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# A HYBRID AEROSOL JET, ULTRASONIC SPRAY, AND ELECTRODEPOSITION APPROACH FOR ADDITIVELY MANUFACTURING MULTI-LAYER TRANSFORMERS ON MAGNETIC SUBSTRATES

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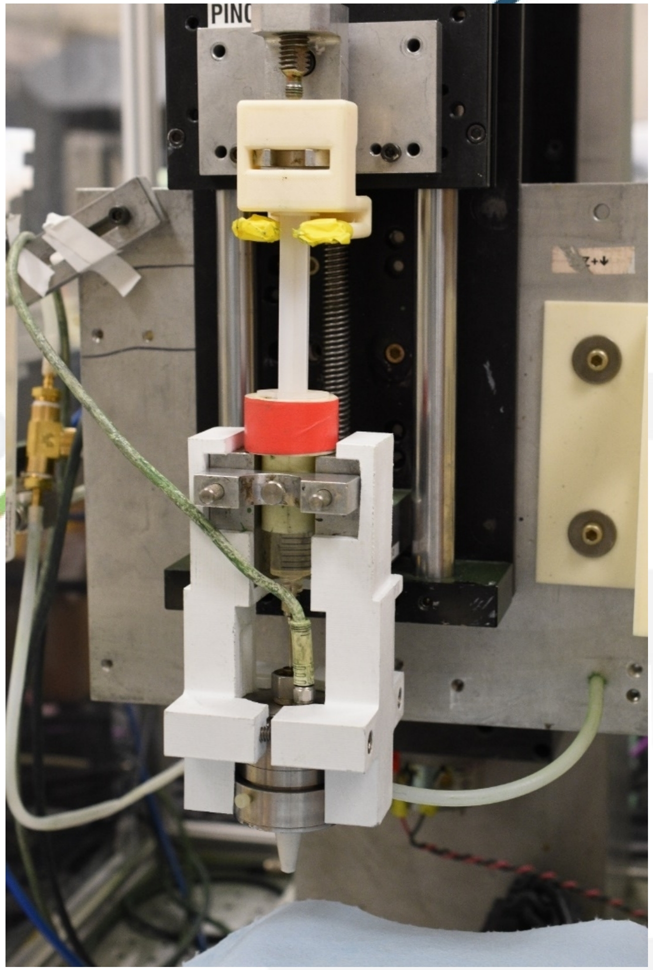

CENTER FOR MICRO-ENGINEERED MATERIALS

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Metal Jetting and Droplet Deposition Processes

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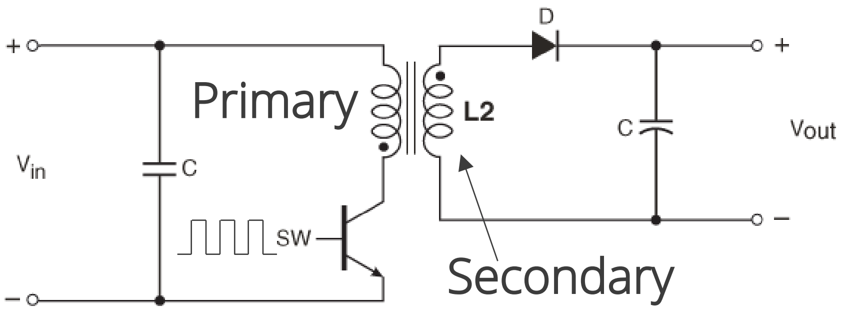
# OVERVIEW

- Motivation: Additive Manufacturing of Flyback Transformers
- Aerosol Jet Printing (AJP) and Electrochemical Deposition (ECD) for Multi-layer Transformers
- Stability Limitations of AJP for Printing Polymer Dielectrics
- 3D Printed Masks for Patterning Ultrasonic Spray (US) of SU8
- Printing and Characterization of Inductors Manufactured by AJP, ECD, and US
- Conclusions and Future Work

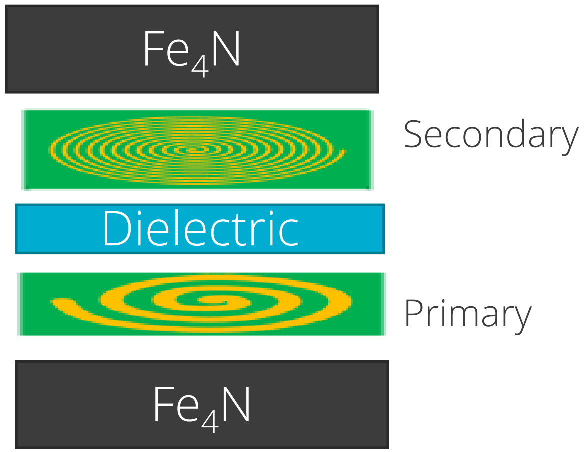
# MOTIVATION: MANUFACTURING OF CORELESS FLYBACK TRANSFORMERS

- Flyback transformers are used in voltage conversion in a wide range of applications: power supplies, RF devices, and photovoltaic inverters.
- **Operating Principle**
  - Energy stored in the magnetic field of the **primary inductor** transfers to the **secondary inductor** when current to the primary is switched at 30-500 kHz by a transistor.
  - Capacitor is then charged to output high voltage.
- Traditional magnetic core transformers are bulky, brittle, and heavy.
- Flyback transformers with planar cores are a lightweight, robust option.
- **Objectives**:
  - Minimize resistance of primary (ESR < 1 Ω).
  - Maximize inductance of secondary.
  - Integrate of $Fe_4N$ as magnetic material to enhance transformer performance.



Typical Flyback Converter Schematic [1]

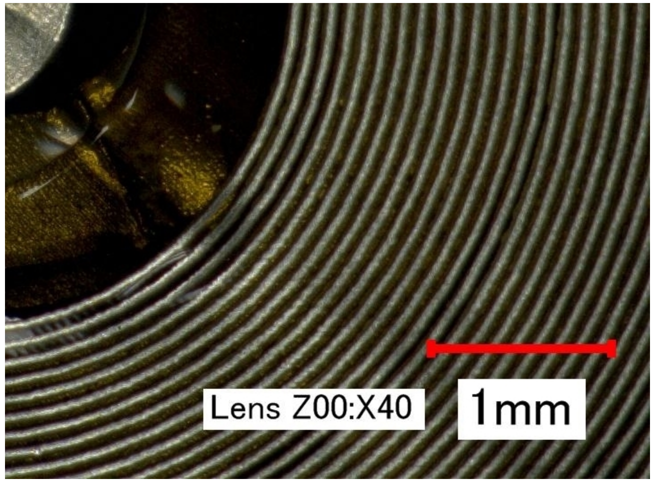

Commercial Wire Wound Magnetic Core Transformer



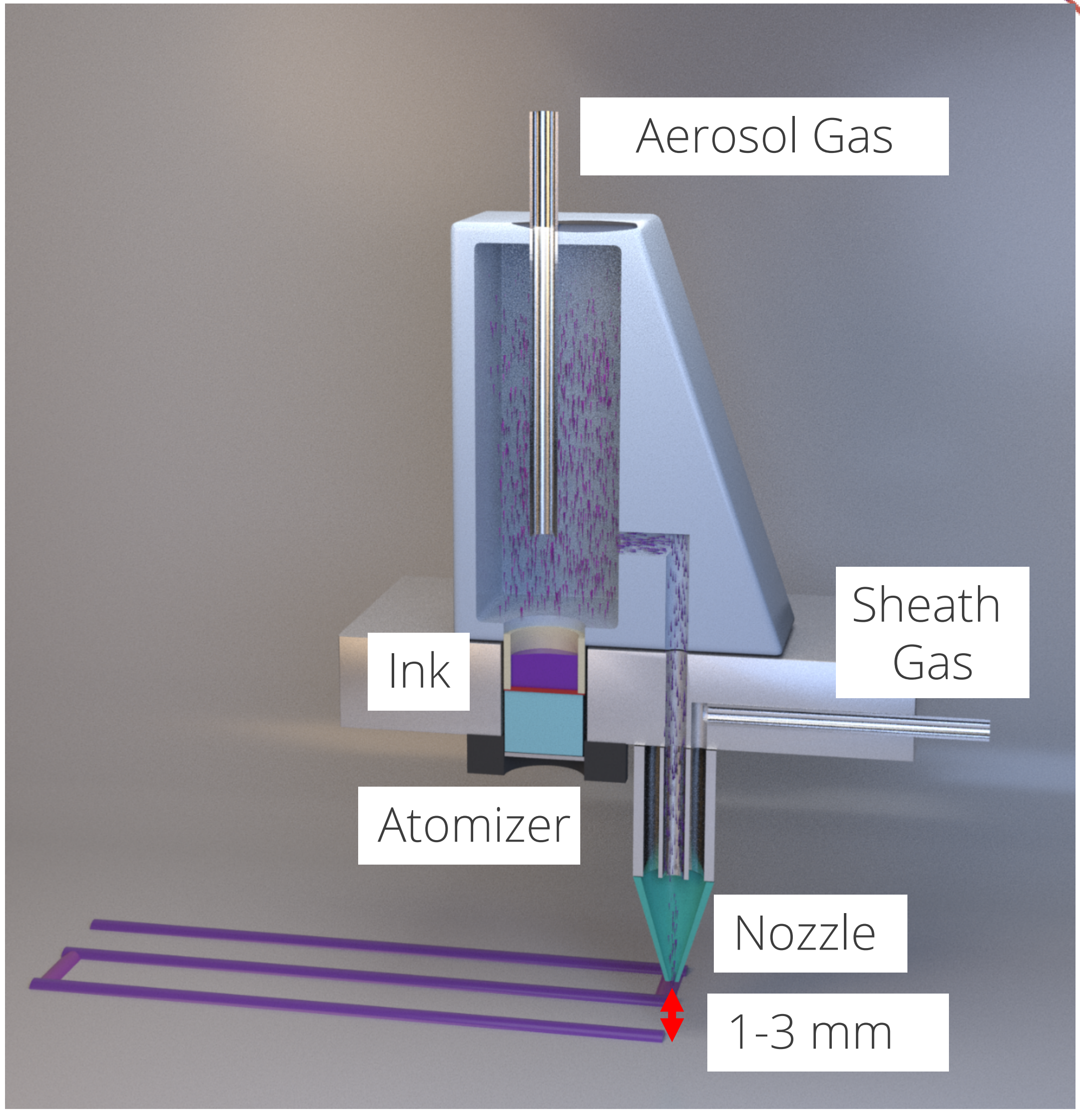

[1] Coilcraft. "A guide to flyback transformers." https://www.coilcraft.com/en-us/edu/series/a-guide-to-flyback-transformers/

# AEROSOL JET PRINTING

- Aerosol Jet Printing (AJP) is a direct write AM technology that prints low viscosity inks ( < 10 cPs) of metal nanoparticle (NP) and dielectric polymers.
- Action of sheath gas and aerodynamic focusing generates an X-Y resolution of 10 μm.
- 1-3 mm stand-off enables printing on stepped and rounded surfaces.
- **Limitations**:
  - Low conductivity of NP inks vs. bulk (35-40% bulk Ag).
  - Thickness is usually only a few μm for metal inks.
  - Limited selection of NP inks for high quality films.

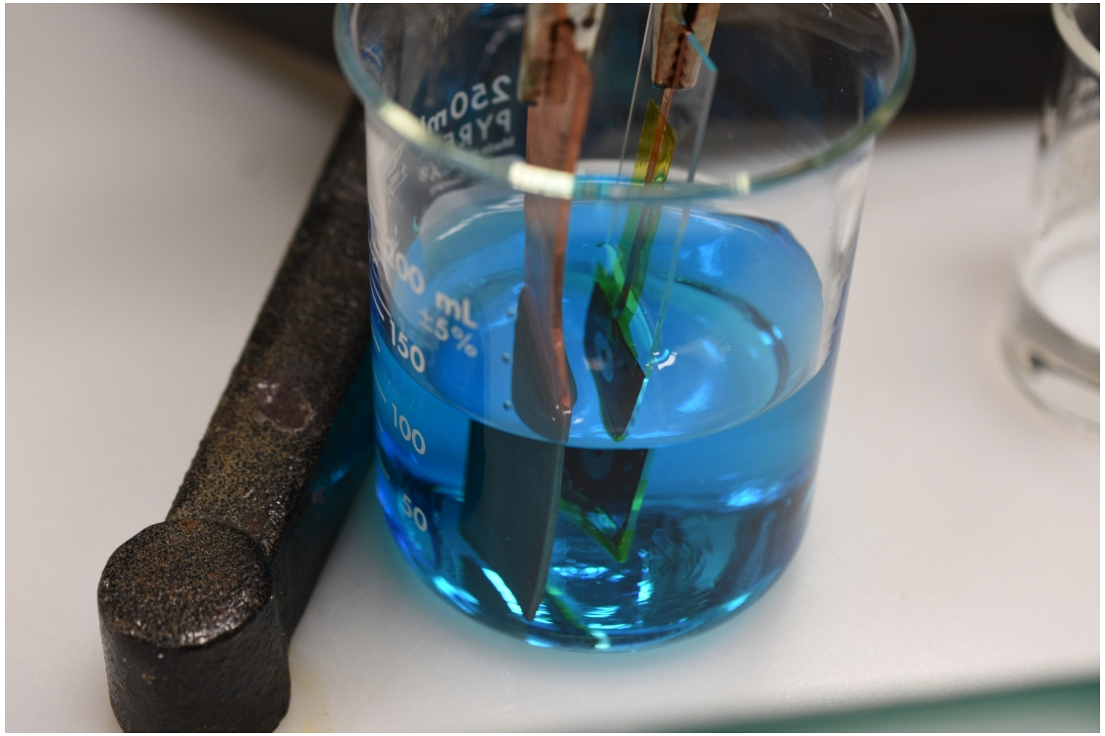



Ag lines of 60 μm width

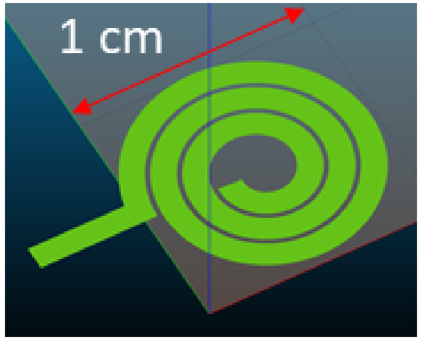


# ELECTROCHEMICAL DEPOSITION

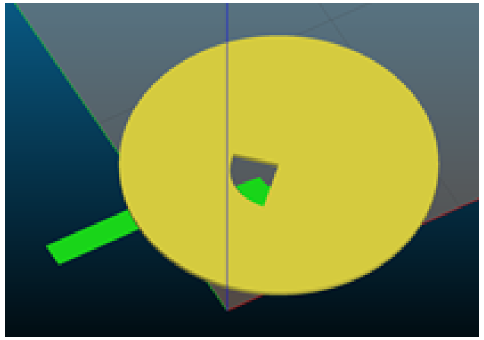
- **Electrodeposition** is widely used in the microelectronics manufacturing industry.
- Capable of depositing 10s of µm thick films of a wide variety of metals (Cu, Ni).
- **Limitations:** Patterning methods such as photolithography are expensive or require access to clean room PVD methods to deposit the conducting seed layer.
- Combination of AJP process for **high resolution, low cost patterning** + electrochemical deposition for **high density and conductivity** films gives us the best of both worlds.



