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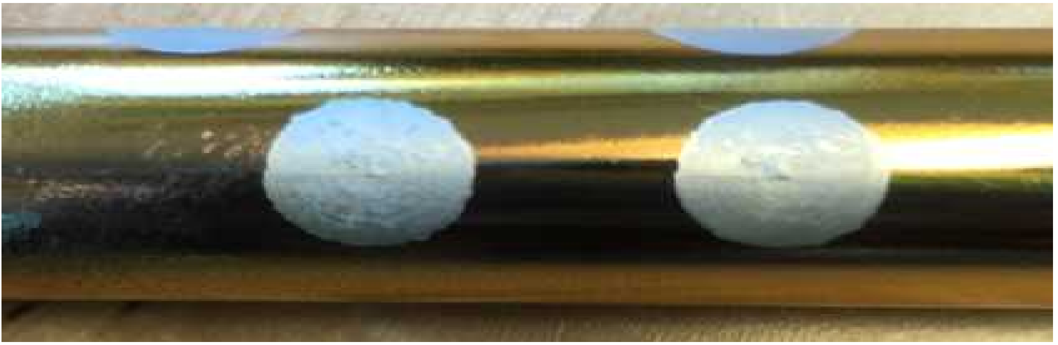

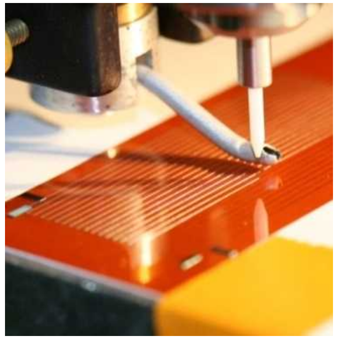

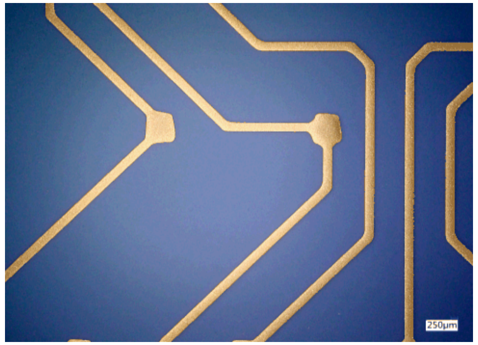

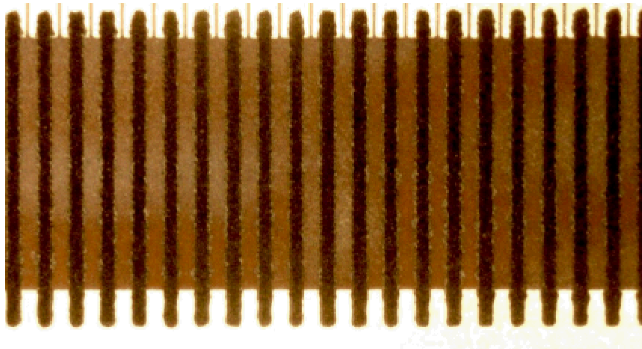

# Additive Manufacturing for Embedded Microelectronics

Zachary Beller[1], David Keicher[1], Marcelino Essien[2], Judith Lavin[1], Shaun Whetten[1], Sita Mani[1]

[1] Sandia National Laboratories
[2] Integrated Deposition Systems

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# Outline

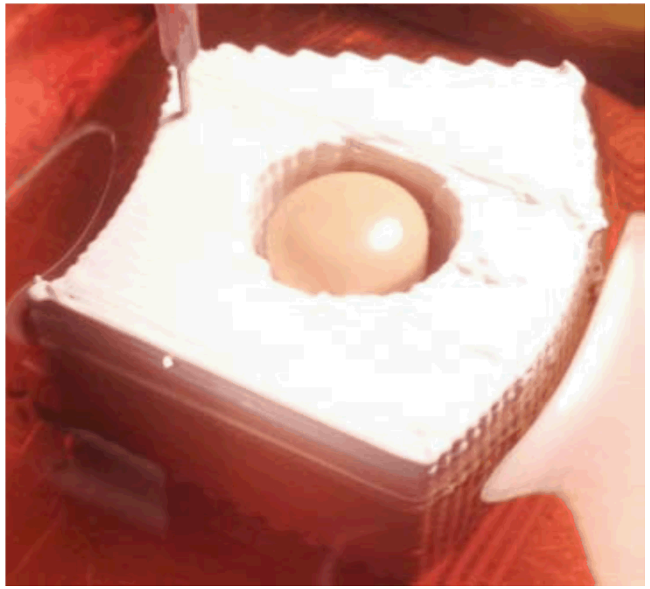
- Introduction
  - Embedded Electronics
  - Additively Manufactured Electronics
  - Embedded Additively Manufactured Electronics
- Utilized Capabilities
- Studied Sensor
  - Sensor Details
  - Sensor Curing Profile
  - Sensor Properties and Performance
- Reflection
- Future Steps Toward Implementation
- Conclusion

# Introduction to Embedded Electronics

Sandia National Laboratories

- Embedding Electronics and Sensors Allows Them to be Placed at Critical Points
  - Not Limited To Available Surface Space
- Uses
  - Monitoring of Critical Load Bearing Structures
    - Bridge Supports
    - Aircraft Joints
    - Ship Hulls
  - Monitoring of Devices Subject to Extreme Environments
    - Unmanned Probes
    - Turbine Blades

- Embedding Strategies
  - Pause of Print Insertion

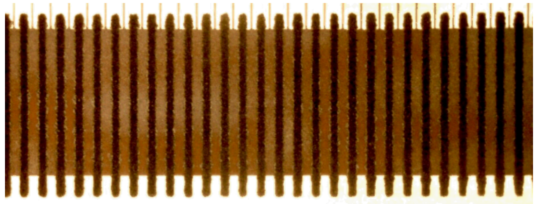


[1]

