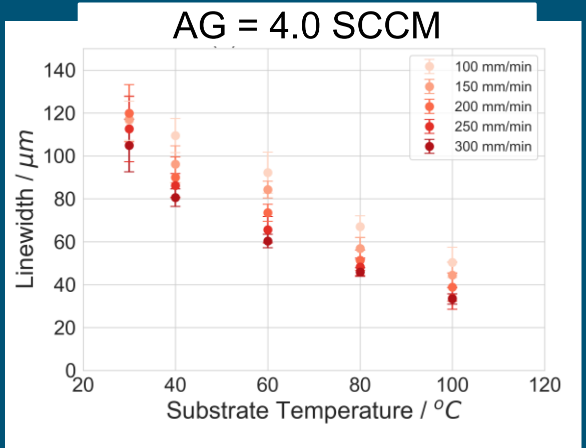
Multi-material Printing: 3-layer toroidal inductor with magnetite core and Ag windings.

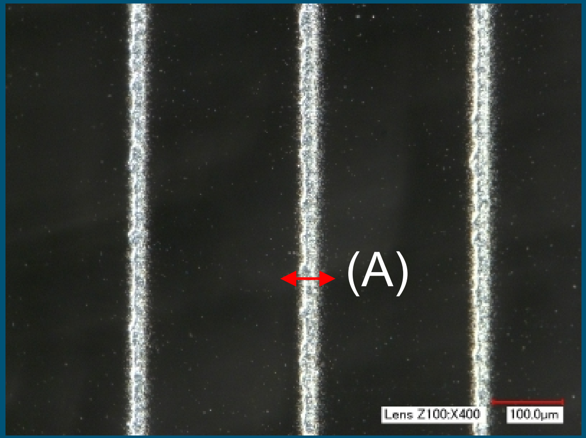
Rotational Printing: Conformal printing on cylindrical and spherical surfaces.

High Resolution Printing

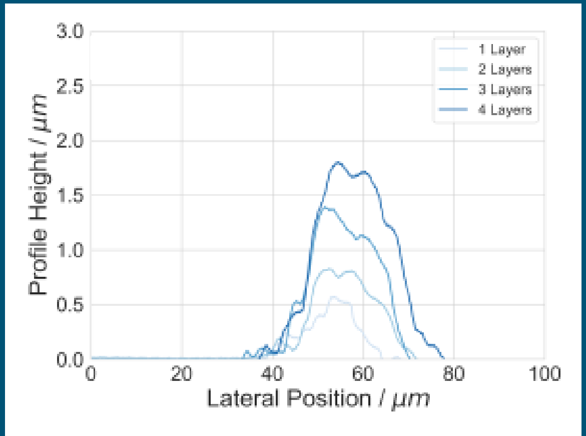
- Linewidth was measured on samples printed at:
  - AG = 2.0 – 4.0 SCCM
  - SG = 40 SCCM
  - Platen Temperature = 30 – 100^{o}C
- Temperature of the substrate was identified to strongly influence linewidth.
- As temperature increases, the xylenes in the ink volatilize faster and the ink line is prevented from spreading on the surface.
- Linewidths of < 20 μm are achievable with overspray inhibited.
- Line height increases from 0.5 to 1.75 μm with increasing number of layers from 1 to 4.







AG = 3.0 SCCM
SG = 40 SCCM
Substrate 100^{o}C



Profilometry of (A)

Figures: Tsui, L.; Kayser, S. C.; Strong, S.A.; Lavin, J. M. 2021 *ECS J. Solid State Sci. Technol.* **10** 047001

Options to Improve Conductivity

Challenge: Although we can achieve fine resolution printing, nanoparticle Ag inks used in AJP only achieve ~15-25% bulk conductivity.

	Mechanism	Limitations
Multiple Layers	Increasing the number of layers increases the cross sectional area of the printed trace, decreasing resistance.	Increasing the number of layers decreases the line resolution due to ink spreading. Increases print time. Impractical for thick films (~10 μm).
Nanoparticle-free Reactive Inks	Chemical reaction produces large crystallites which have been demonstrated to achieve >73% of bulk Ag conductivity.[1]	High viscosity of reactive inks incompatible with ultrasonic atomization without dilution. Possible materials incompatibilities with ink housing. High processing temperature reported in [1] (300^{o}C) limits available working substrates.

Electrodeposition and Electroless Deposition adds thicker, high density, high conductivity films without sacrificing resolution. AJP printed parts can be used as a templating layer.