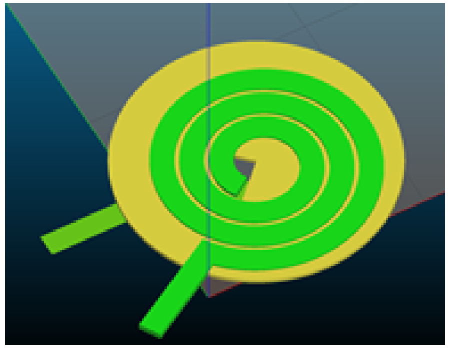
# 2-LAYER PRIMARY + 2-LAYER SECONDARY TRANSFORMER DESIGN



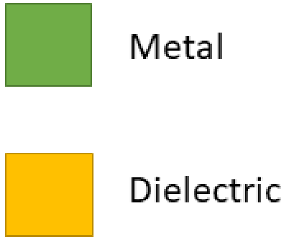

Primary Layer 1

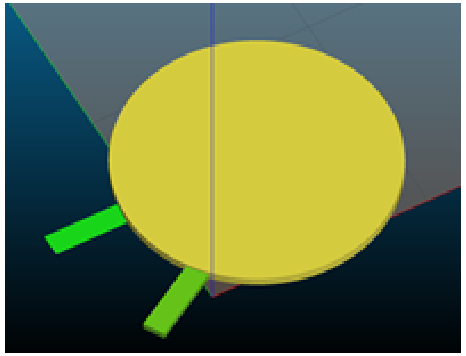


NOA61 Dielectric



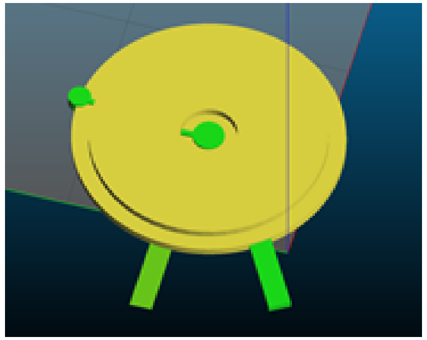
Primary Layer 2



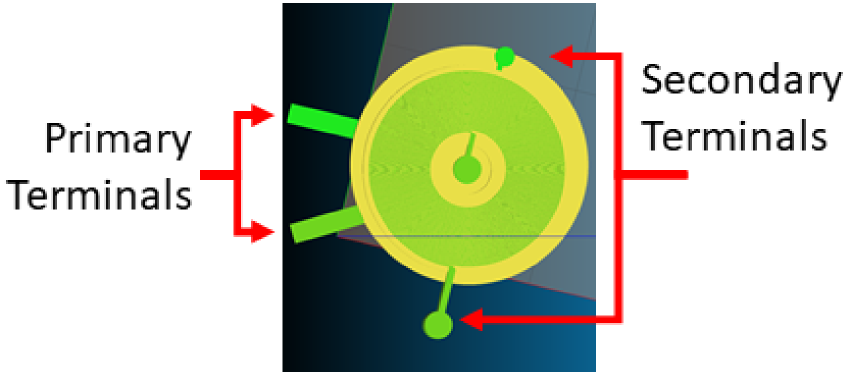



NOA Dielectric

Secondary Layer 1



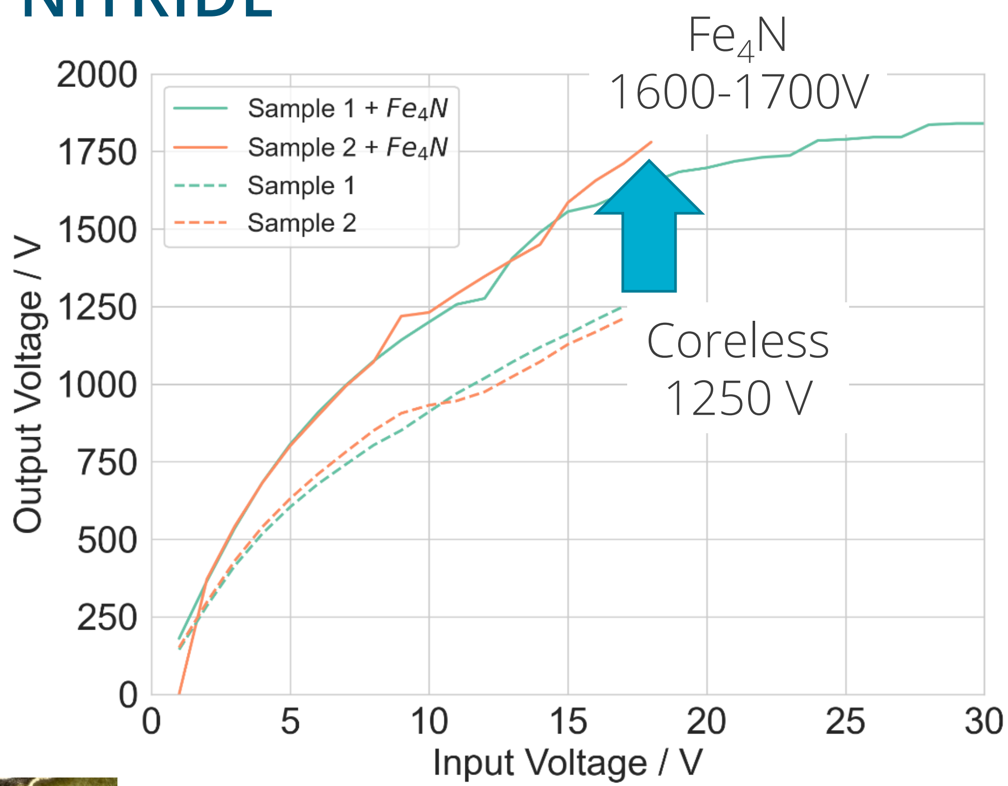
NOA Dielectric

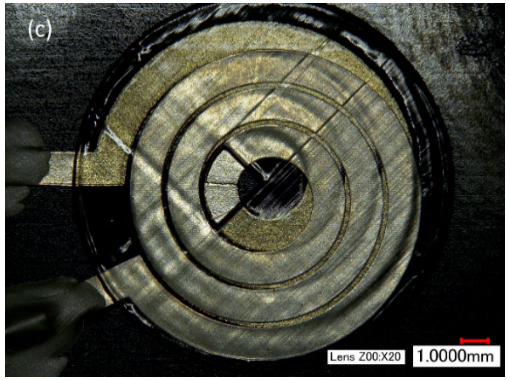



Secondary Layer 2

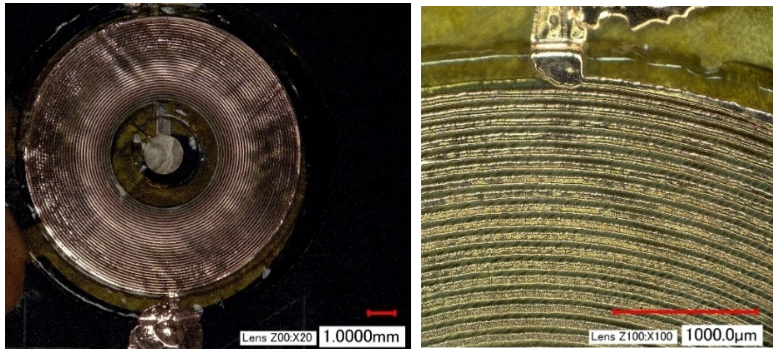
# ENHANCED PERFORMANCE WITH IRON NITRIDE

- $Fe_4N$ plates were formed by mixing $Fe_4N$ in epoxy and cast into a mold.
- **Proof of Concept**: The previous coreless transformer was sandwiched between $Fe_4N$ plates and secured with tape.
- Inductance is increased by 40 % - 117 %.
- At an input voltage of 17 V, the output voltage increased from 1250 V to 1600-1700 V with a gain of 95-100X due to the enhanced inductance of the transformer components.
- Interfacing with magnetic material would be better if transformer is directly built on $Fe_4N$.

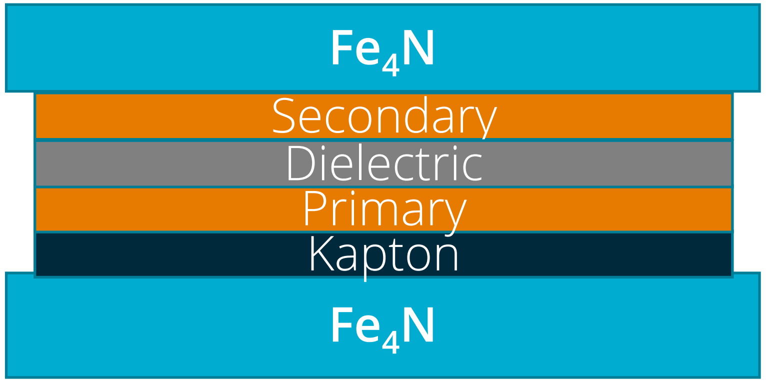



Primary Inductor



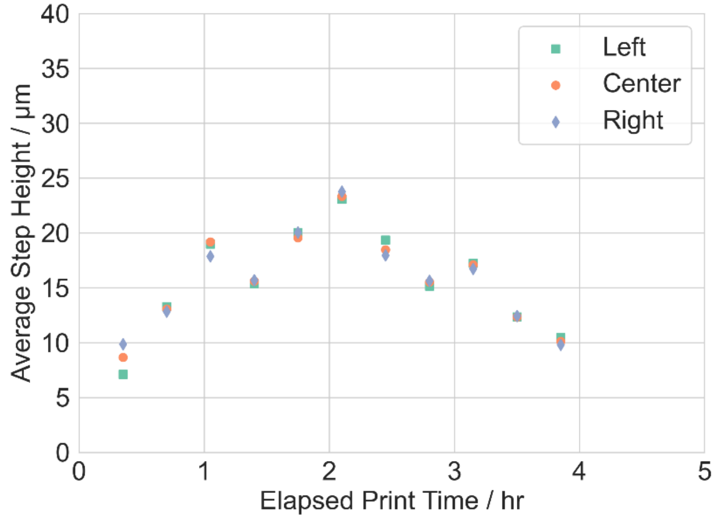

Secondary Inductor



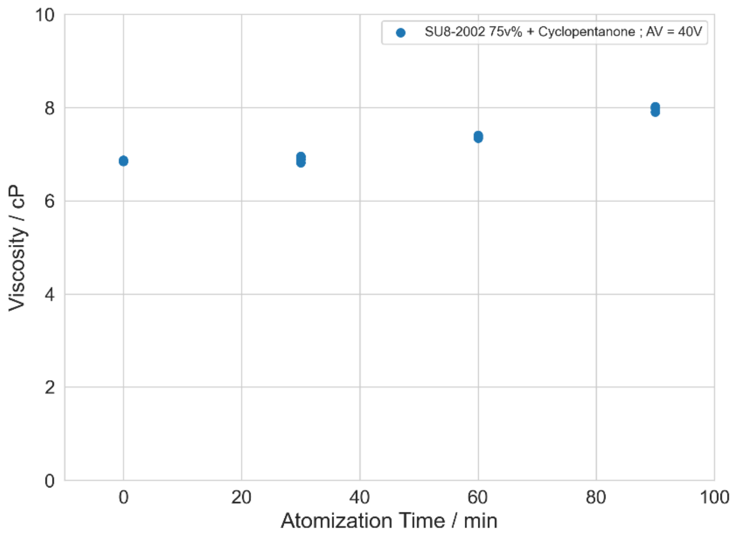
# LIMITATIONS OF AEROSOL JET PRINTING FOR POLYMER INKS

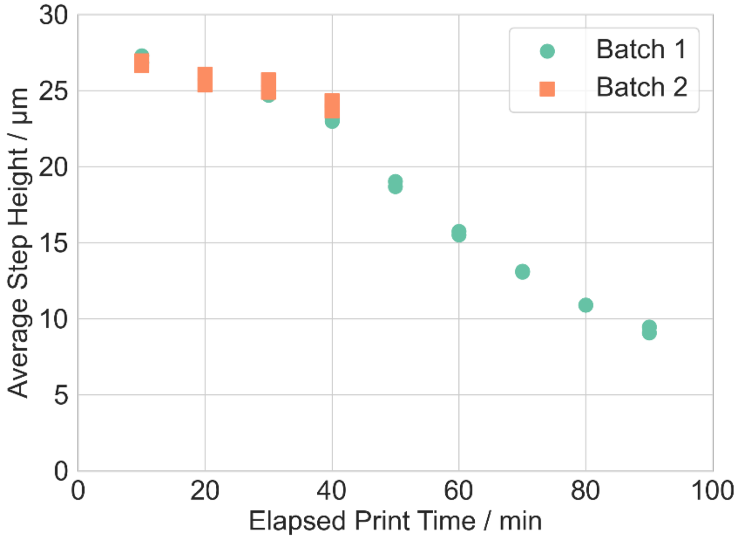
- We transitioned away from AJP of dielectrics because of stability limitations:
  - **Norland Optics NOA61**
    - Variations in the deposition rate during printing and day to day made it difficult to reproduce samples.
    - Clogging of the nozzle occurred due to photopolymerized material accumulating on the tip ruined parts.
  - **SU8-2000.5**
    - SU8 is a thermally cured, negative photoresist. The viscosity of the ink increases during printing due to energy imparted by ultrasonic atomizer, resulting in a continuous decrease in deposition rate over time.
- Long print times of over 1 hour per sample increased chance of failure by AJP.