*[1] M. Leu, et. al, Missouri S&T, 2015*

# Additively Manufactured (AM) Electronics

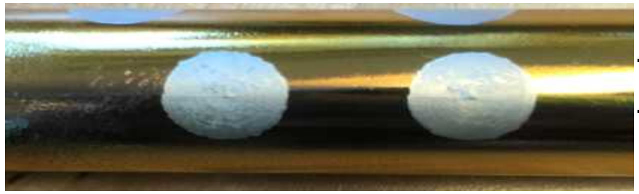
- Circuit Components
  - Resistors



Series of Resistive Lines

*Ag Resistive Ink*

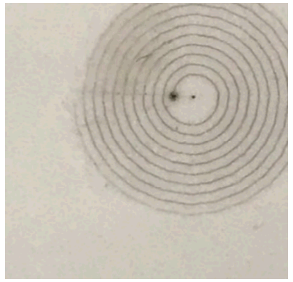
  - Capacitors



Capacitors on Cylindrical Rod

*Ag Pads, Polyimide Dielectric, Au Cylindrical Rod*

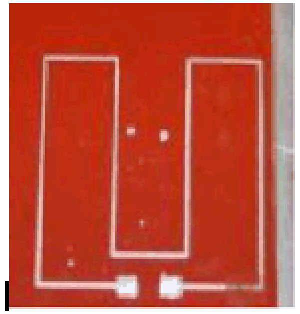
  - Inductors



Spiral Inductor

*Ag Ink*

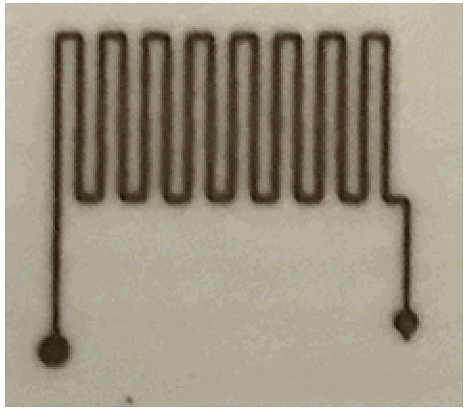
- Simple Strain Gauges



~ 5 cm

*Ag Paste*

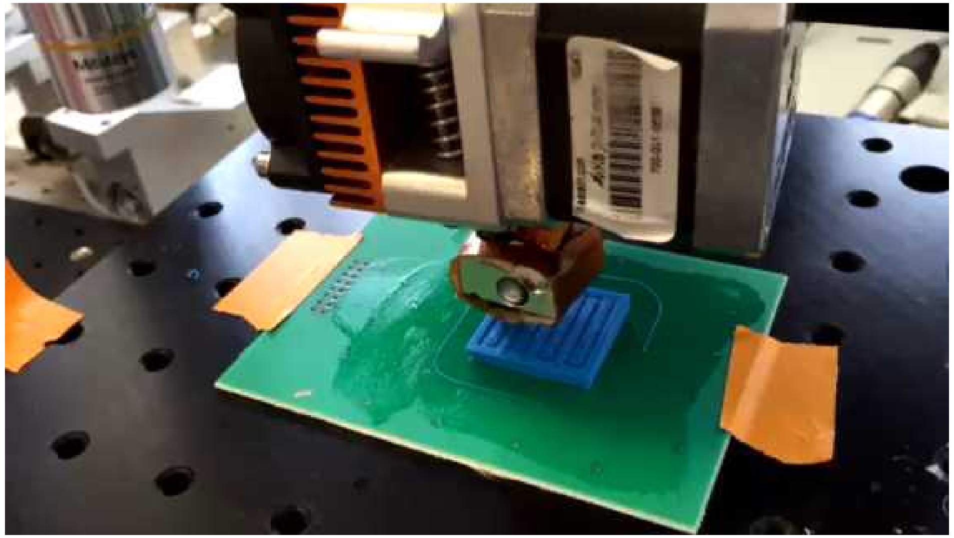
- Heating Elements



*Ag Ink*

# Embedded AM Electronics

- Multi-Material Print Processes
  - Manufacturing of Both Structures and Electronics
- Multiple Machine Process
  - Part is Switched Between Machines Depending on Required Structure/Electronic Needs at a Given Point
- Methods of Embedding
  - Incorporated Tool-Paths