[1] Rosker et al. *ACS Appl. Mater. Interfaces* 2020, 12, 26, 29684–29691

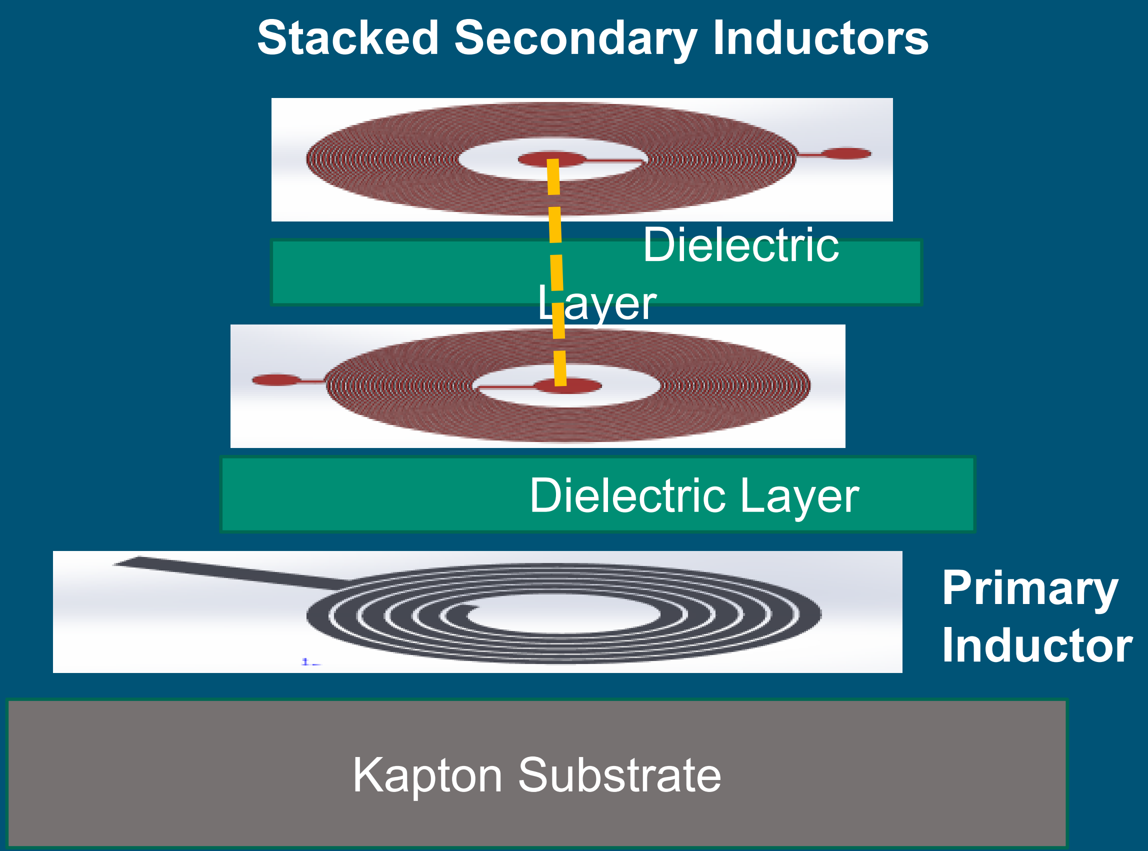
Objectives and Procedure

- **Project Objective**: Develop methods to print planar spiral transformers for conversion of low voltage signals to high voltage signals.
- Transformers consist of a **Primary** and a **Secondary Inductor.**
  - $Transformer\ Equation\ [1]: \frac{V_S}{V_P} = \frac{N_S}{N_P}$

Volts Turns

- Component Objectives:
  - Primary inductor: 6 turn spiral. **Minimize resistance (< 1 Ω)**.
  - Secondary inductor: **Maximizing the number of turns**. Line widths 50-100 μm with gaps 50-100 μm.
- Deposition Conditions:
  - Ink:
    - UTDots Ag40X Ag Nanoparticle Ink 20 v%.
    - Terpineol 20 v%.
    - Xylenes 60 v%.
  - Sheath Gas: Xylenes saturated.
  - Platen Temperature: 100°C.
  - Number of Layers: 4.
  - Post-Treatment: Anneal at 200°C for 3 hours.
  - Substrate: Kapton.