NOA 61 Print Stability



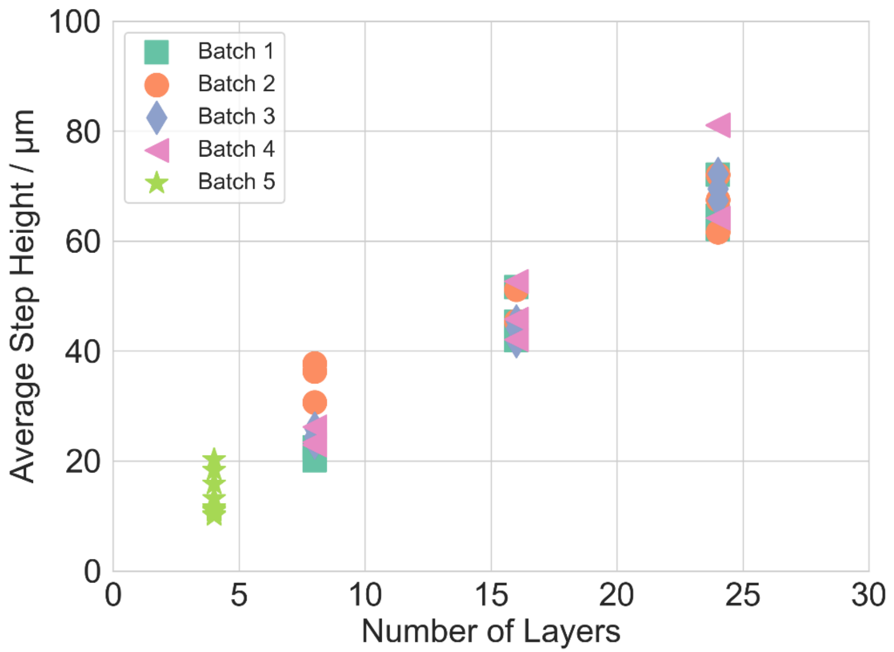

SU8 2000.5 Print Stability

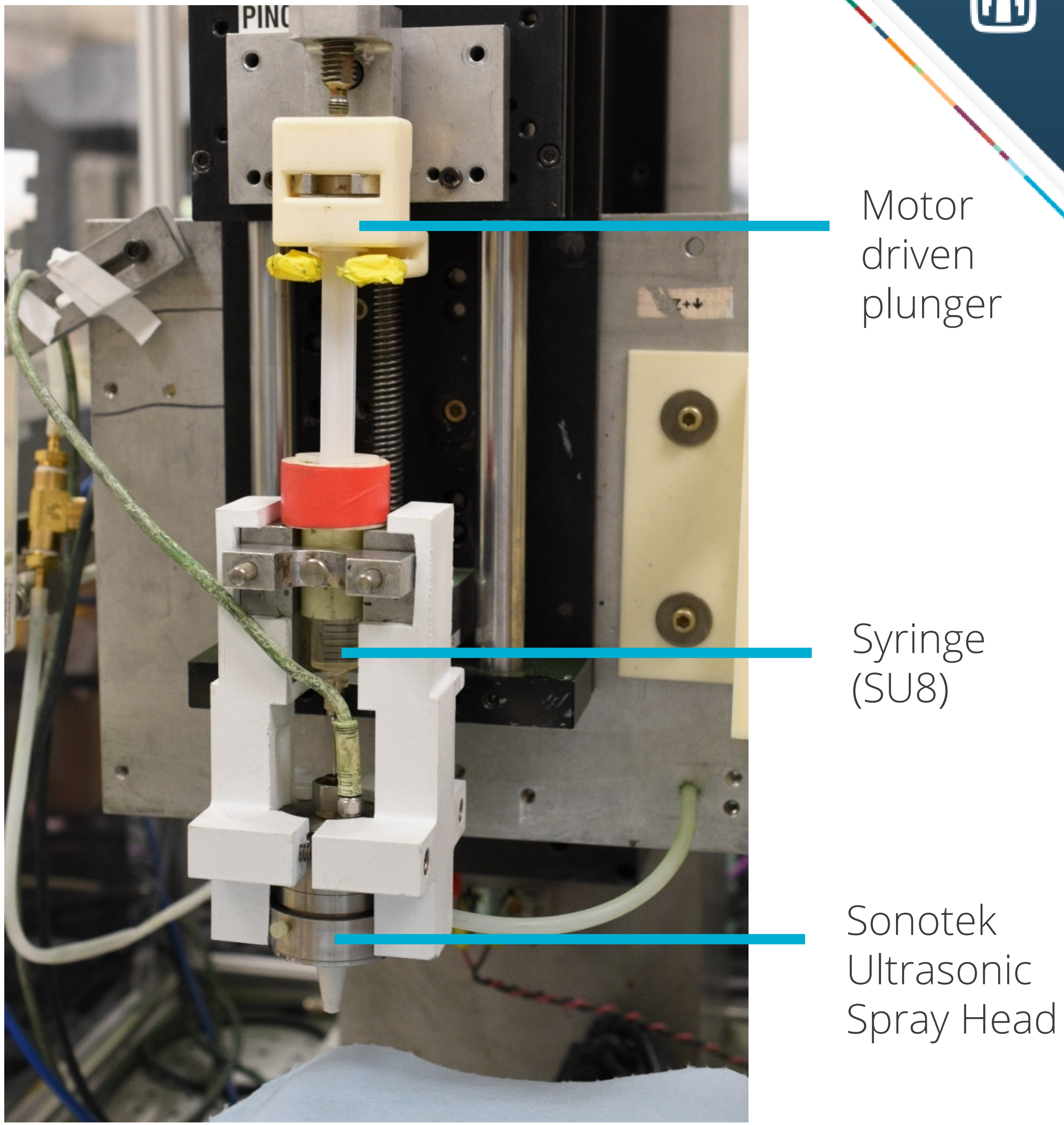


# ULTRASONIC SPRAY

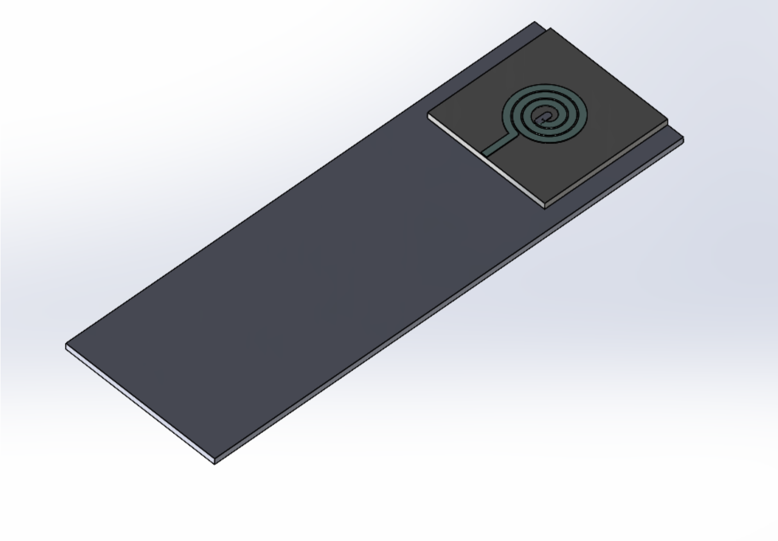
- Ultrasonic Spray (US) is a technology that deposits coatings with uniform layers of fluids atomized into a mist.
- Ultrasonic energy is only applied as the ink passes through the nozzle, so the bulk viscosity in the syringe does not change.
- Lower resolution than AJP, but can cover large areas in a faster time.
- Thickness of 10-20 μm reproducibility across multiple batches without any tuning.



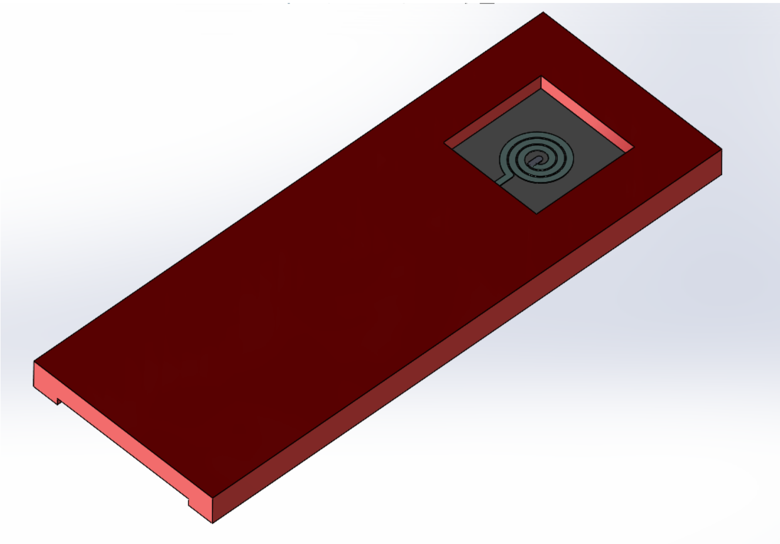



# MASKING DESIGN

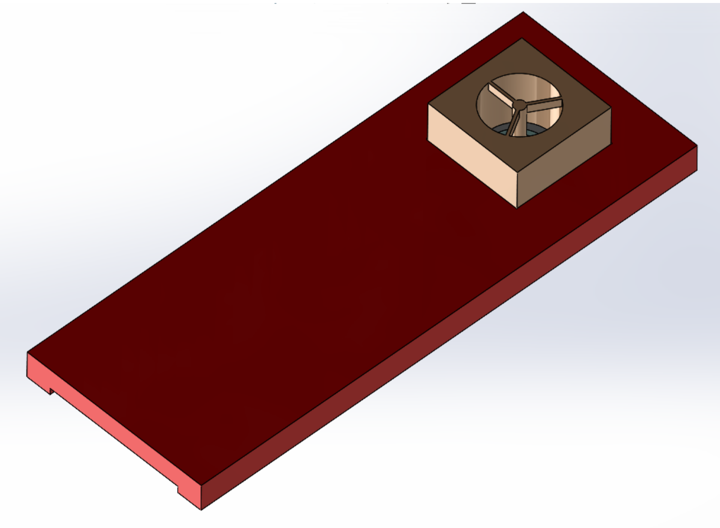
- Spray resolution is on the order of mm, so masks are used to pattern the dielectric films.
- Masks feature a Y-shape supported center column which opens a hole in the pattern for connecting inductor layers.
- Printed on Stratasys Polyjet in VeroClear.



1x3" glass slide
20 x 20 mm $Fe_4N$ substrate



Mask Holder

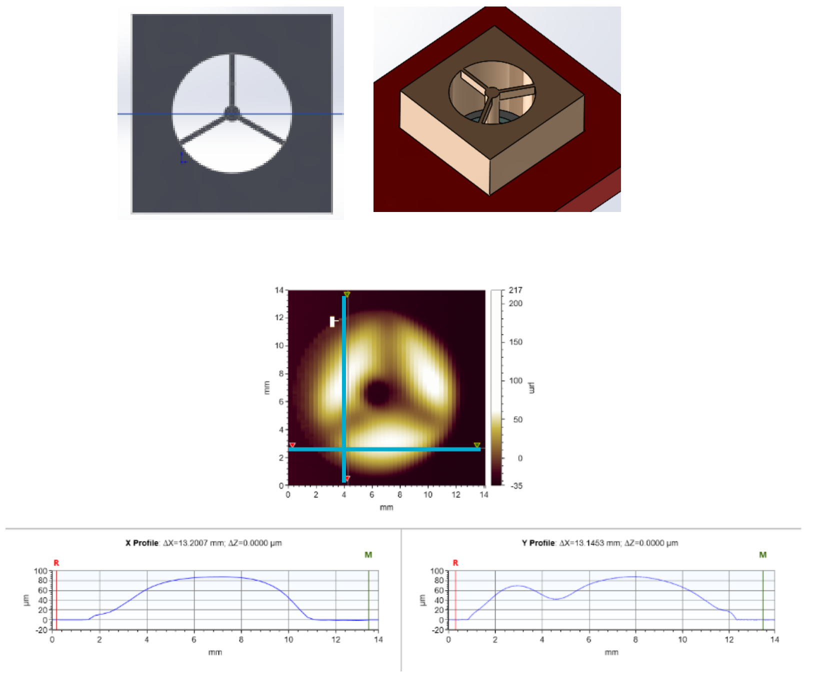


Customizable Mask Pattern

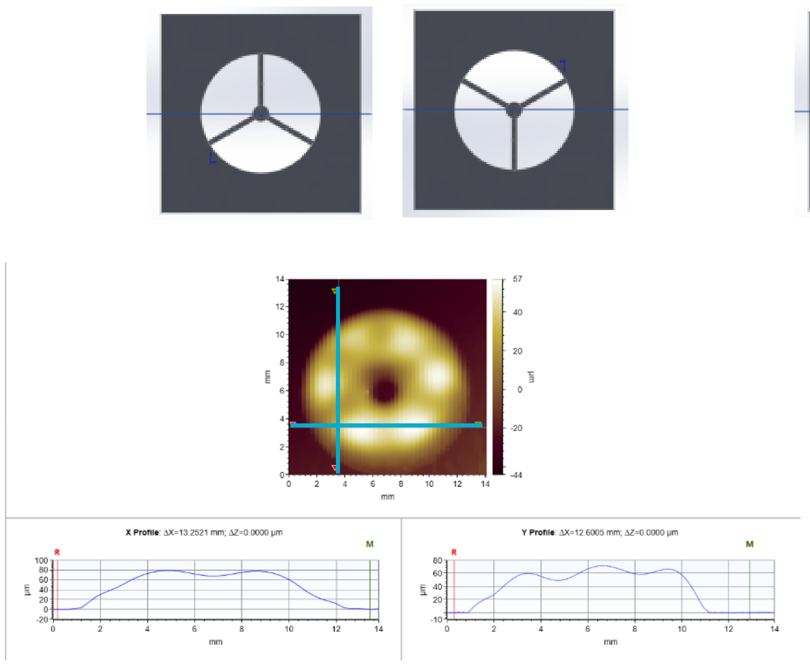
# UNIFORM DEPOSITION WITH CENTER COLUMN SUPPORTS

- The shadowing effect of the support bars for the center column result in uneven coatings.
- Rotating the mask during deposition smooths out the deposited film.