# Sought Components

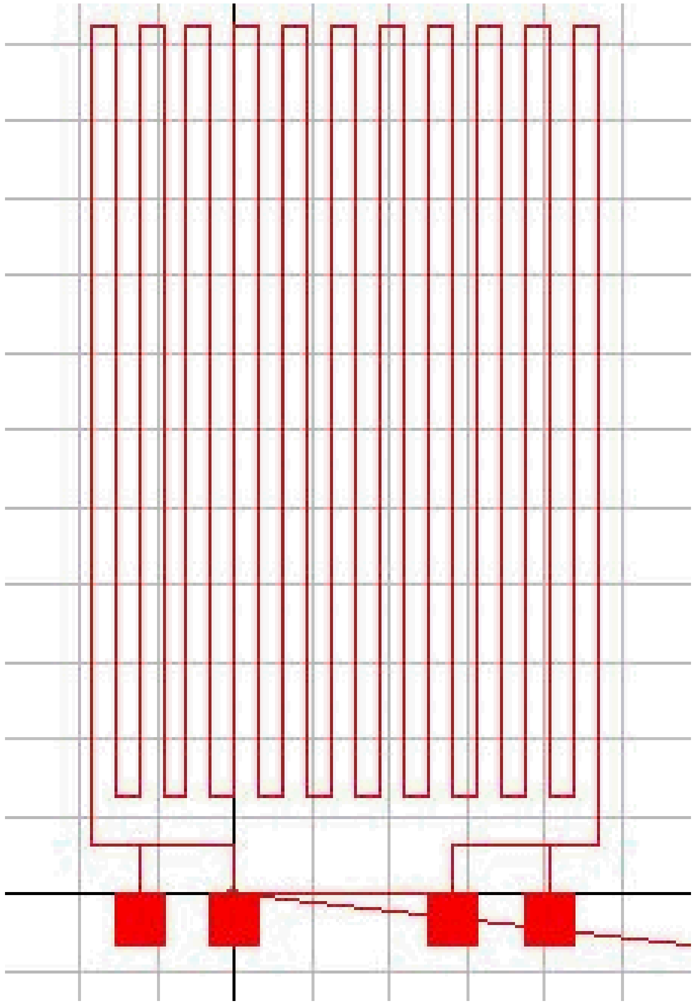
**Strain Gauge**

- *Measure Stress and Deflection of Component*
- Strain Causes Change in Cross-Sectional Area of Trace
  - Changes Resistance of Circuit
- Maximized Circuit Length Accentuates Change in Resistance

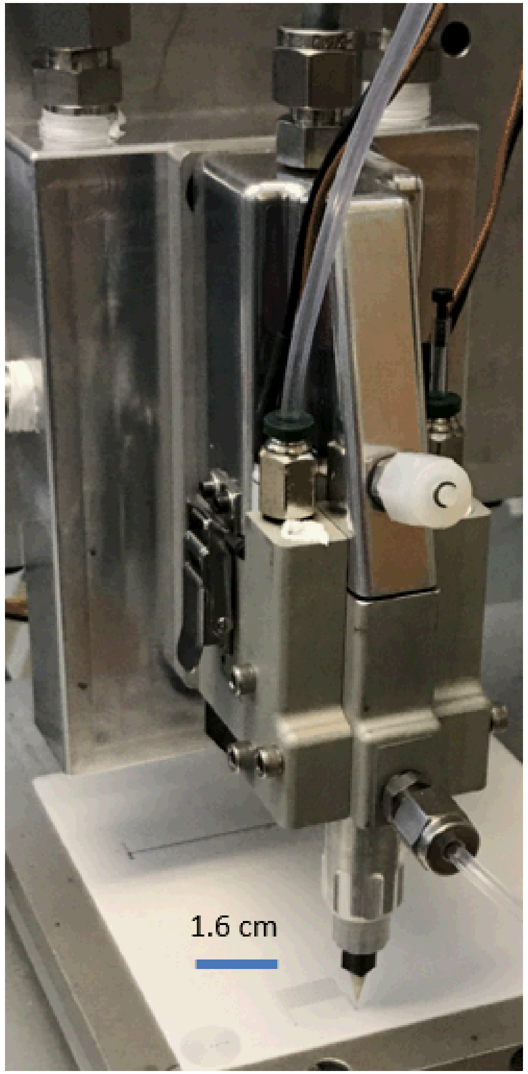
**Temperature Sensor**

- *Measure Surface Temperature of Component*
- Coefficient of Thermal Resistivity Causes a Change in Resistance of the Circuit
- Maximized Circuit Length Accentuates Change in Resistance