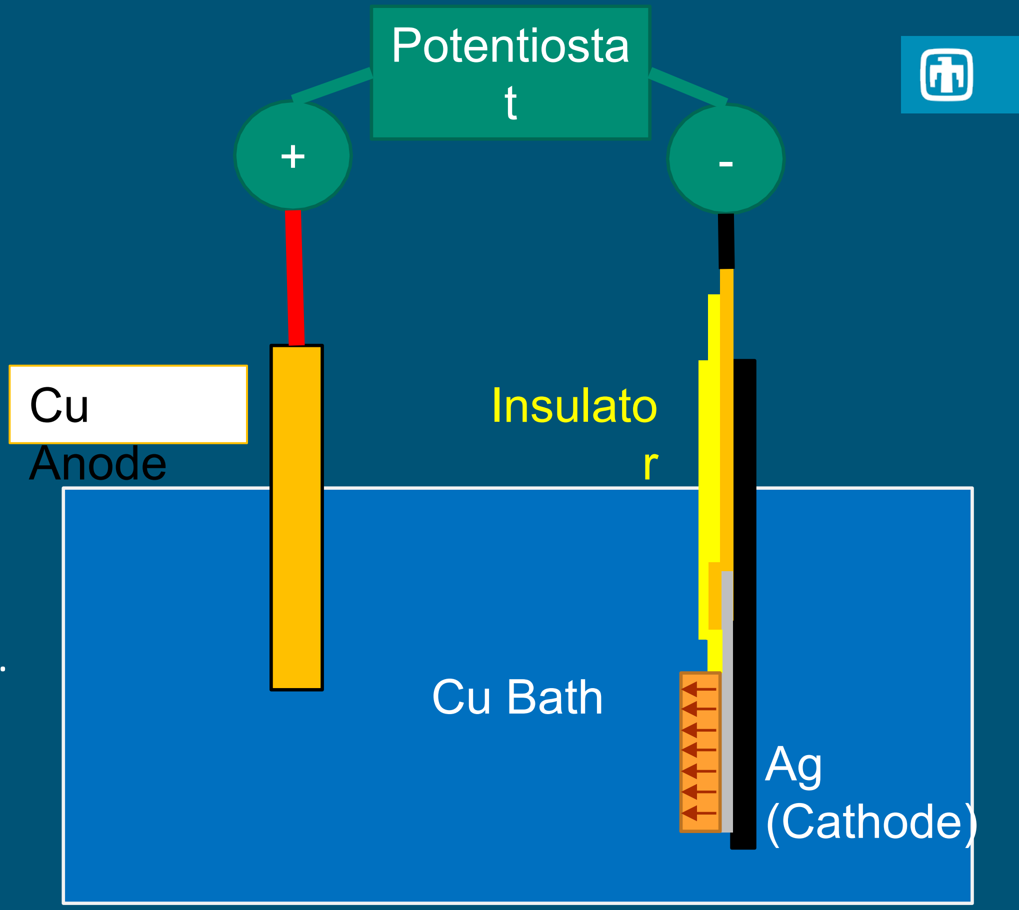
Transformer Components

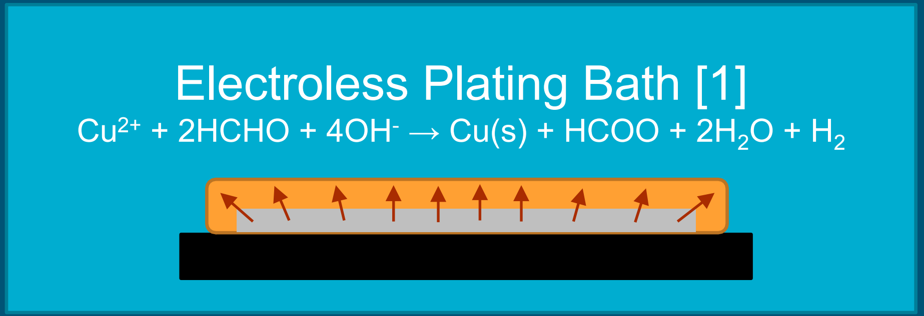


[1] http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/transf.html

Electrodeposition and Electroless Deposition

- **Electrodeposition**:
  - Anode: $Cu_{(s)} \longrightarrow 2Cu^{2+}_{(aq)} + 2\,e^-$
  - Cathode: $Cu^{2+}_{(aq)} + 2e^- \longrightarrow Cu_{(s)}$
  - Electrolyte: Microfab SC + Microfab SC MD/LO
    - Cu^{2+} -17g/L
  - **Pro:** Produces dense films with growth directed mainly by electric field.
  - **Con:** Deposition rate is non-uniform if there is a large Ohmic drop across a sample.
- **Electroless Deposition:**
  - Reaction [1]: $Cu^{2+} + 2HCHO + 4OH^- \longrightarrow Cu(s) + 2HCOO^- + 2H_2O + H_2$
  - Solution: Circuposit 3350-1 Electroless Cu Solution.
  - **Pro:** Deposition occurs wherever Ag metal is present to catalyze reaction.
  - **Con:** Less dense films which grow in all directions without electric field guidance.
- **Combination Approach:**
  - Brief electroless deposition of printed Ag samples to reduce Ohmic resistance.
  - Electrodeposition to further reduce resistance by depositing dense Cu.