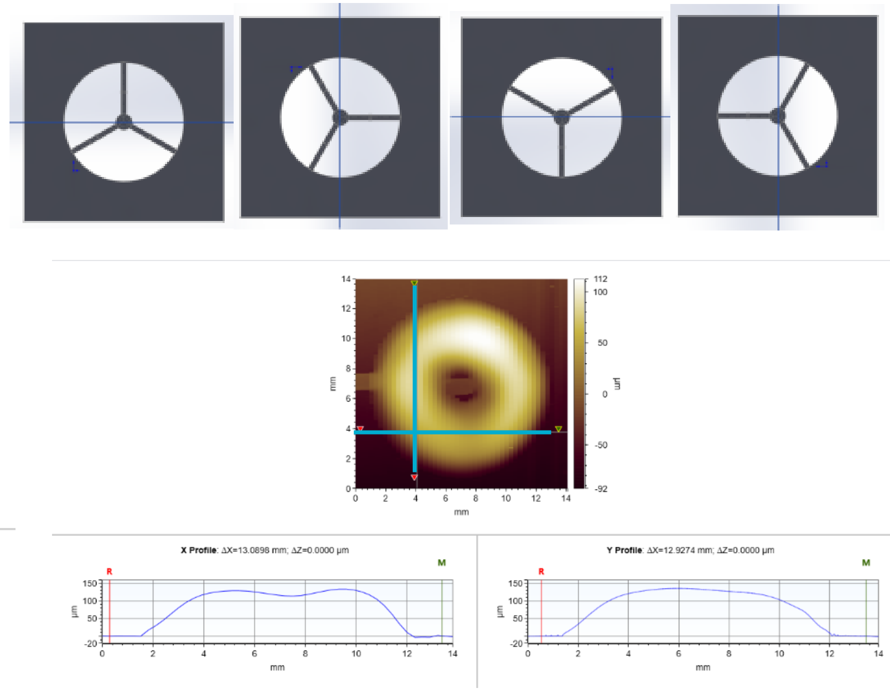
No Rotation




180 Degree Rotation x2

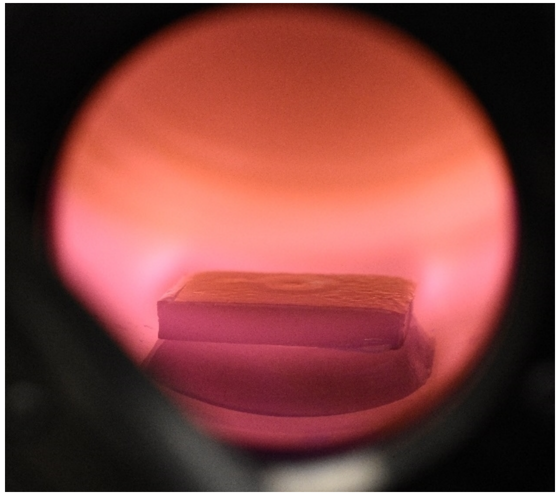



90 Degree Rotation x4

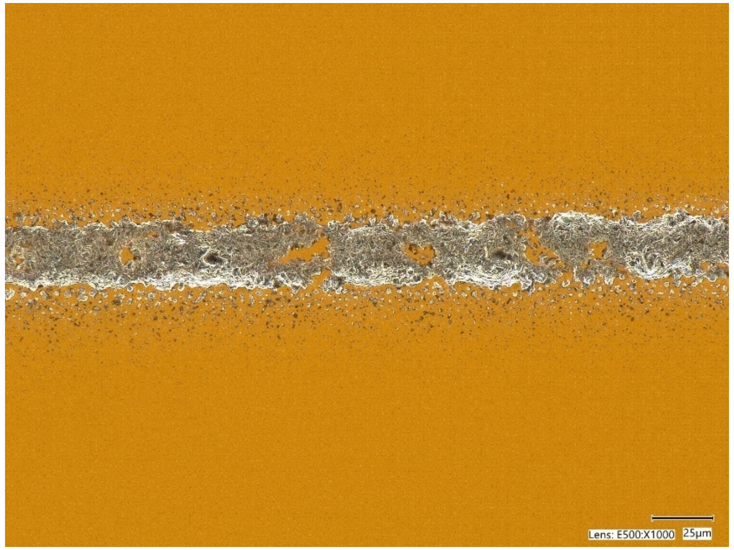


# WETTING OF AG INKS ON SU8

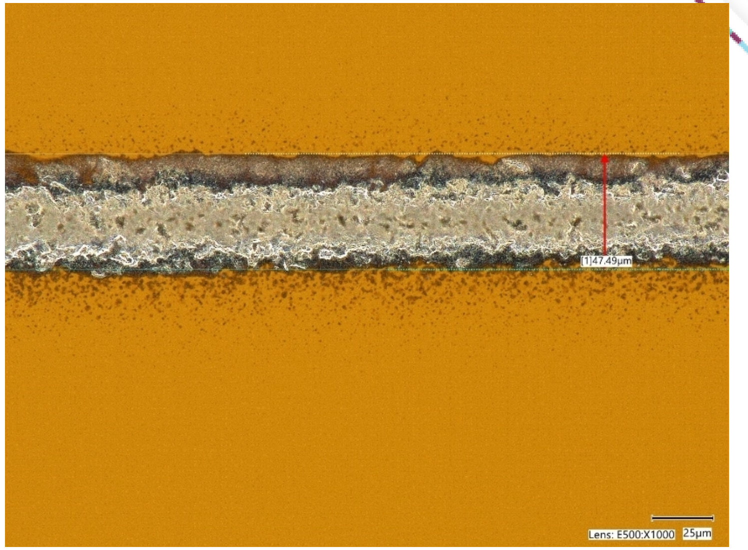
- AJP of Ag inks do not wet to SU8. Lines formed are patchy and discontinuous.
- Plating of Cu on unmodified SU8 results in incomplete coverage with Cu.
- Discontinuous patches of Ag are connected as Cu grows laterally.
- Surface modification by $N_2$ plasma improves adhesion, resulting in continuous Ag lines.
- Plating of Ag lines propagates quickly along the trace, resulting in a fully plated inductor.



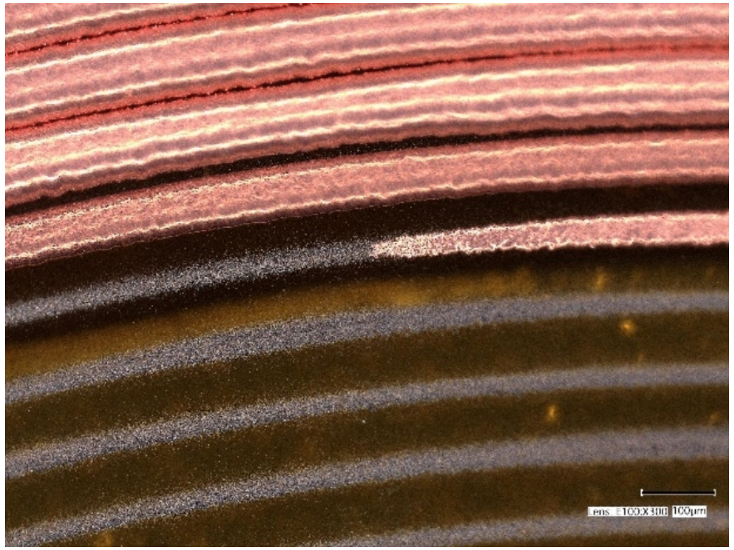
Untreated SU8 + AJP Ag



$N_2$ Plasma SU8 + AJP Ag



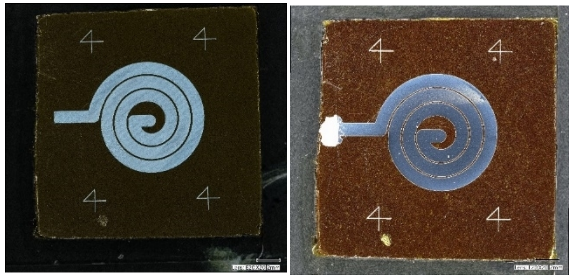
After Cu Plating



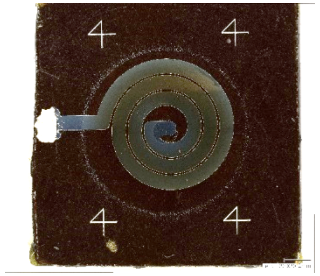
After Cu Plating

# PROCESS OVERVIEW: MANUFACTURING OF A MULTI-LAYER TRANSFORMER

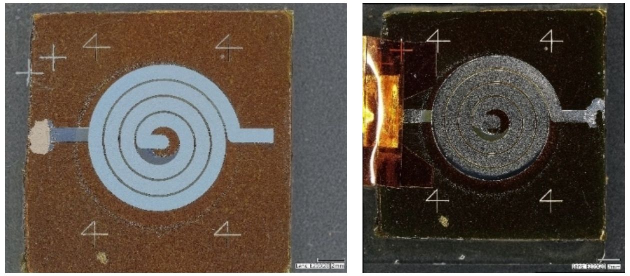
Casting of $Fe_4N$ Plates



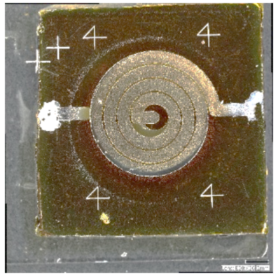
Primary Layer 1
(Ag, Cu, Ni)
AJP + ECD



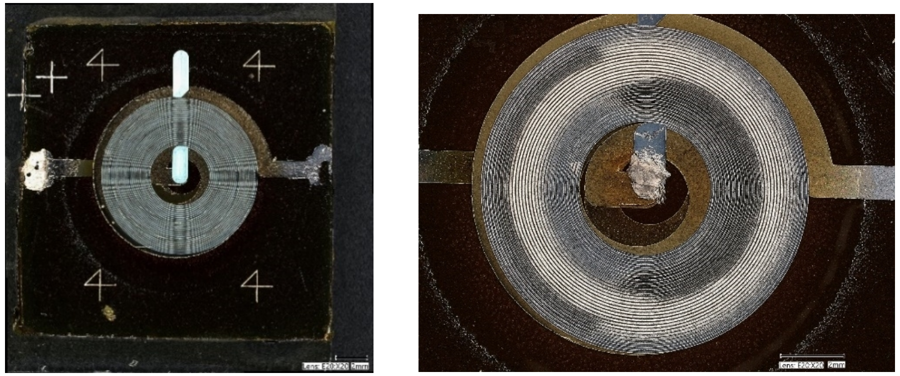
Primary Separator
(SU8)
US



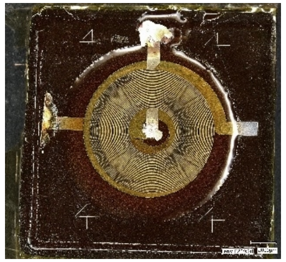
Primary Layer 2
(Ag, Cu, Ni)
AJP + ECD



Primary-Secondary Separator
(SU8)
US



Secondary Layer 1
(Ag, Cu, Ni)
Plasma + AJP + ECD

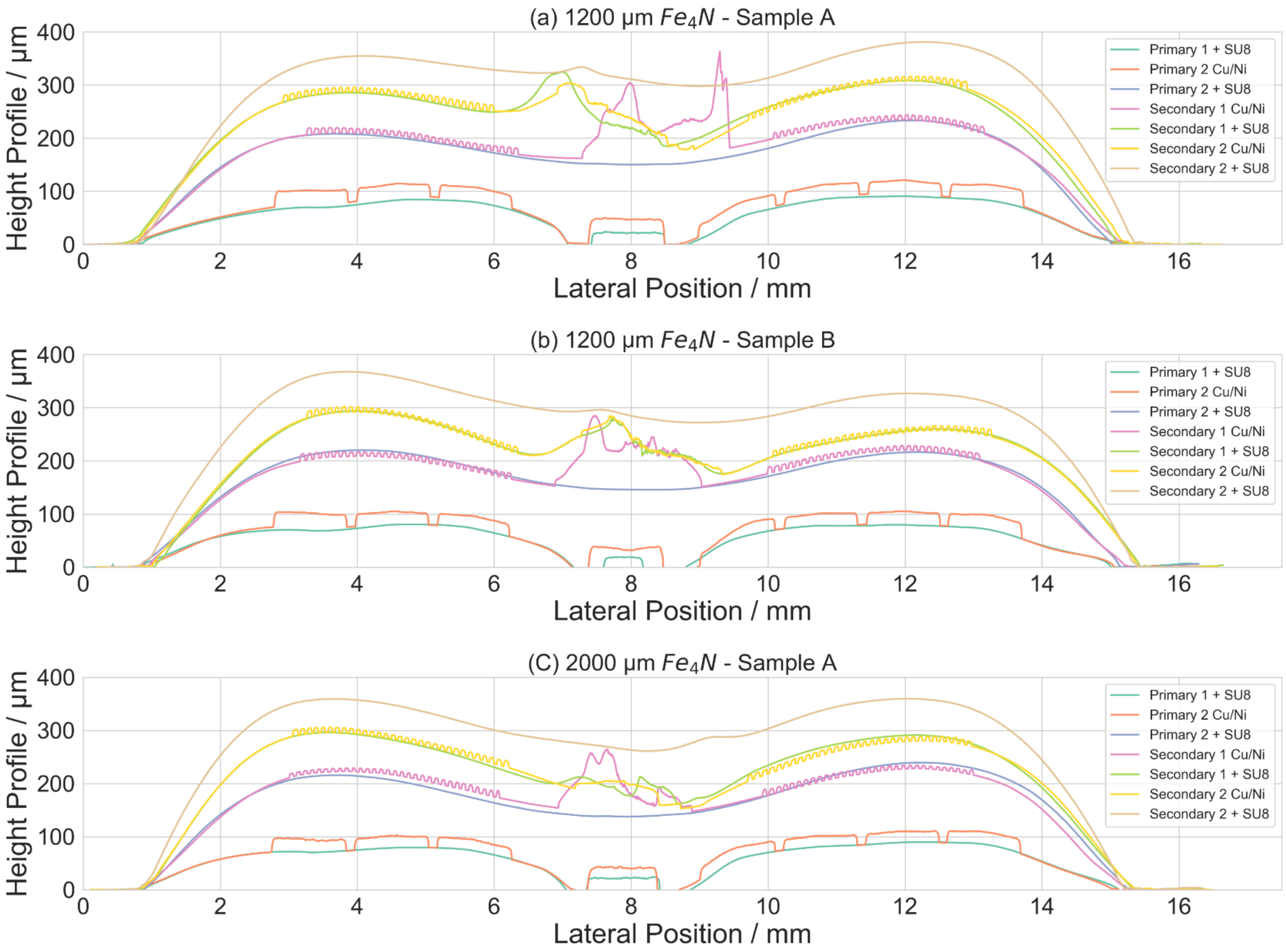


Secondary Separator
(SU8)
US

Secondary Layer 2
(Ag, Cu, Ni)
Plasma + AJP + ECD

Secondary Final Overcoat
(SU8)
US

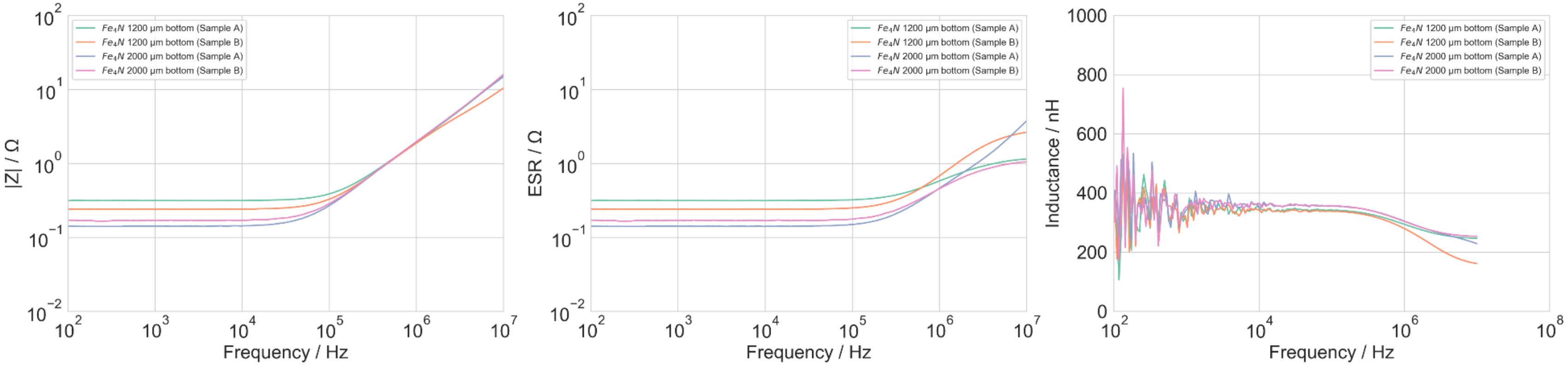
# PROFILOMETRY



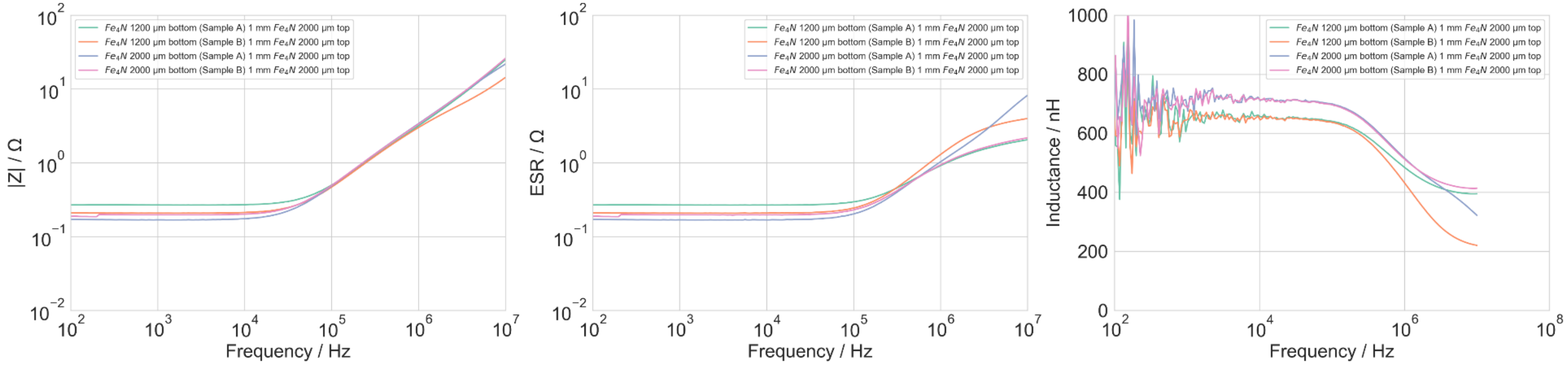
# PRIMARY INDUCTOR IMPEDANCE

- Inductance measurements were taken with an impedance analyzer from 10 Hz to 10 mHz.
- Two batches of samples were made, with extended plating time for secondary in Batch 2.
- Measurements were taken with and without a layer of $Fe_4N$ placed on top.
- Inductance increases with increasing $Fe_4N$ substrate thickness.