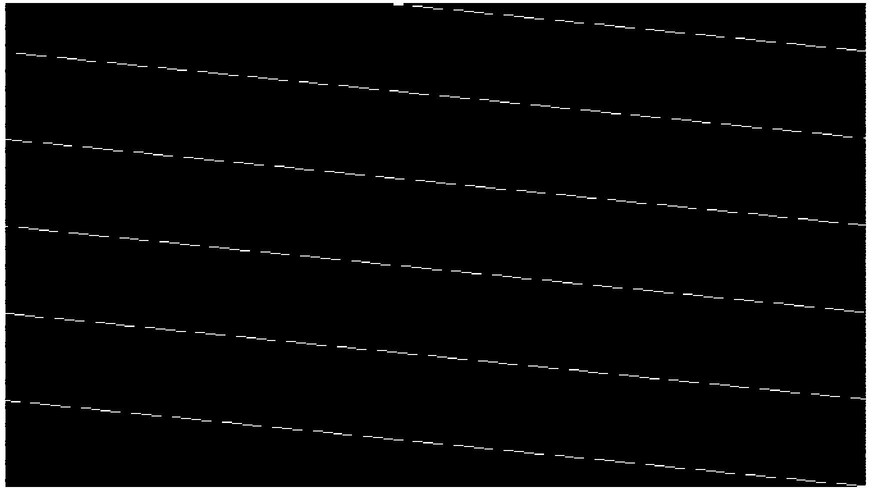
# Component Design



# Capabilities – Nanojet©

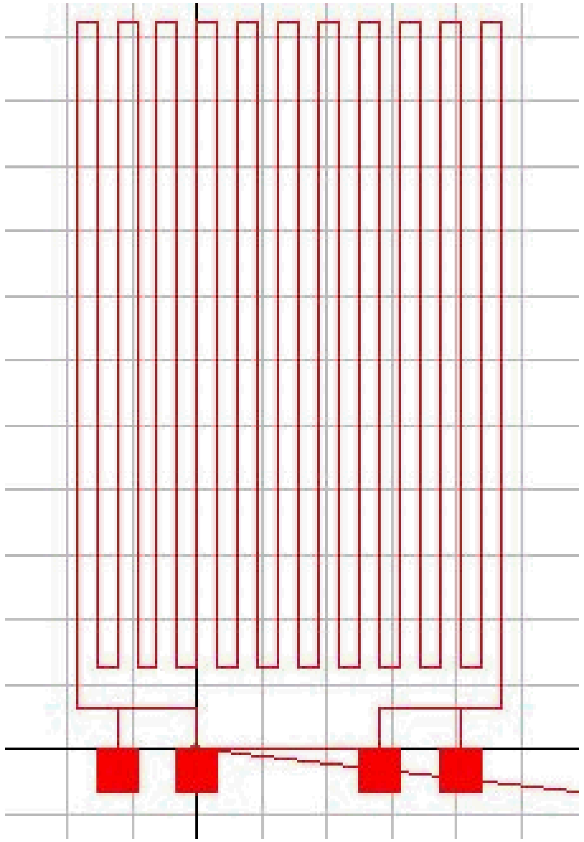


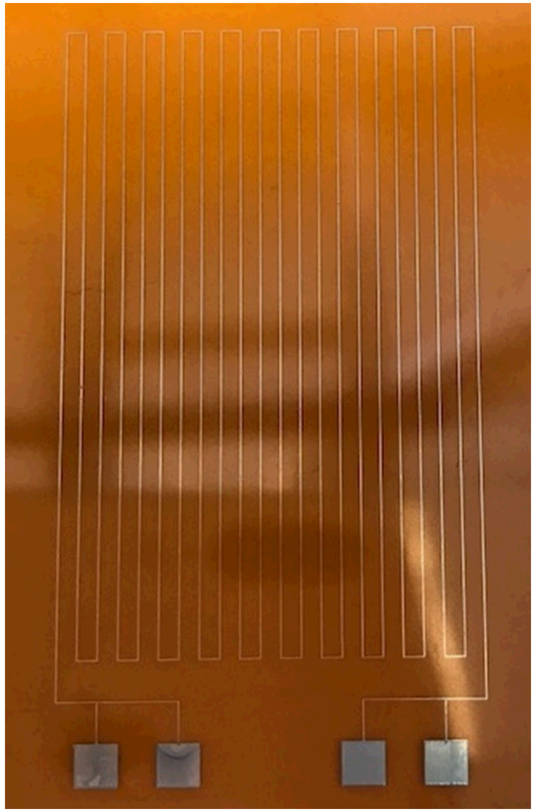

- Aerodynamic Focusing of Aerosolized Materials
  - Conductive Nanoparticle Inks
  - Dielectric Polymers
- Low Profile, Well Focused Traces
  - Trace Width From 50 to 300 µm
  - Single Layer Height of ~1.5 µm
- Parameters
  - Aerosol Flowrate
  - Sheath Gas Flowrate
  - Atomizer Voltage
  - Tip Height



# Sensor Details

- Prototype Print
  - Deposited onto Kapton film
  - Silver Nanoparticle Ink in Xylenes
    - Well Known Material Profile
    - Predictable Coefficient of Thermal Resistivity
    - Test Component Printed Using Proven Technology (Aerosol Jet)
      - Sample Resistivity: 4.29E-8 Ω*m
      - Bulk Resistivity: 1.59E-8 Ω*m