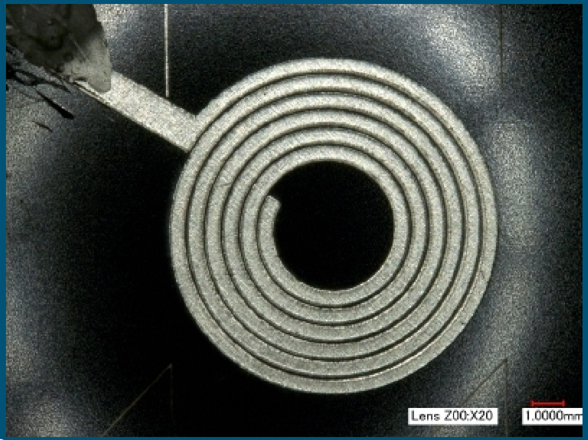


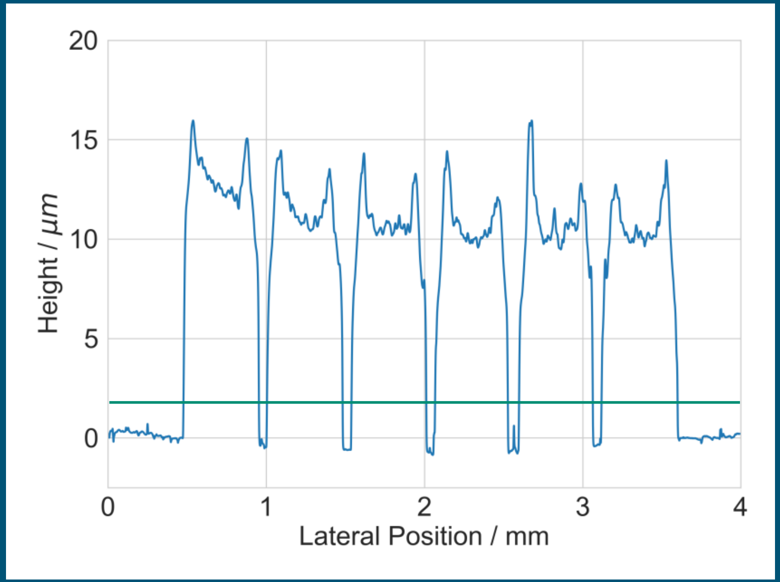
[1] Schlesinger, M, & Paunovic, M (eds) 2014, Modern Electroplating, pp 433

Primary Inductor

- Deposition Conditions:
  - 25 μm infill.
  - 4 layers.
  - 300 mm/min print speed.
- Modification by Electrodeposition:
  - Electrodeposition of Cu:
    - 30 mA/cm^2 – 30 min (Constant Current)
  - Follow up Ni plating in Ni Sulfamate plating bath for oxidation protection.
    - 15 mA/cm^2 – 1 min (constant Current)
- Electrodeposition increases thickness from < 2 μm to > 10 μm.
- Traces remain well separated.
- Resistance decreases from 5 Ω to 0.2-0.6 Ω, meeting objectives for resistance of the primary spiral design.
- No change in resistance after annealing at 200°C in air for 3 hours which enables building of multiple layers with air sintering steps.