## $Fe_4N$ Bottom Only




## $Fe_4N$ Bottom + 1 mm Top



# INDUCTANCE/ESR – 100 KHZ – PRIMARY (2 LAYERS)

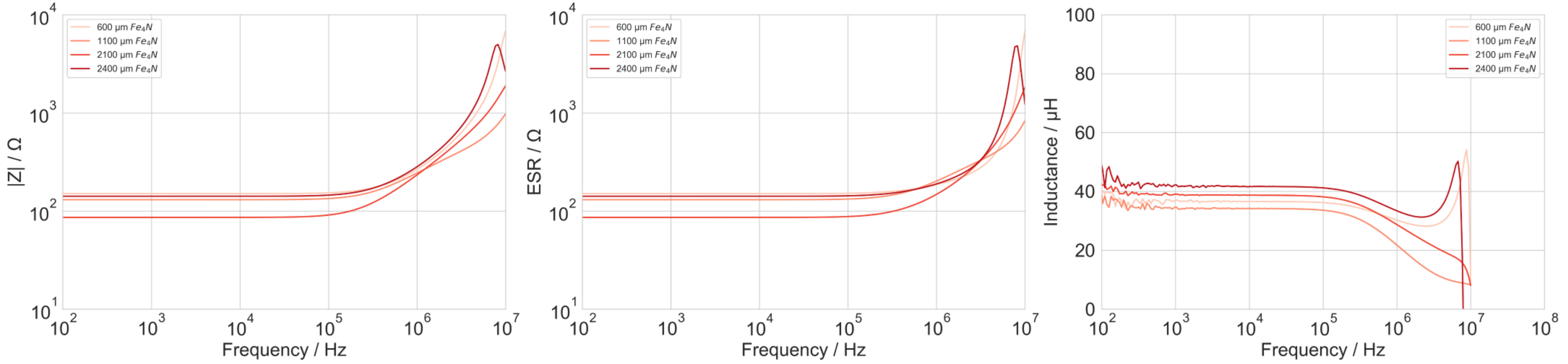
- Inductance approximately doubles after addition of Fe4N to close the magnetic loop.
- The Primary ESR is below the target of 1 Ω.

| | | $Fe_4N$ Bottom Only | | $Fe_4N$ Bottom + 1 mm Top | |
|---|---|---|---|---|---|
| Batch | $Fe_4N$ Substrate Thickness | Inductance (100 kHz) | ESR (100 kHz) | Inductance (100 kHz) | ESR (100 kHz) |
| 1 | 600 μm $Fe_4N$ | 0.327 μH | 0.232 Ω | 0.561 μH | 0.241 Ω |
| 1 | 1100 μm $Fe_4N$ | 0.365 μH | 0.110 Ω | 0.722 μH | 0.164 Ω |
| 1 | 2100 μm $Fe_4N$ | 0.383 μH | 0.192 Ω | 0.781 μH | 0.228 Ω |
| 1 | 2400 μm $Fe_4N$ | 0.386 μH | 0.178 Ω | 0.809 μH | 0.218 Ω |
| 2 | (A) 1200 $Fe_4N$ | 0.342 μH | 0.322 Ω | 0.639 μH | 0.300 Ω |
| 2 | (B) 1200 $Fe_4N$ | 0.341 μH | 0.240 Ω | 0.645 μH | 0.209 Ω |
| 2 | (A) 2000 $Fe_4N$ | 0.356 μH | 0.149 Ω | 0.711 μH | 0.167 Ω |
| 2 | (B) 2000 $Fe_4N$ | 0.357 μH | 0.176 Ω | 0.697 μH | 0.231 Ω |

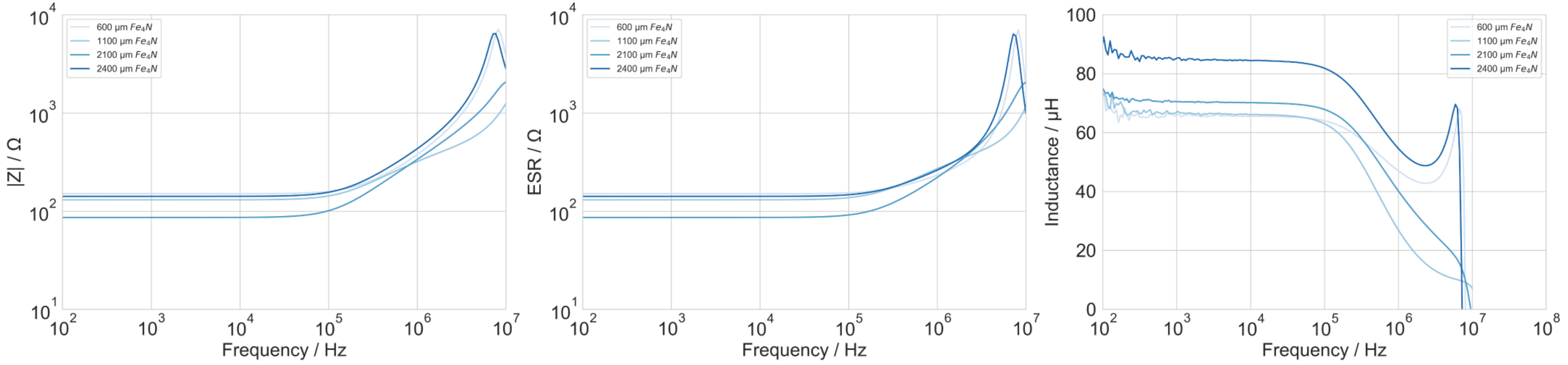
# IMPEDANCE MEASUREMENTS (SECONDARY INDUCTORS)

Impedance measurements of Secondary inductor measured with and without a top plate of 1 mm $Fe_4N$

## Bottom $Fe_4N$ Only




## Bottom $Fe_4N$ + 1 mm $Fe_4N$ top



# INDUCTANCE/ESR – 100 KHZ – SECONDARY (2 LAYERS)

| | | $Fe_4N$ Bottom Only | | $Fe_4N$ Bottom + 1 mm Top | |
|---|---|---|---|---|---|
| Batch | $Fe_4N$ Substrate Thickness | Inductance (100 kHz) | ESR (100 kHz) | Inductance (100 kHz) | ESR (100 kHz) |
| 1 | 600 µm $Fe_4N$ | 36.18 µH | 152 Ω | 63.98 µH | 154 Ω |
| 1 | 1100 µm $Fe_4N$ | 33.58 µH | 132 Ω | 62.94 µH | 137 Ω |
| 1 | 2100 µm $Fe_4N$ | 38.14 µH | 87.8 Ω | 67.54 µH | 92.1 Ω |
| 1 | 2400 µm $Fe_4N$ | 41.18 µH | 143 Ω | 81.81 µH | 148 Ω |
| 2 | (A) 1200 $Fe_4N$* | 32.31 µH | 73.01 Ω | 59.04 µH | 76.64 Ω |
| 2 | (B) 1200 $Fe_4N$ | 37.93 µH | 73.72 Ω | 70.30 µH | 75.99 Ω |
| 2 | (A) 2000 $Fe_4N$ | 39.52 µH | 88.33 Ω | 75.43 µH | 91.29 Ω |
| 2 | (B) 2000 $Fe_4N$ | Sample failed (Dust contamination) | | | |

- Batch 2 – Plating time of the secondary inductor was increased to from 45 min to 1 hr 15 min and reduces the ESR by about ½.
- * Short observed in outer three layers of layer 1 leading to reduced inductance

# CONCLUSIONS AND FUTURE WORK

- We developed an ultrasonic spray technique with 3D printed masks for deposition of SU8 photoresist coatings as separation layers for our multi-layer transformers.
- This was integrated into an existing AJP and ECD process for deposition of Ag, Cu, and Ni for the inductor.
- Inductances of 0.5-0.8 μH for a 2-layer primary and 60-80 μH for a 2-layer secondary inductor were measured. The primary ESR was less than 0.3 Ω.
- Transformer testing is currently in progress.
- **Future work**:
  - Exploring alternative magnetic materials including commercially available products.
  - Improving yield of our manufacturing process – Dust remains a major issue.
  - Increasing number of inductor layers stacked to improve inductance further.

**Acknowledgements**

- We thank Jamin Pillars and Christian Arrington (SNL) for assistance with development of electroplating processes.
- Todd Monson and Melinda Hoyt (SNL) developed the manufacturing process for casting $Fe_4N$ plates. Josh Tarantino (SNL) performed the casting and curing.

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# EXTRA SLIDES

# ELECTROLYTE BATH COMPOSITION

**Copper Plating Bath:**

Microfab SC (32 g/L $CuSO_4$)

Additive mixture:

Microfab SC MD:LO = 1:4 by volume

16 mL additive per 1L Microfab SC

**Nickel Plating Bath:**

Ni-Sulfamate: 80 g/L

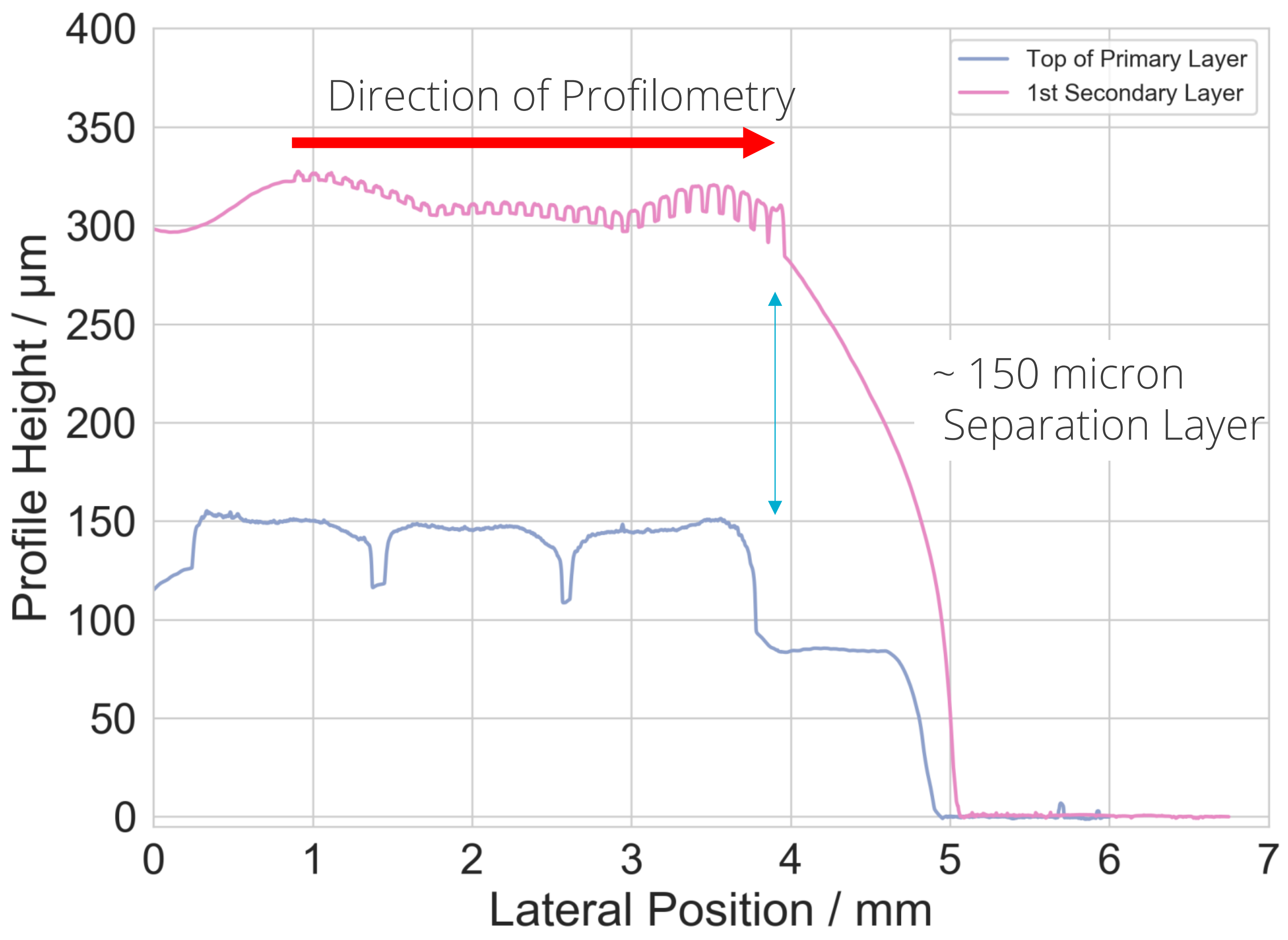
Boric Acid: 40 g/L

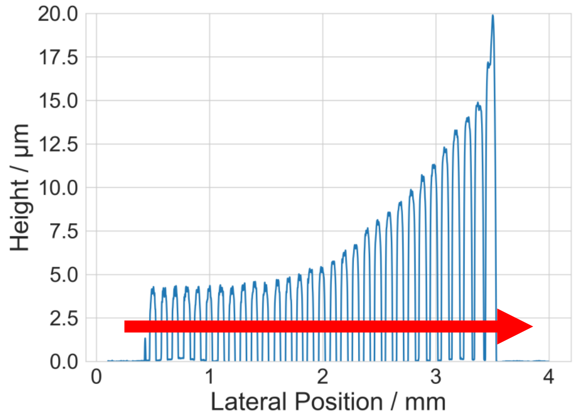
pH = 3.8

# ELECTRODEPOSITION CONDITIONS

| Part | Material | Current Density | Time |
|---|---|---|---|
| Transformer Primary Inductor | Cu | 30 $mA/cm^2$ | 90 min |
| | Ni | 3.75 $mA/cm^2$ | 4 min |
| Transformer Secondary Inductor | Cu | 15 $mA/cm^2$ | 30 min |
| | Ni | 2 $mA/cm^2$ | 16 min |