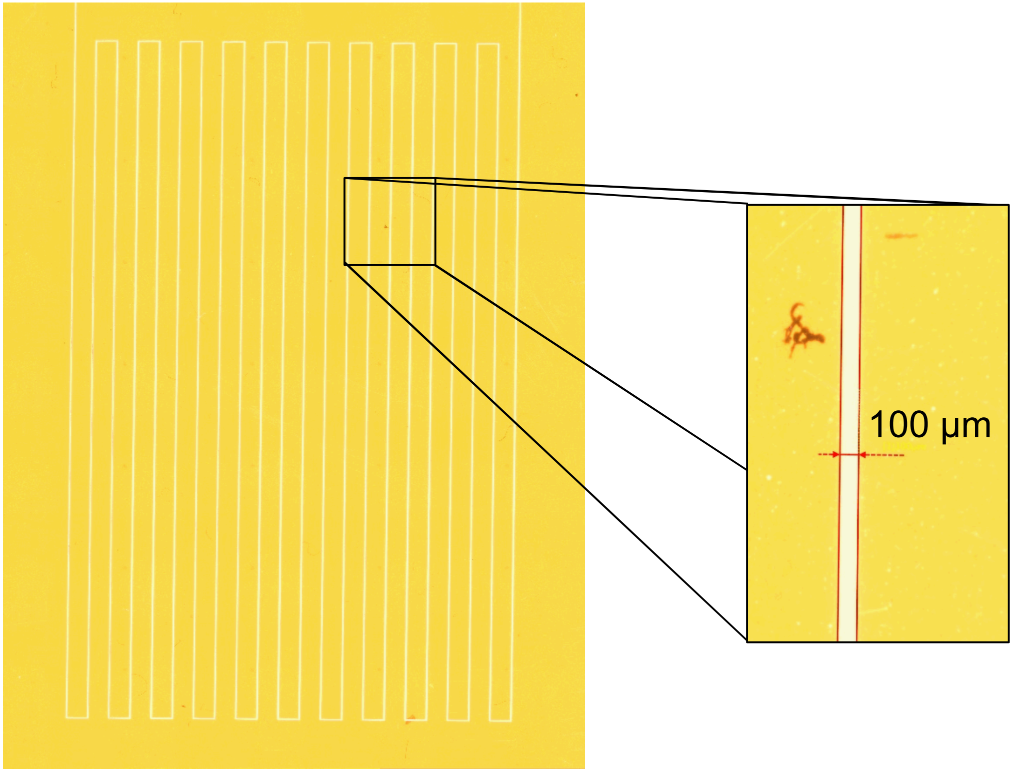


# Sensor Curing Profile

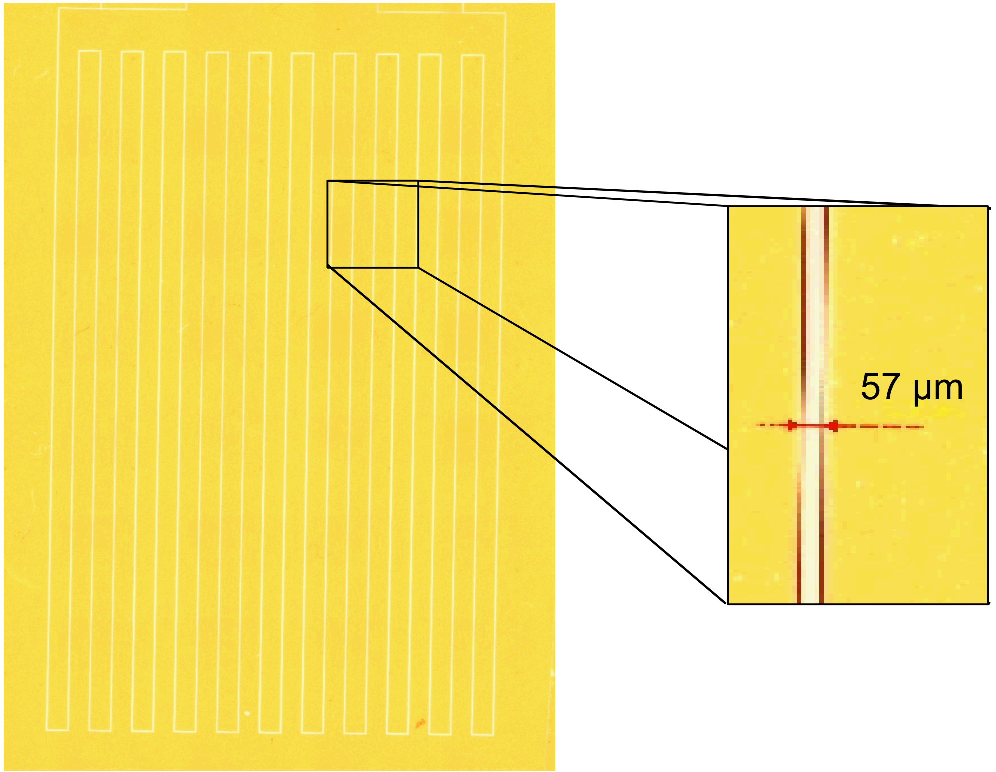
- Bulk Thermal Curing
  - Heated on hot plate at 170° C for 45 minutes
- Alternatives
  - Photonic Forge Curing
    - Low temperature
    - Short curing time commitment
  - Pulsed Laser Sintering
    - Accurate sintering of selected material