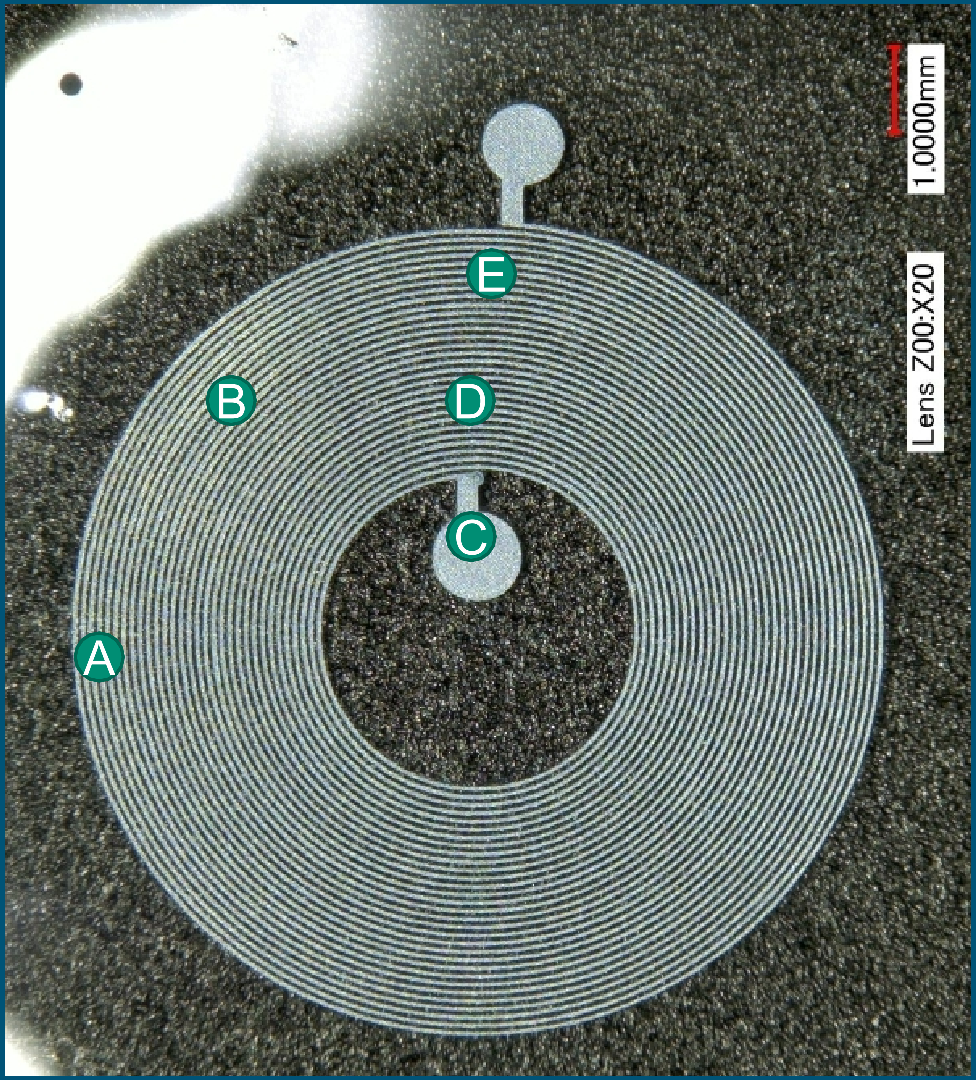
450 μm linewidth

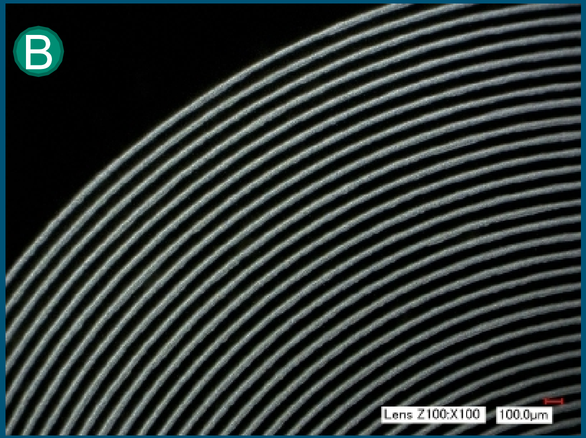


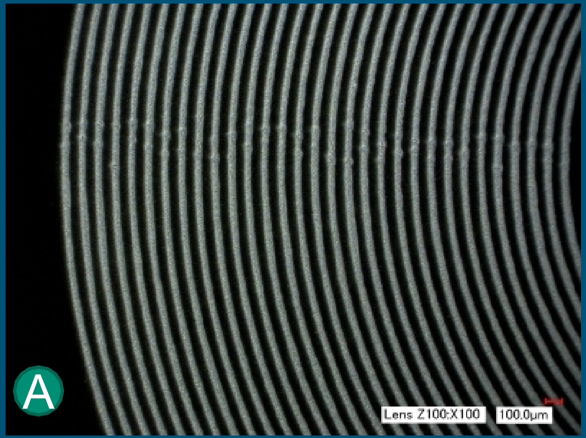


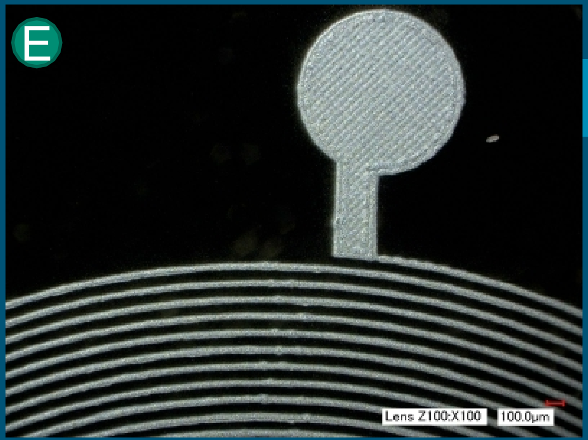
Starting Thickness ~ 1 micron

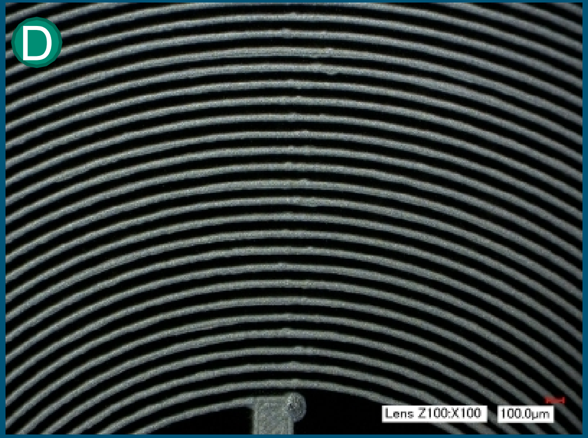
Secondary Inductor – As Printed

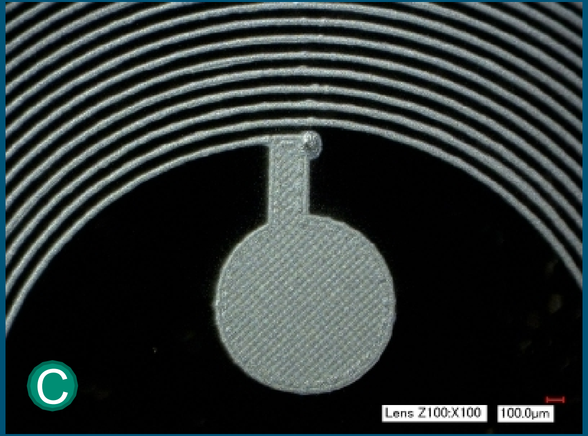








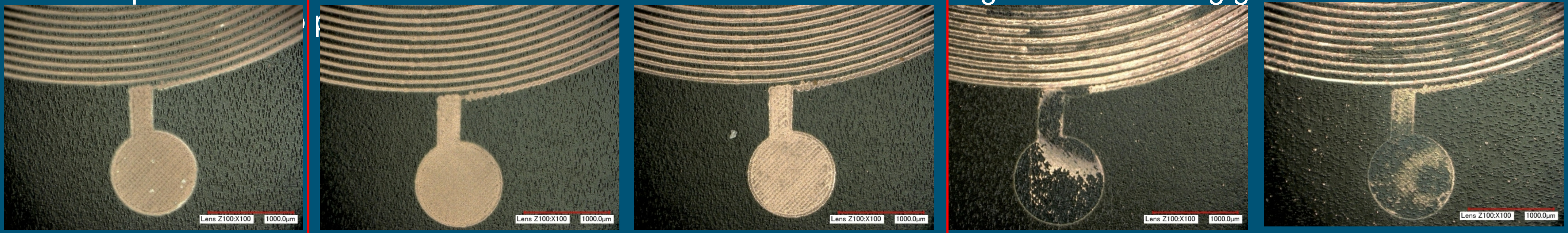




- Deposited with 25 µm infill with pads, single curve for spirals, 300 mm/min speed.
- Lines are well separated (33 µm linewidth + 60 µm gap) with no visible