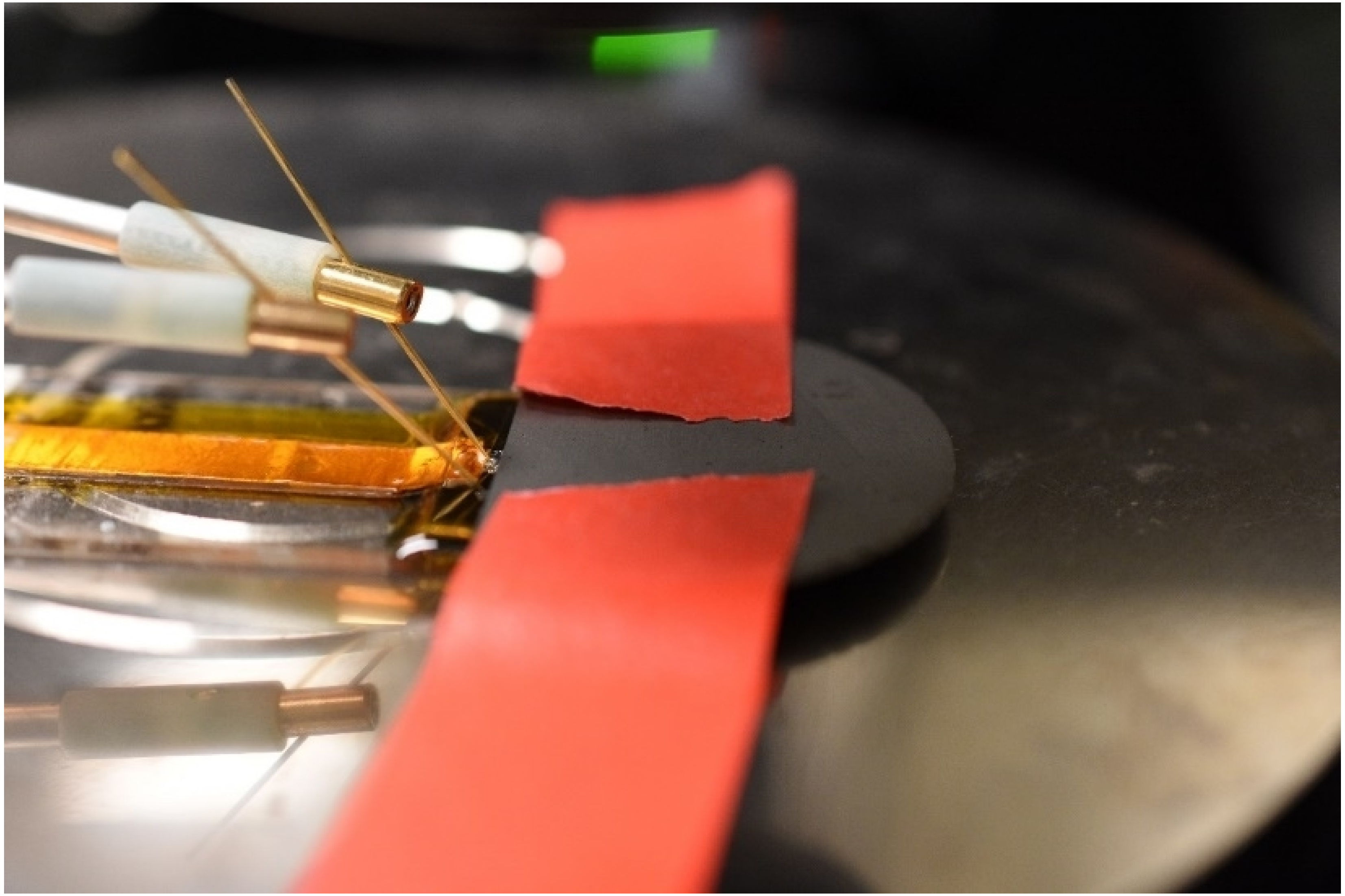
# STRUCTURE PROFILOMETRY: PRIMARY + SECONDARY




| Component | Thickness |
|---|---|
| Primary Layer 1+2 | +150 µm |
| NOA Separation Layer | +150 µm |
| Secondary Layer 1 | +5-20 µm |

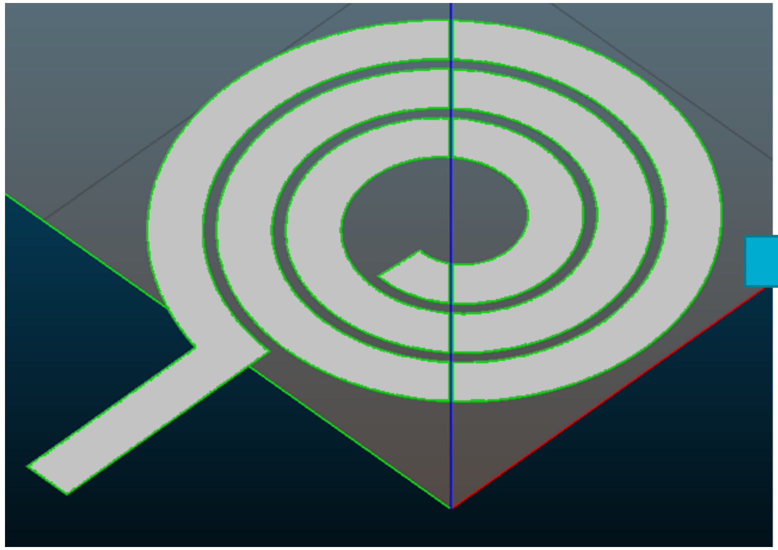
# FE4N TESTING SETUP

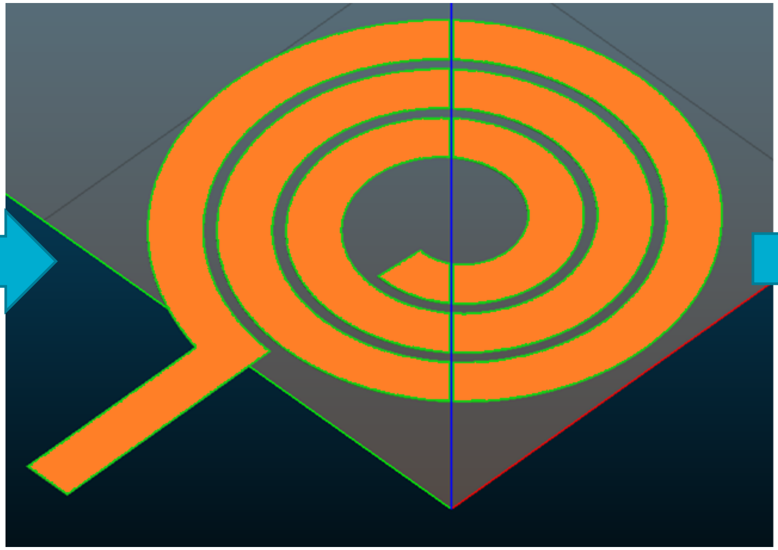


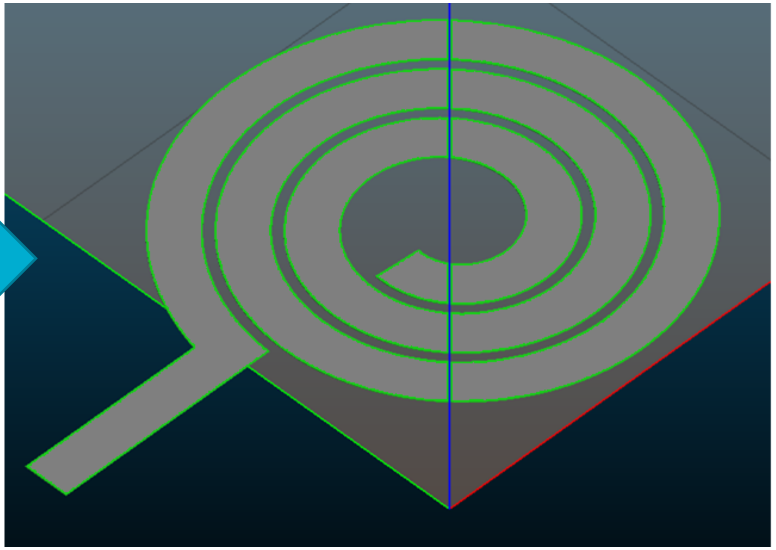
# HYBRID METAL PATTERNING PROCESS

**Aerosol Jet Printing**

**Electrochemical Deposition**







**Silver**
Seed Layer on Kapton Substrate

Ag NP ink (UTDots Ag40X)
Sinter at 200°C in air for 3 hrs

**Copper**
High Conductivity

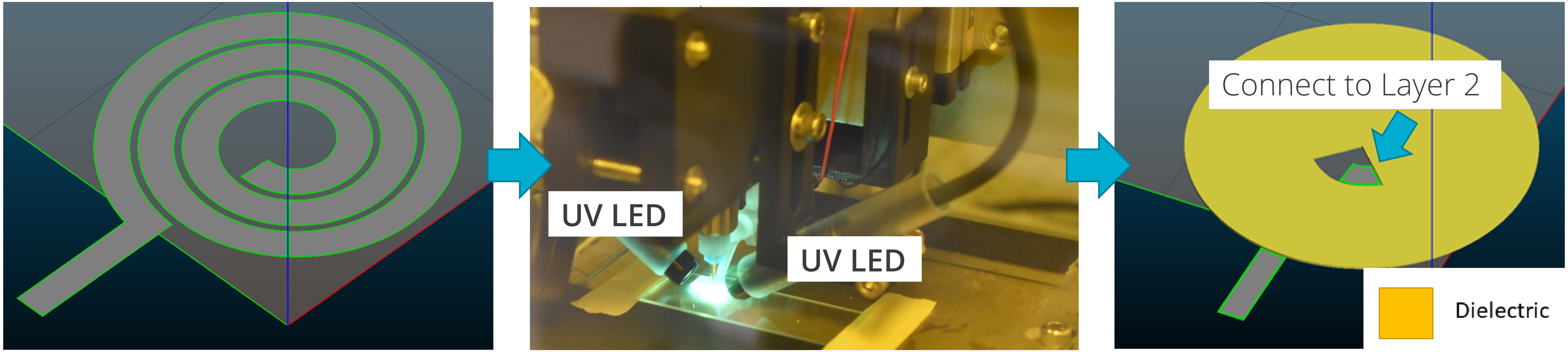
**Electroless Deposition**
Circuposit 3350B
(Optional)

**Electrodeposition:**
Microfab SC (Acidic $CuSO_4$)

**Nickel**
Oxidation Protection

Ni Sulfamate + Boric Acid

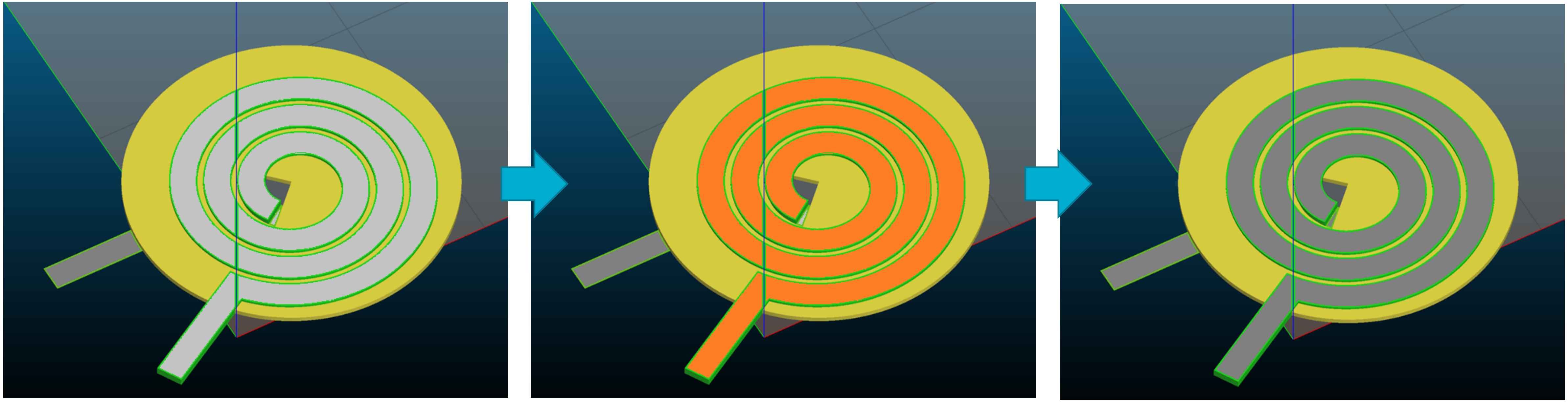
# DIELECTRIC SEPARATION LAYER




- Norland Optics NOA61 is deposited by AJP to separate layers.
- UV-curing is performed with two UV-LEDs *in-situ* during printing.
- Post cured under a UV-flood lamp for 5 minutes followed by annealing at 200°C for 6 hours in air.

# SECOND CONDUCTOR LAYER

**Aerosol Jet Printing** | **Electrochemical Deposition**



Silver Seed Layer | Electrodeposited Cu | Electrodeposited Ni

- Second conductor layer is deposited by AJP of the silver seed layer followed by electrochemical deposition of Cu and Ni.
- Additional dielectric separation layers may be added, followed by more conductor layers.
- Each layer’s linewidth and number of turns can be customized to achieve a specific target inductance.

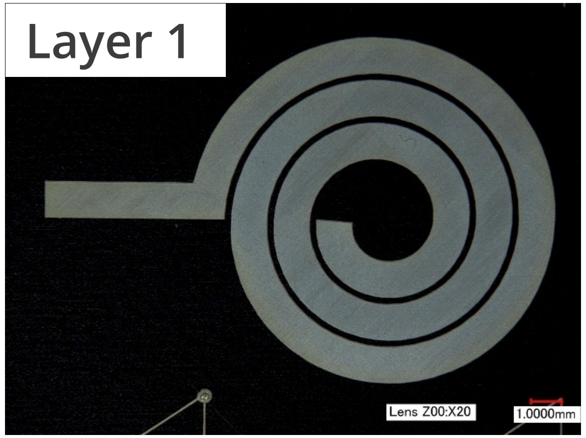
# CORELESS FLYBACK TRANSFORMER – PRIMARY INDUCTOR

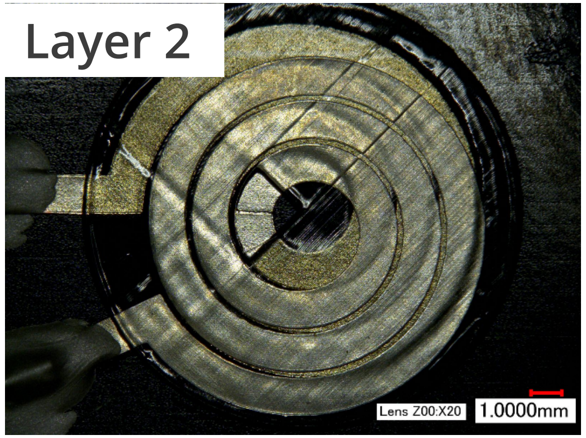
The primary inductor is a 3-turn per layer, 2-layer structure separated by a printed dielectric polymer:

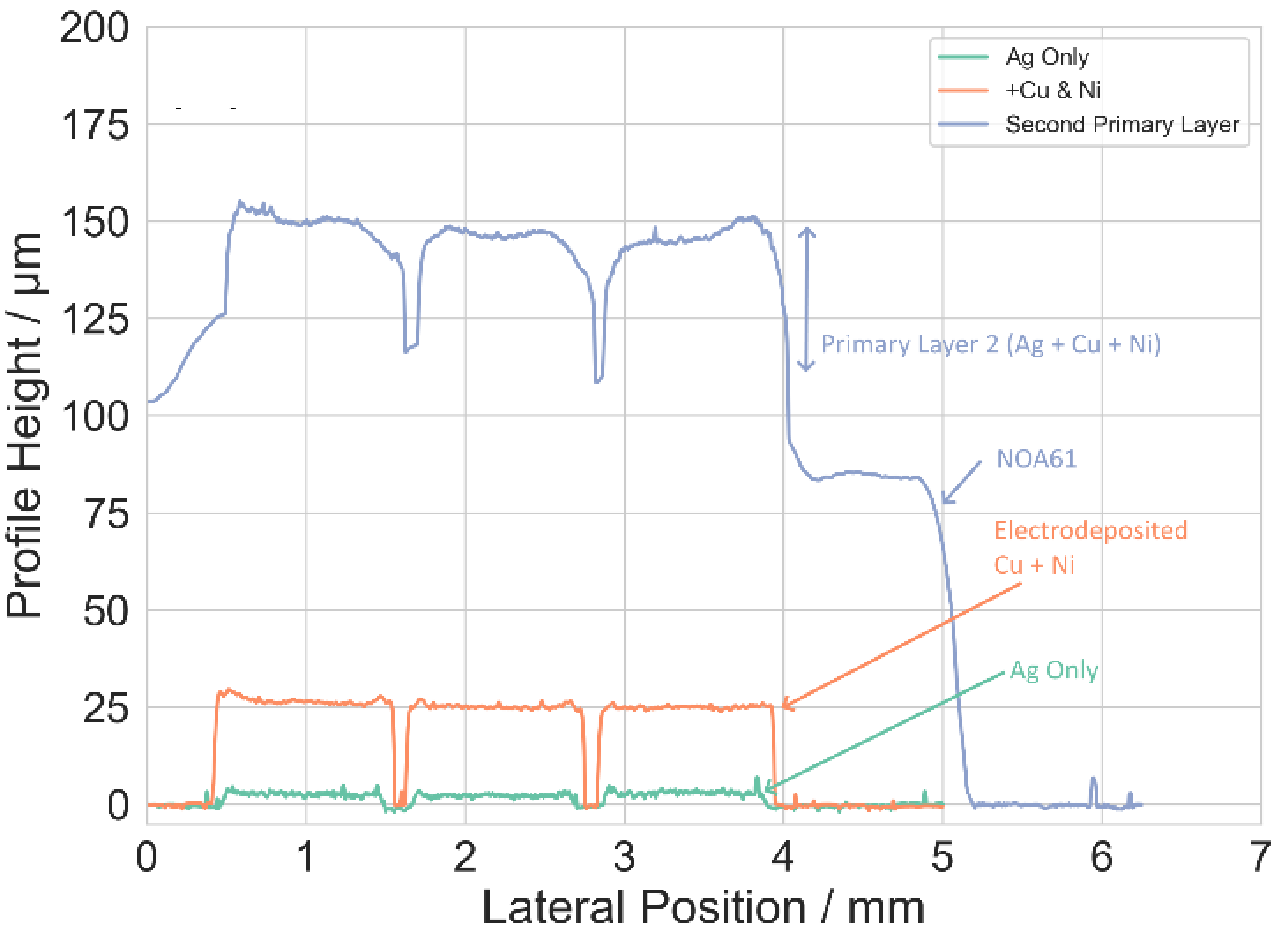
- Linewidth = 1021 μm
- Gap = 176 μm

Profilometry was used to measure thickness of each layer:

- AJP Silver Seed Layer: < 2 μm
- Electrodeposited Cu + Ni: 25 μm
- AJP Dielectric: 75 μm



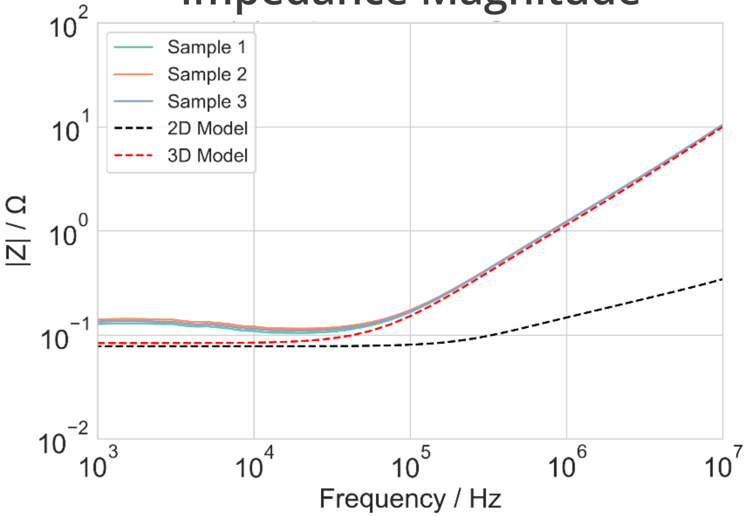



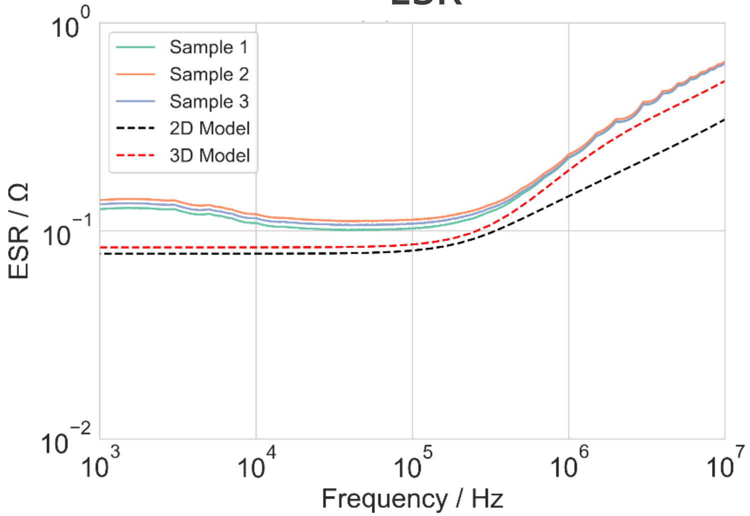
# CORELESS FLYBACK TRANSFORMER – PRIMARY INDUCTOR

- Inductance was measured using an impedance analyzer from $10^3$ to $10^7$ Hz and the equivalent series resistance (ESR) and inductance were calculated.
- COMSOL simulation was performed using both a 2D and 3D model to predict the ESR and inductance and showed a good match between simulation and experimental results.

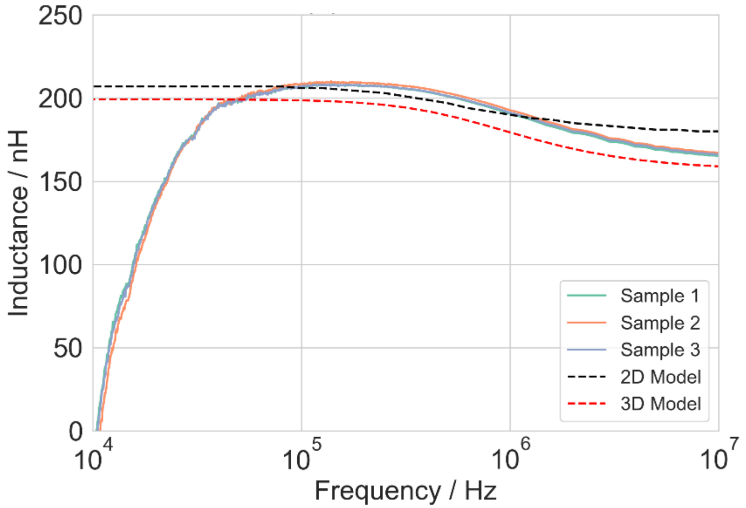
**Impedance Magnitude**




**ESR**




**Inductance**

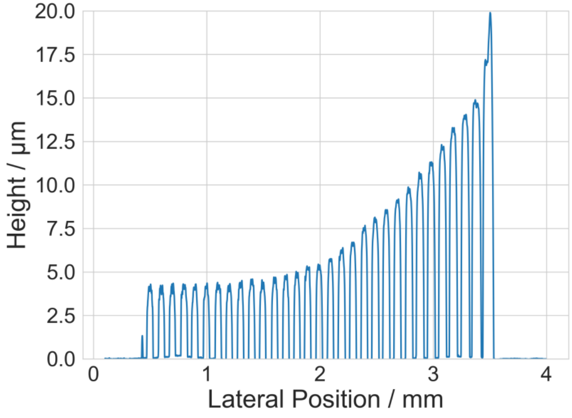


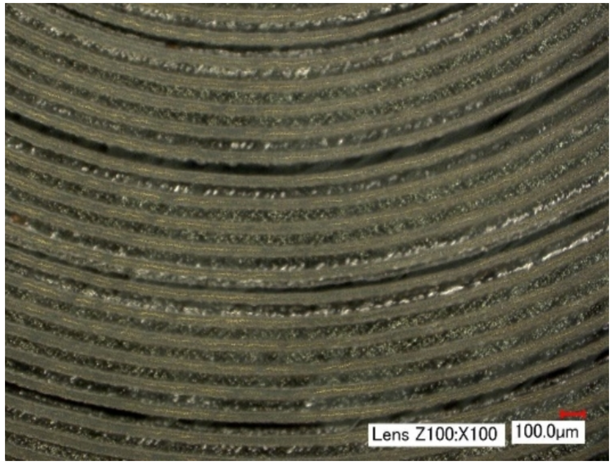

**Measured and Modelled Inductances at 100 kHz**

| Sample 1 | Sample 2 | Model (2D) | Model (3D) |
|---|---|---|---|
| 206 nH | 208 nH | 206 nH | 199 nH |

# CORELESS FLYBACK TRANSFORMER – SECONDARY INDUCTOR

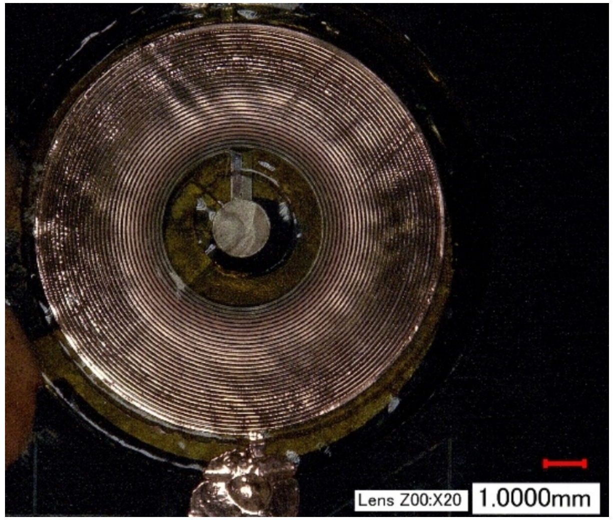
- Secondary inductor is a 31-turn per layer, two layer structure:
  - Linewidth = 62 µm
  - Gap = 31 µm
- High resolution of AJP and no overspray allows for printing of tightly spaced traces without adjacent traces shorting.
- Electroless deposition had a low yield due to high stresses during deposition.
- Gradient in thickness from 5-20 µm due to remaining high Ohmic resistance during plating.

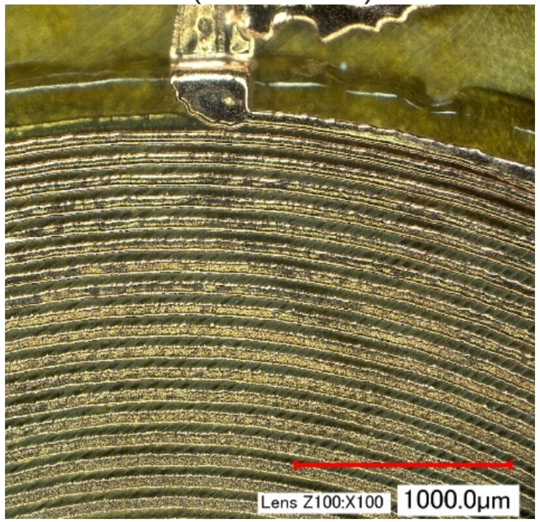



Ag Seed Layer


After Electroless Deposition (1.5 min)

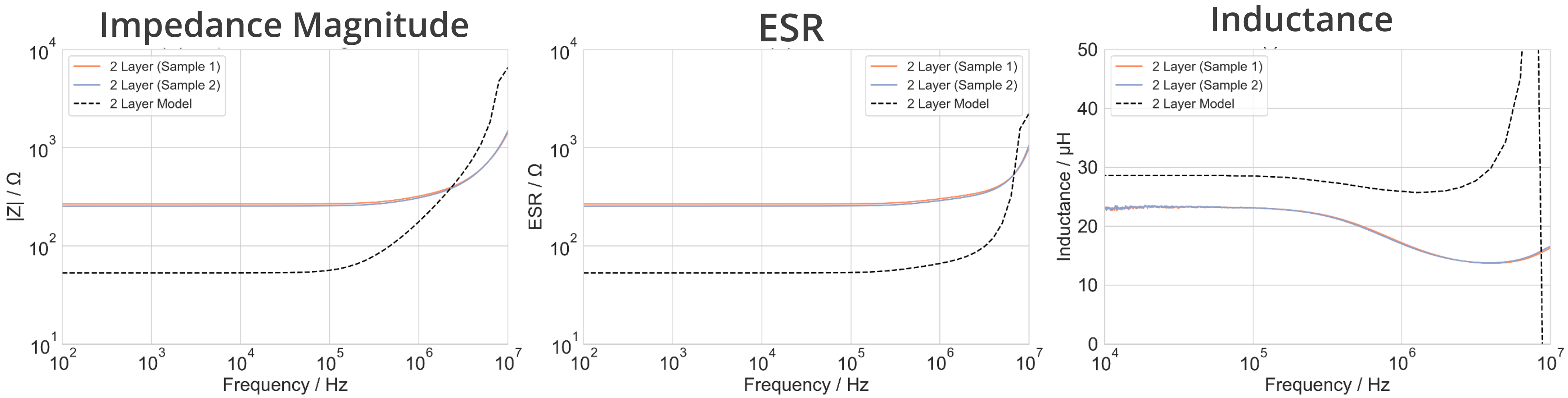



Cu Plating

# CORELESS FLYBACK TRANSFORMER – SECONDARY INDUCTOR

- Higher ESR (270 Ω vs. 58 Ω) than modeled was measured due to long pathlength, non-uniform Cu profile, and inter-layer resistance.
- Inductance of 19.4-23.1 µH are in better agreement with model prediction of 28.5 µH.
- Results are reasonable within the limitations of a 2D axisymmetric model and non-idealities of our device.