# Effects of Curing

## Before Curing

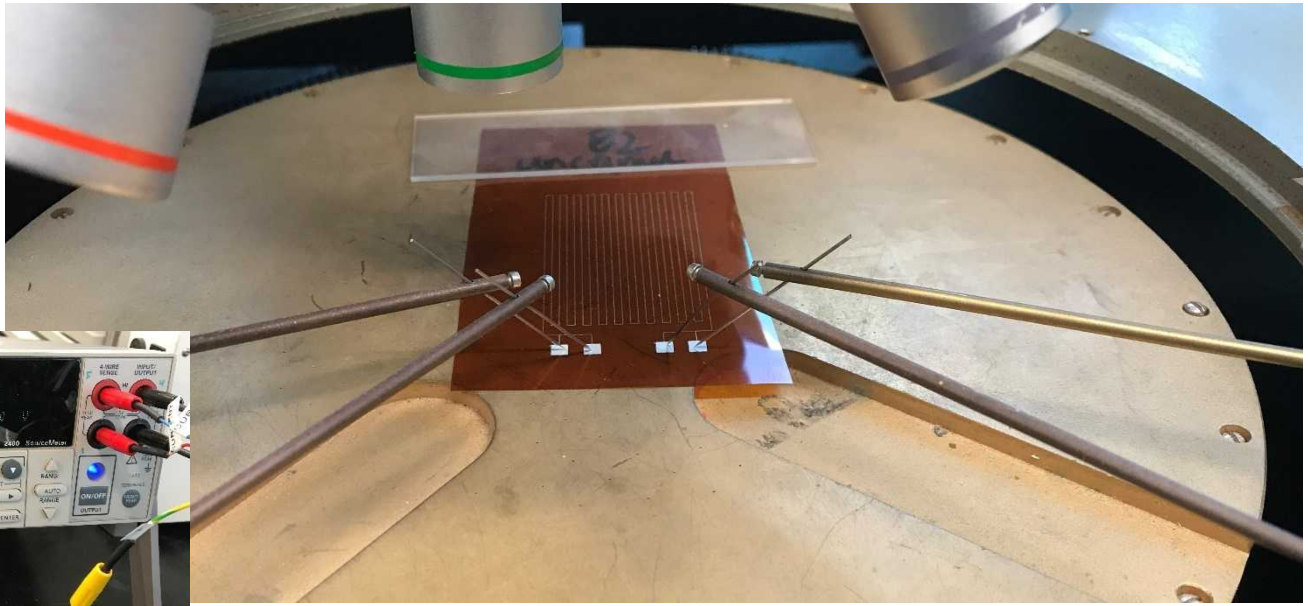



## After Curing



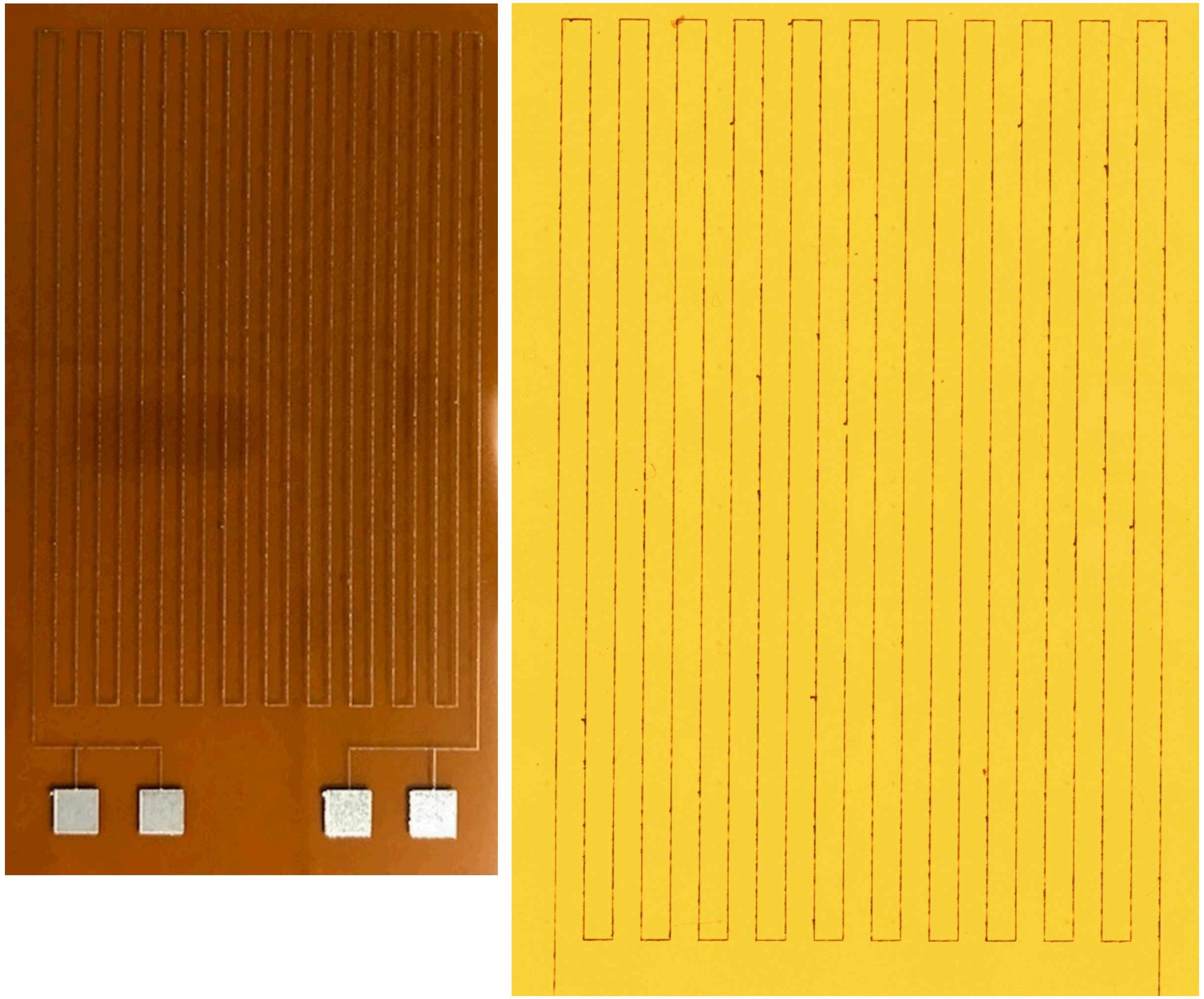
# Printed Sensor Properties and Performance

- Issues Achieving Uniform, High-Quality Printed Sensors
- Issues Regarding Reliability in Circuit Continuity
- Lack of Continuity Prevented Measuring of Resistance and Calculating of Bulk-Resistivity
- Fragile Component Qualities
  - Testing Caused Damage to System