Secondary Inductor – Electroless Deposition

- The long length of the secondary inductor introduces high Ohmic resistance which suppresses uniform deposition.
- Samples were immersed in an electroless deposition plating bath at 42°C from 5-20 minutes with no agitation.
- Samples immersed for 15-20 minutes showed delamination of Cu. High stresses during growth of Cu



2.5 min | 5 min | 10 min | 15 min | 20 min

Incomplete Coverage

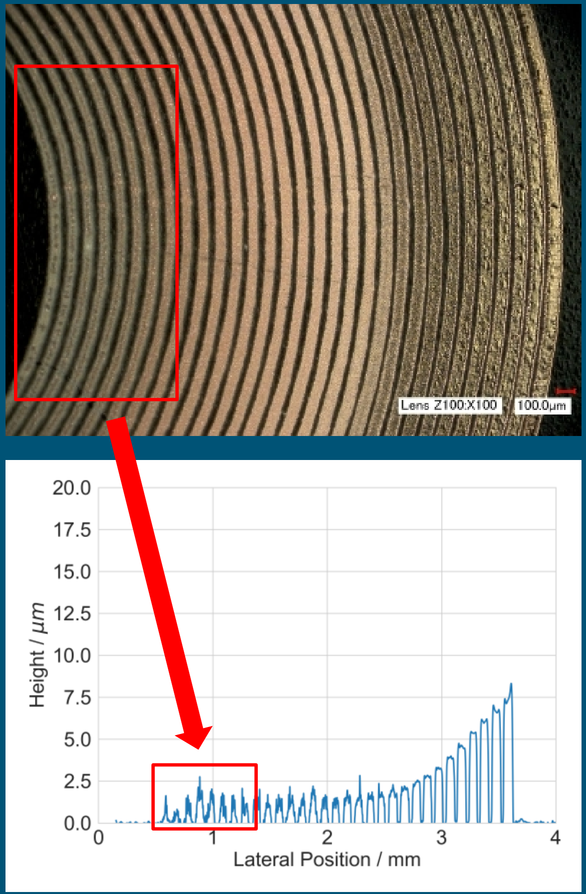
Continuous coverage of Cu

Delamination due to stresses built up during deposition

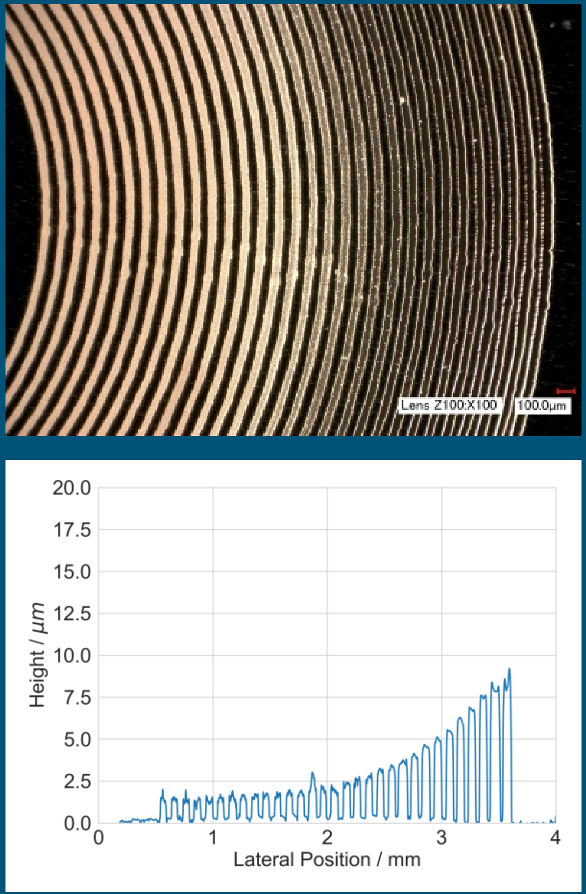
Follow up these samples with electrodeposition.