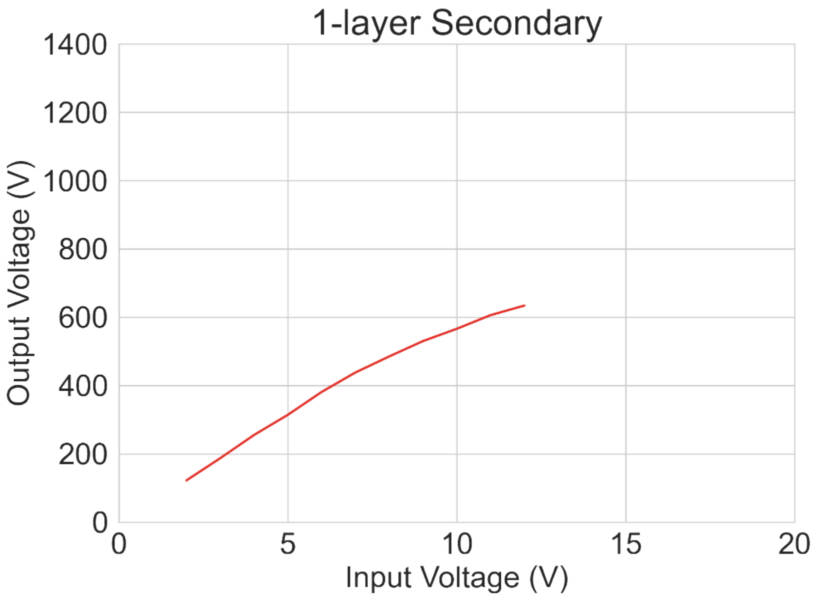


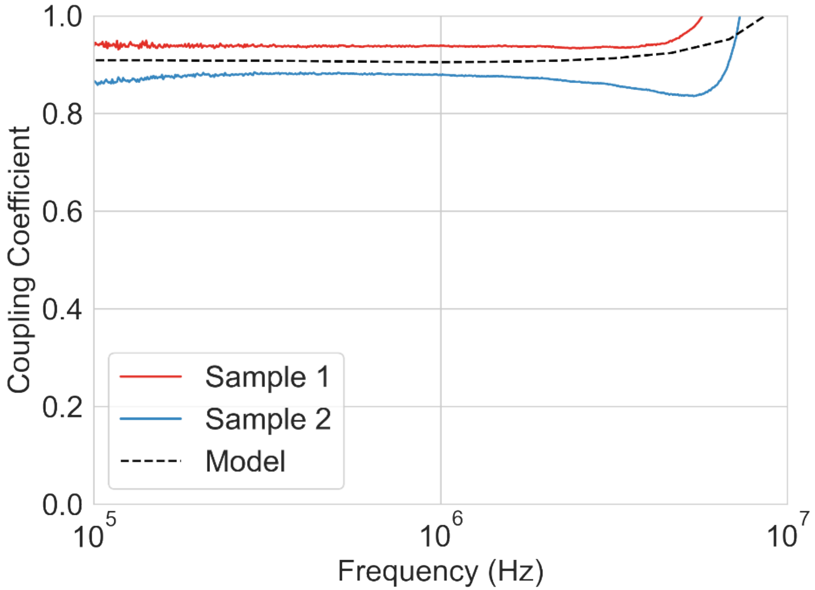

**Measured and Modelled Inductances at 100 kHz**

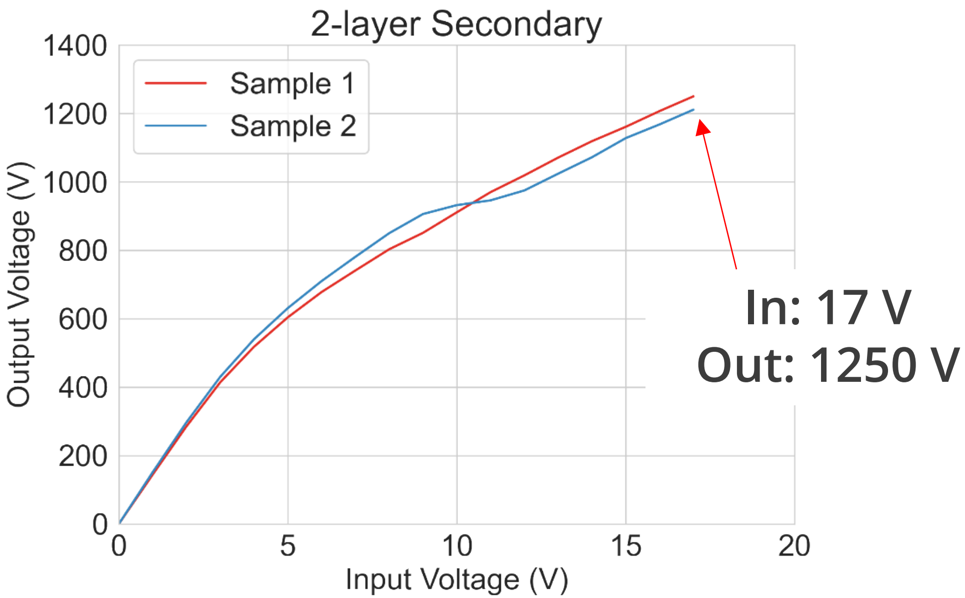
| Sample 1 | Sample 2 | 2D Axisymmetric Model |
|---|---|---|
| 19.4 µH | 23.1 µH | 28.5 µH |

# TRANSFORMER PERFORMANCE

- Coreless flyback transformer performance was evaluated at a frequency of 400 kHz between 0 and 17 V.
- A 1-layer secondary transformer was tested and reached an output voltage of 634 V before failure.
- For a 2-layer secondary transformer, at an instrument-limited input of 17 V, the output voltage was 1250 V, corresponding to a gain of 73.5x.
- Coupling coefficient of the primary and secondary inductors were measured at 0.88-0.94. Good agreement with COMSOL modelling which predicted a coupling coefficient of 0.91.



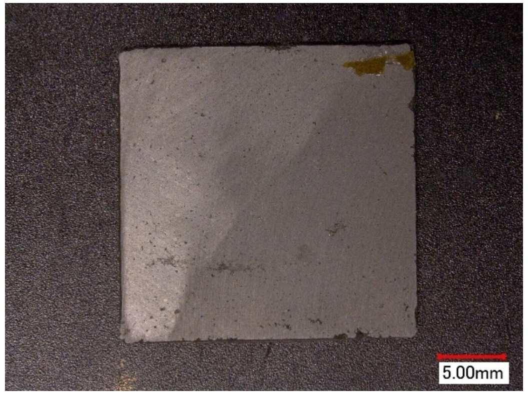



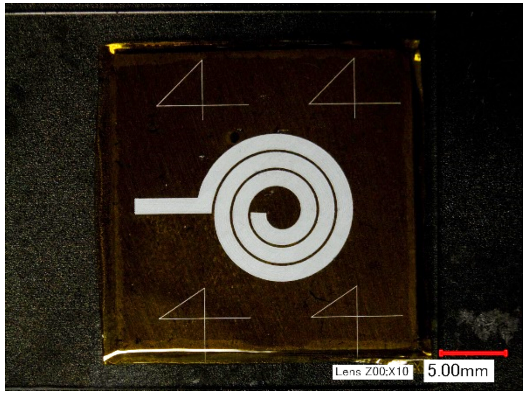

Tsui, L.; Hartmann, T. M.; Dye, J.; Lavin, J. M. "Additive Manufacturing of Coreless Flyback Transformers using Aerosol Jet Printing and Electrochemical Deposition" IEEE Transactions on Components, Packaging, and Manufacturing Technology (2023), 13, 8, 1302 – 1309.

# PRINTING OF PRIMARY INDUCTOR ON IRON NITRIDE PLATES

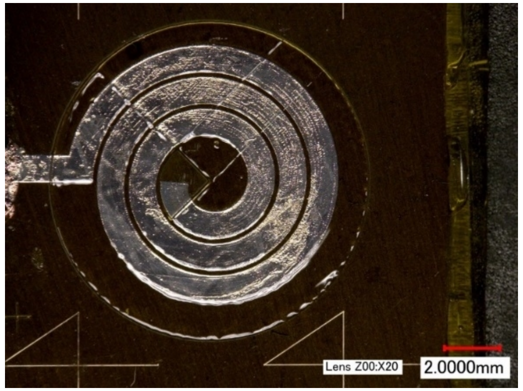
- Plates of $Fe_4N$ have a textured surface and voids from the casting process.
- Due to the roughness of the surface, a layer of Kapton tape was applied to provide a smooth surface to print an Ag seed layer by AJP.
- Deposition of Cu and Ni was completed by electrodeposition following process used to manufacture of the coreless transformer.



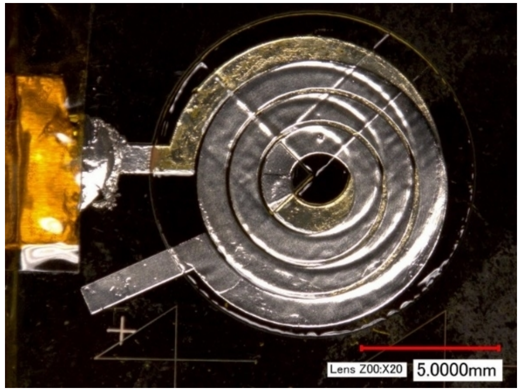

$Fe_4N$ Plate




Printed Ag Seed Layer




1 Layer Primary

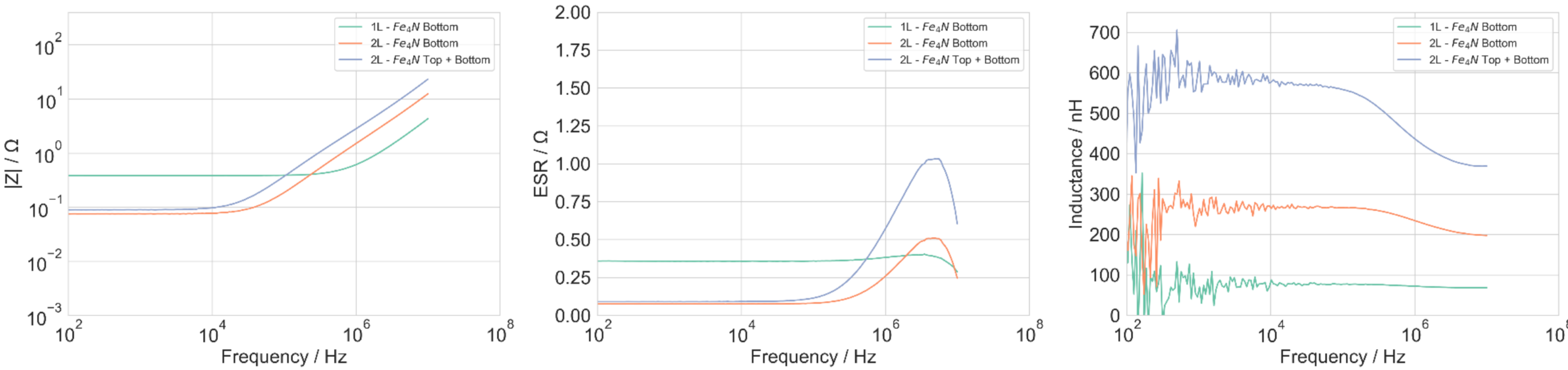



2 Layer Primary

# CHARACTERIZATION OF PRIMARY INDUCTOR + IRON NITRIDE

- The inductance of the 2-layer primary was measured with and without an $Fe_4N$ plate on top and taped to the probe stage.
- The top $Fe_4N$ plate provides a closed loop for the magnetic field to travel through, so increase in inductance with bottom layer only is small.
- An increase in the inductance by a factor of 2X with the sandwich structure was measured.
- COMSOL model predicts a higher enhancement, but may result from non-ideal interface.

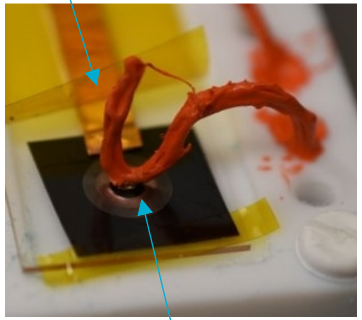
| 100 kHz Inductance | COMSOL Model | Experimental |
|---|---|---|
| 2 Layer Primary - Without $Fe_4N$ | 207 nH | 199-206 nH |
| 1 Layer Primary - $Fe_4N$ Bottom | 86 nH | 77 nH |
| 2 Layer Primary - $Fe_4N$ Bottom | 331 nH | 234 nH |
| 2 Layer Primary - $Fe_4N$ Top + Bottom | 856 nH | 559 nH |



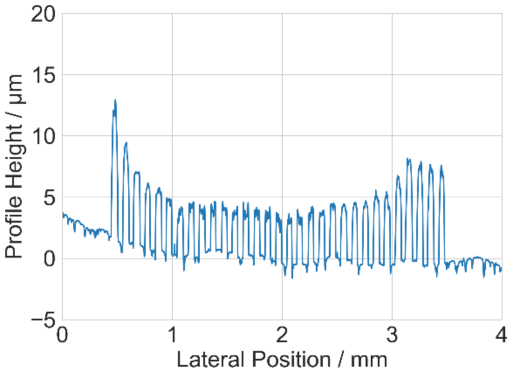
# TWO-CONTACT PLATING

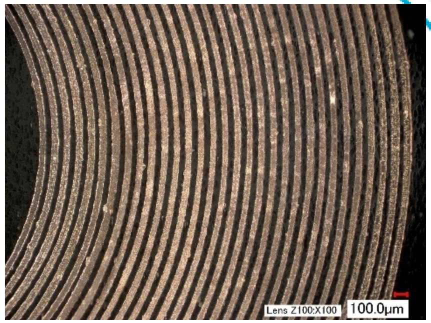
- We developed a fixture to make contact with both the exterior and interior of the secondary inductors using piano wire.
- This allows us in principle to skip electroless deposition and improve secondary inductor uniformity.
- Electrodeposition of Cu on a Ag seed layer printed onto Kapton was performed under current control at 5 mA/cm$^2$ for 45 minutes (13.5 C/cm$^2$).
- Initial tests on isolated single-layer secondary inductors show an improvement in the thickness uniformity.
  - Min 5 µm and Max 10 µm
- Impedance measurements at 100 kHz show an inductance of 6.16 µH which matches our single layer secondary inductor results.
- Next step will be to apply this to a transformer device.

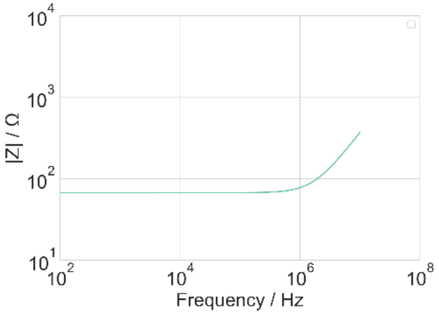
Cu Tape Contact to Exterior of Inductor

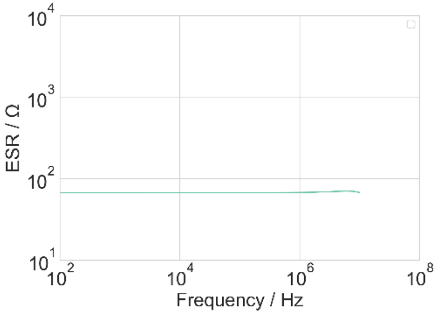


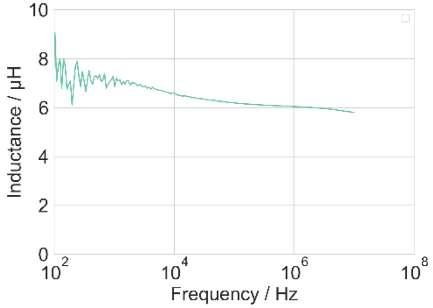
Wire Contact to Interior of Inductor




| ESR (100 kHz) | Inductance (100 kHz) |
|---|---|
| 67.4 Ω | 6.16 µH |