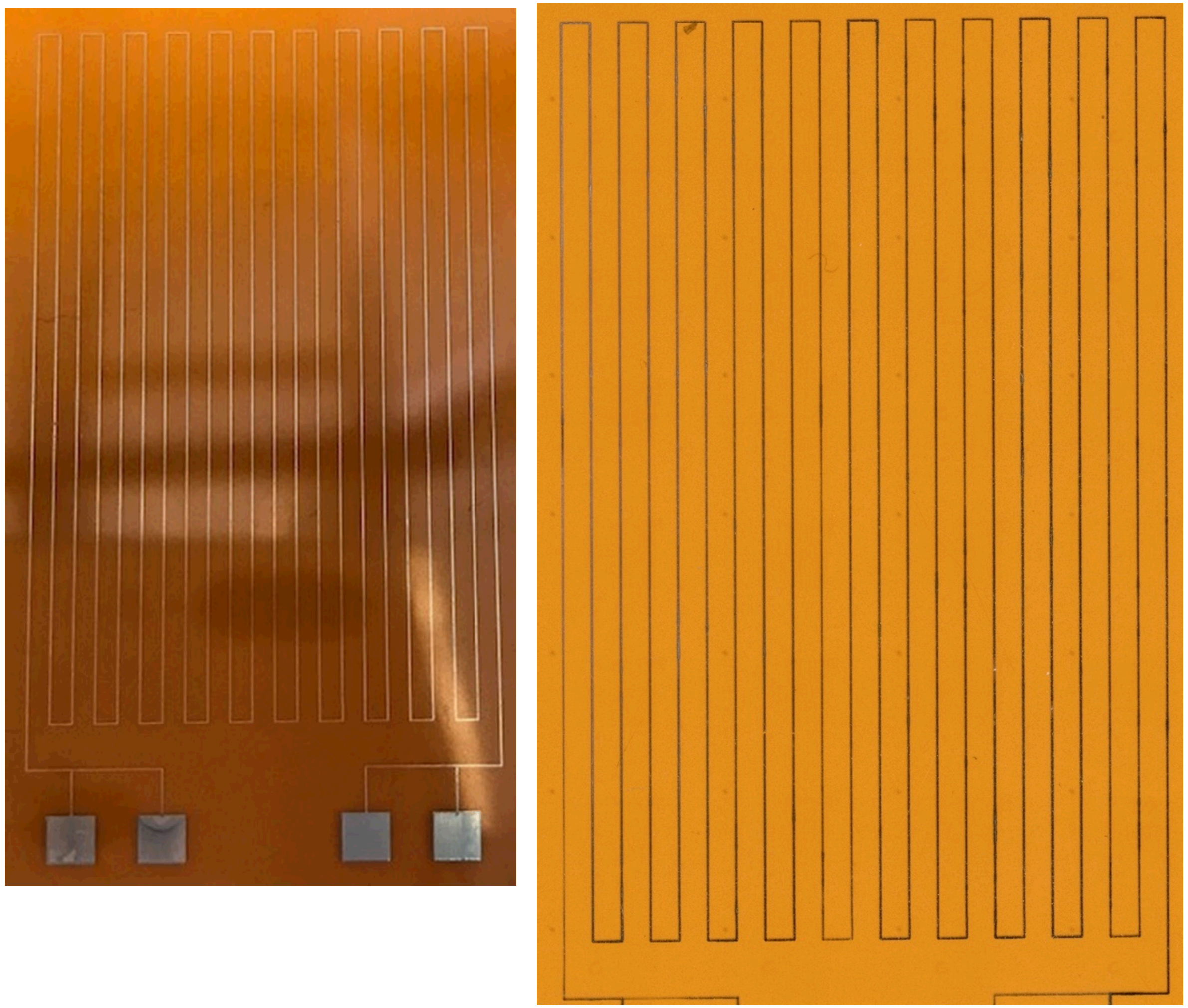


# Sensor Properties and Performance (Cont.)

## Poor Quality Printed Sensor



## High Quality Printed Sensor



# Reflection

- Extensive issues producing multiple usable samples proved to be a major stumbling block
  - Failure to establish repeatable print parameters
  - Prevented proper testing of components

- Possible sources of error include:
  - Coagulation of particles as ink aged
  - Inability to achieve accurate and precise tool height above substrate
  - Build up of material on nozzle as printing went on
  - Improper heating profile prevent sintering of particles

# Future Steps

- Scale Stain Gauge Design to Sense in Multiple Axes
  - Insulating dielectric layer between serpentine paths
- Investigate the Production of Additively Manufactured Antennas
  - Wireless power transfer for passive electronics
  - RF sensors to remotely transmit information
  - Fracture detection
- Investigate Other Conductive Materials for More Adaptable Curing Profiles
  - Low Temperature curing materials
  - High Temperature curing materials
  - Non-temperature dependent curing materials
- Multiple Process Integration into Single Machine
  - Complete, Multi-material components in single print

# Conclusion

- Continuing advancements in the Additive Manufacturing of both structure and electronics have created the opportunity to integrate the two into single vision
- Design of integrated components requires the consideration of both technology and material limitations
  - Material compatibility and curability require further investigation
- Further exploration is required into passive and remote components
- Eventual implantation of all-in-one systems to fully produce a finished, sensing part

# THANK YOU!

# POCKET SLIDES/QUESTIONABLE WORK IN PROGRESS SLIDES

# Long Term Goals

- Embedded Health Monitoring
  - Stress monitoring
  - Temperature monitoring
- Passive Electrical Components
  - No need for incorporated batteries or power banks
- Remote Communication with Sensors
- Single Process Prints
  - One machine to build both structures and embedded electronics

# Long Term Goals

- Embedded Health Monitoring
  - Stress monitoring
  - Temperature monitoring
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  - One machine to build both structures and embedded electronics

# Complication – Material Compatibility

- Solvents Used to Suspend Nano-particles Can Damage Substrate
  - Xylenes corrode plastics
- Non-uniform Wetting of Aerosols onto Different Materials
- Profilometry and picture of substrate that has had suspending solvent eat through it
  - Profilometry should have a valley along the trace

# Solution – Material Compatibility

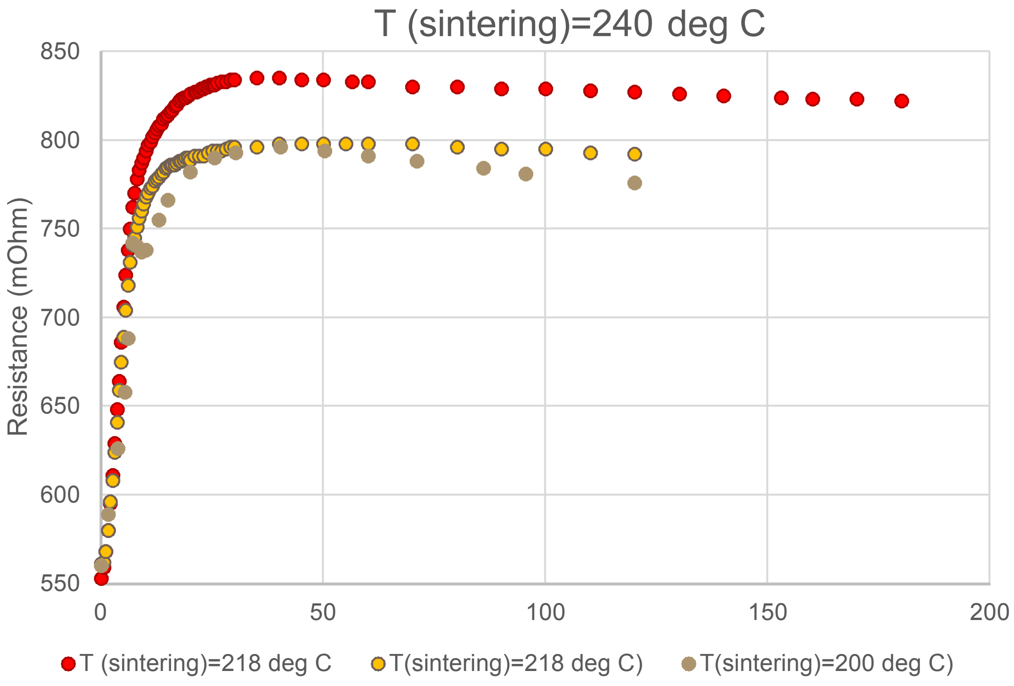
- Substitution of solvent for less aggressive solvent
  - Requires large inventory to ensure compatibility across all materials
- Printing of a protective dielectric between substrate and trace