Secondary Inductor - Electrodeposition

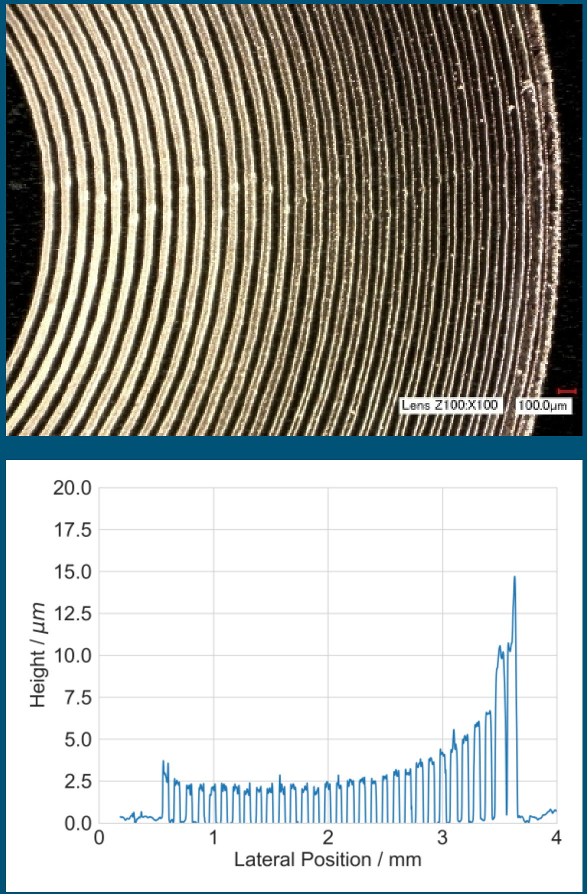
AJP Ag only



Ag + Electroless 5 min



Ag + Electroless 10 min



- All samples deposited at 11 mA/cm^2 for 15 minutes in a constant current configuration.
- Deposition of Cu is inhibited due to high Ohmic resistance towards the interior of the spirals.
- Increased deposition at the spiral interior is observed with electroless deposition modification prior to electrodeposition

Impedance Analysis

- Impedance measurements on the secondary were taken on a Keysight E4990A from 20 Hz up to 10 MHz with an oscillation voltage of 500 mV.

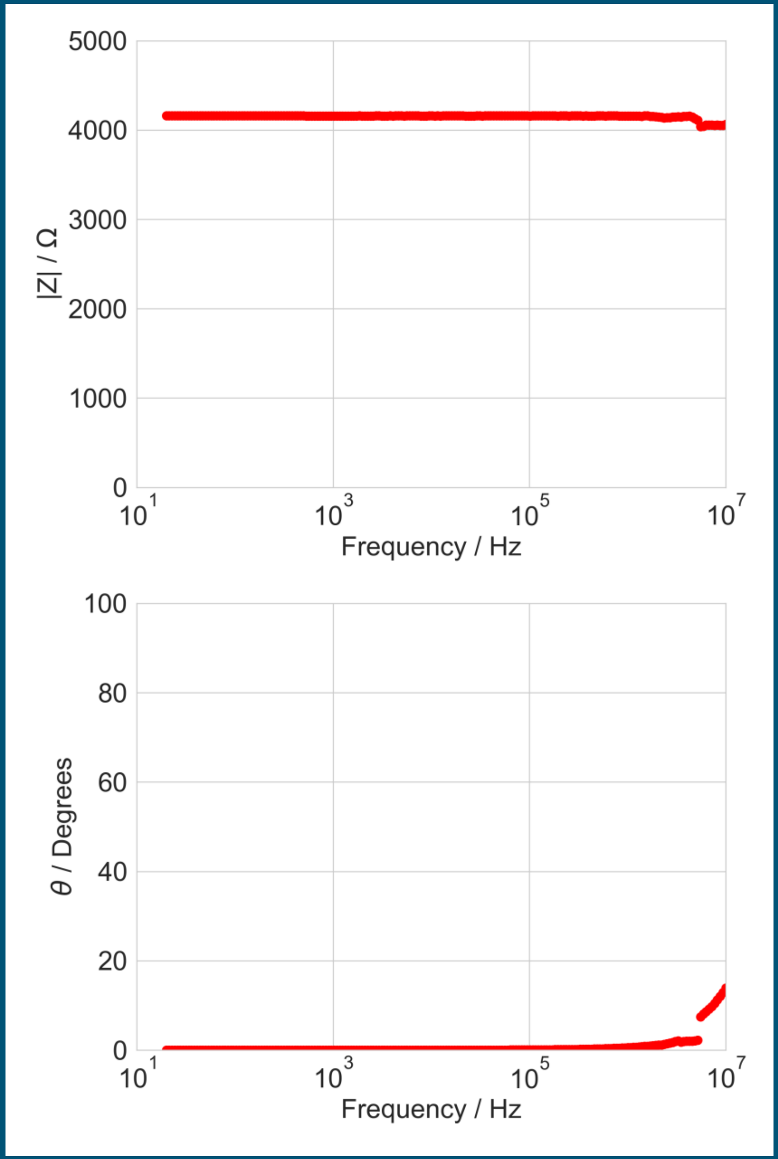
- Impedance spectra were fit to a circuit model:
  - R – L (Resistor in series with Inductor)

Ag only	Ag only	5 min Electroless	10 min Electroless
Without Cu	Cu Electrodeposition		
R = 4.15 kΩ	R = 736 Ω	R = 121 Ω	R = 20.0 Ω
L = N/A	L = 5.5 µH	L =5.0 µH	L = 4.6 µH
Resistance Improvement	X 5.6	X 34	X 208

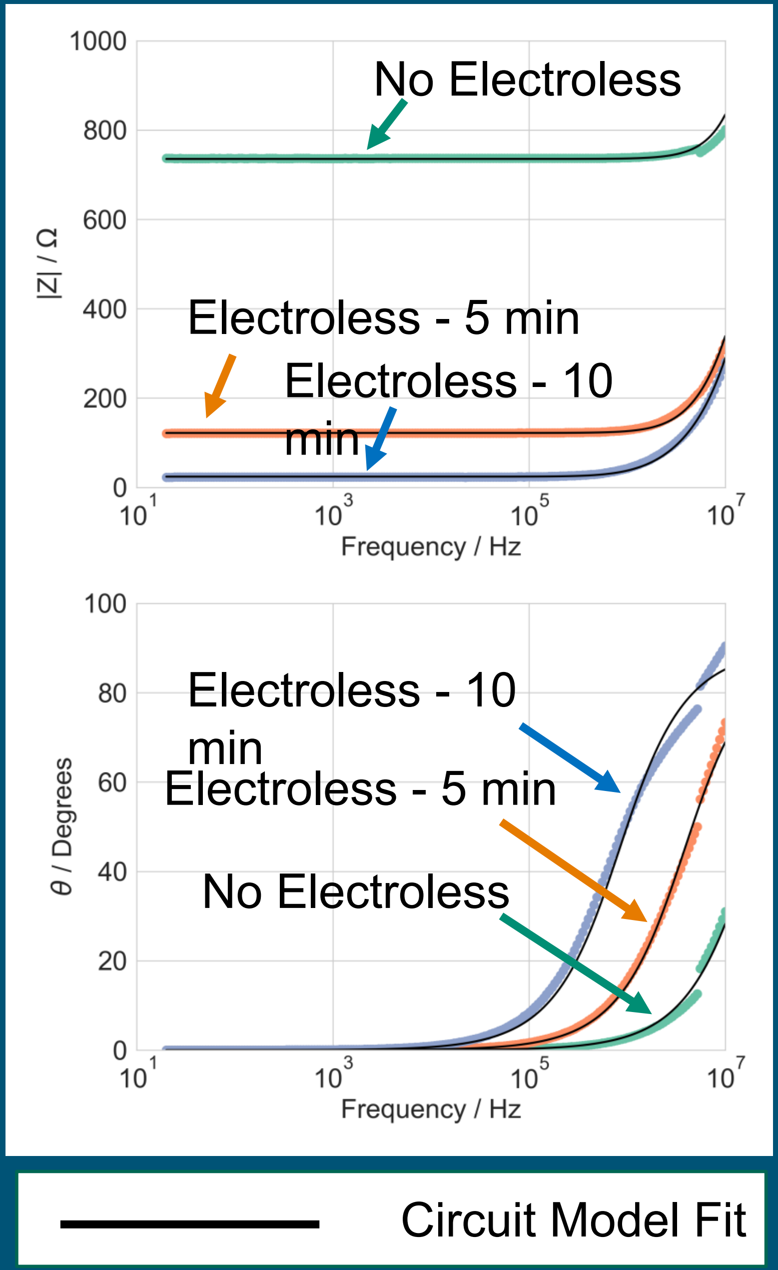
- Without electrodeposition, response completely dominated by 4.15 kΩ Ohmic resistance. Inductance could be measured after electrodeposition to be 4.6-5.5 µH.

- Up to **208x decrease** in resistance observed after electrodeposition.

Ag Only



Ag + Cu Electrodeposition



Conclusions

We have demonstrated the capability to deposit electronic components of high resolution and low resistance with a combined aerosol jet printing and electroless and/or electrodeposition approach.

The resistance for primary inductors was reduced to below 1 Ω and resistance of secondary inductors was reduced by 208X.

Electrodeposition was successfully able to recover the inductive behavior from the printed secondary and inductances around 4.6-5.5 μH were measured.

Future Work:

- Apply printing of dielectric polymers to separate layers and integrate the inductors into a working transformer device.

Acknowledgements:

We thank Jamin Pillars and Christian Arrington (Sandia National Labs) for their assistance with developing the electrodeposition/electroless processes. We also acknowledge Sam Strong (Sandia National Labs) for assistance with optimization of printing hardware, and Emily Weigel (Sandia National Labs) for assistance with electroless deposition and profilometry.

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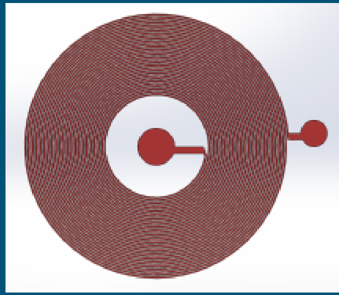
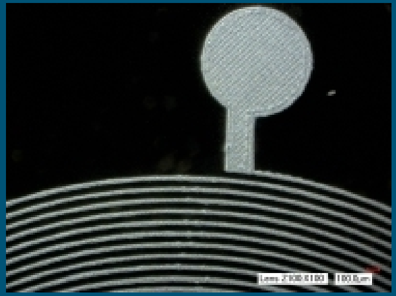
CAD



Aerosol Jet



Electroless Deposition

Electrodeposition