- Picture of protective-layer print

# Complication – Curing Compatibility

- Traces cure between 50 C and 200 C for ~1 hour
  - Plastics begin to flow at about 70 C
  - Ceramics cure at XXXXX C for XXXXX hours

- Show melted substrate w/ cured trace
  - ABS
- Show burned trace on cured substrate
  - Alumina

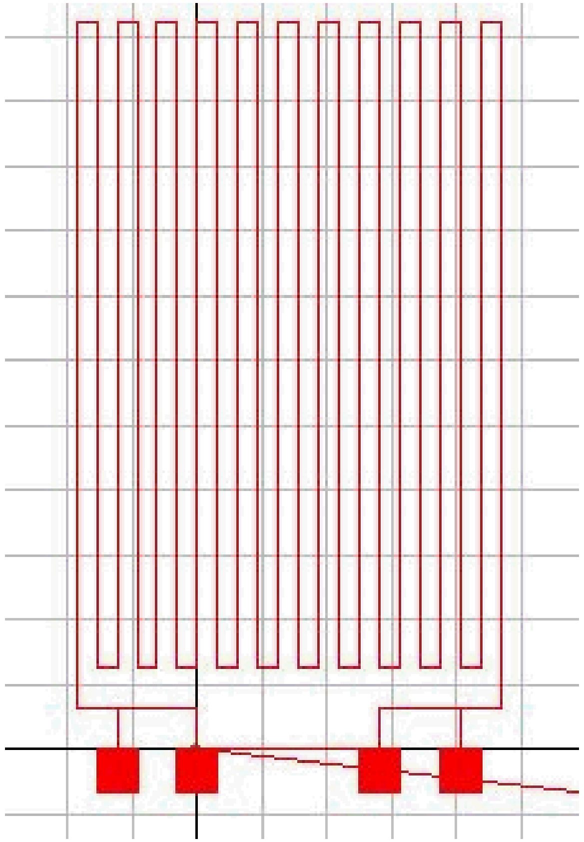


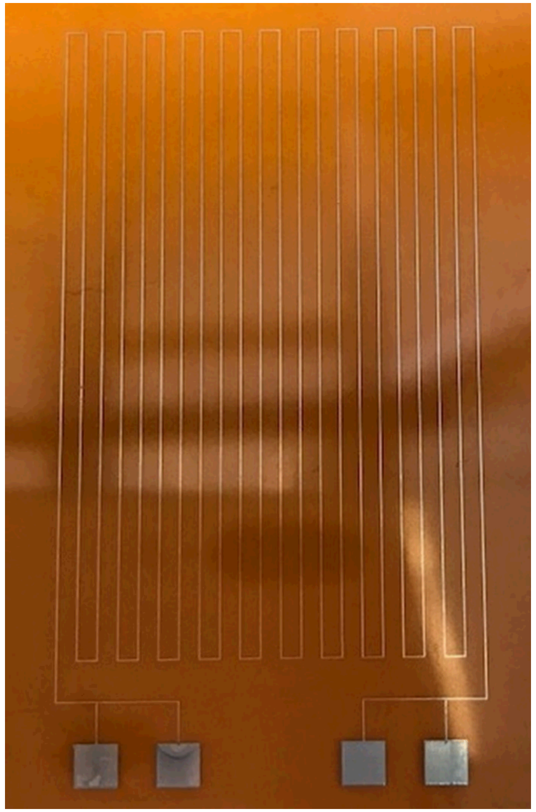
# Interest in Embedded Electronics

- Embedding Electronics and Sensors Allows Them to be Placed at Critical Points
  - Not Limited To Available Surface Space
- Strain Gauges
  - Measure Stress and Deflection of Component
- Temperature Sensors
  - Measure Surface Temperature of Component
- Uses
  - Monitoring of Critical Load Bearing Structures
    - Bridge Supports
    - Aircraft Joints
    - Ship Hulls
  - Monitoring of Devices Vulnerable to Extreme Environments
    - Unmanned Probes
    - Turbine Blades

# Sensor Details

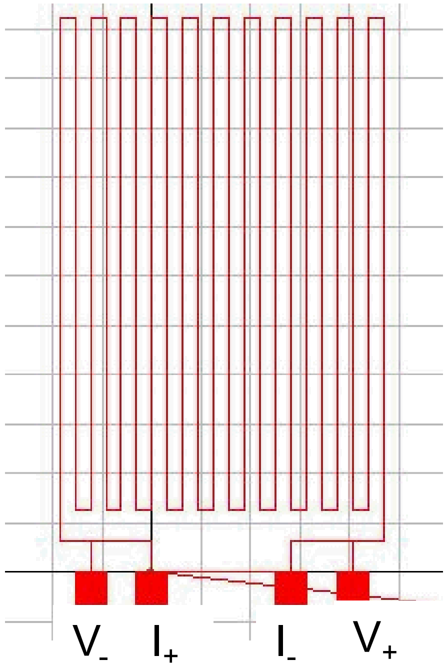
- Design
  - Serpentine Trace
    - Maximizes length in a given area
  - Four Contact Pads
    - 4-point terminal sensing
- Prototype Print
  - Deposited onto Kapton film
  - Silver nanoparticle ink in Xylenes
    - Well known material profile
    - Predictable Coefficient of Thermal Resistivity
    - Test Component Printed Using Proven Technology (Aerosol Jet)
      - Resistivity: 2.05E-7 Ω*m





# Testing Conditions

- 4-Point Probing
  - Supply Constant Current and Voltage to Component
  - Provides Stable and Accurate Resistance Reading




- Cross-Sectional Area Measured Through Profilometry of Sensor

- Sensor Dimensions Used to Calculate Bulk-Resistivity of Material
  - $R = \frac{\rho L}{A}$

# References


- Lazar, Miriam. *Lets Review: Physics, the Physical Setting*. Third edition. United States: Barrons, 2007: 217.