SAND2015-7389C

Advancing 3D Printing of Metals and Electronics using Computational Fluid Dynamics

Exceptional service in the national interest

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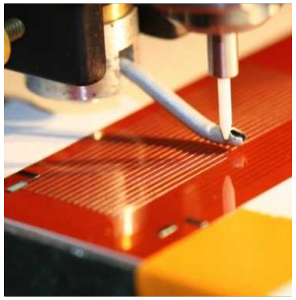
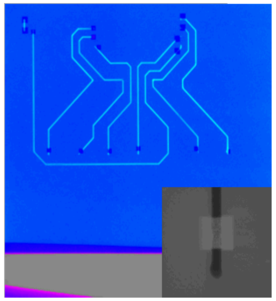
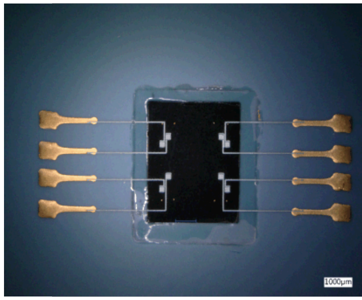
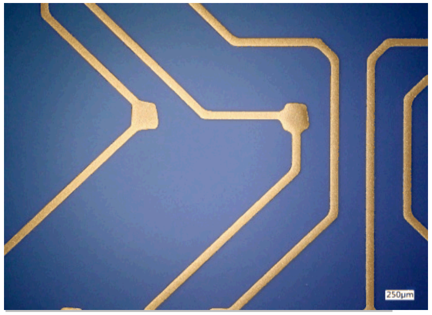
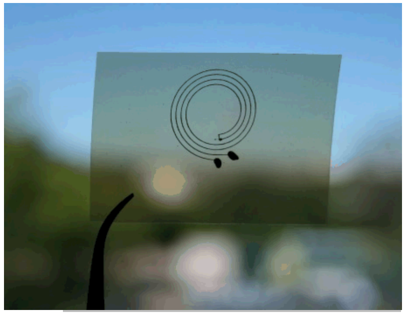

Solid Freeform Fabrication Symposium

Aug. 2015

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OVERVIEW

- Particle based printing technologies
- Promise of printed electronics
- Historical issues
- Addressing run time issues - modeling work, new print head development
- MJ print head performance
- LENS Issues
- Modeling/experimental results
- Conclusions

Particle Based Printing Technologies

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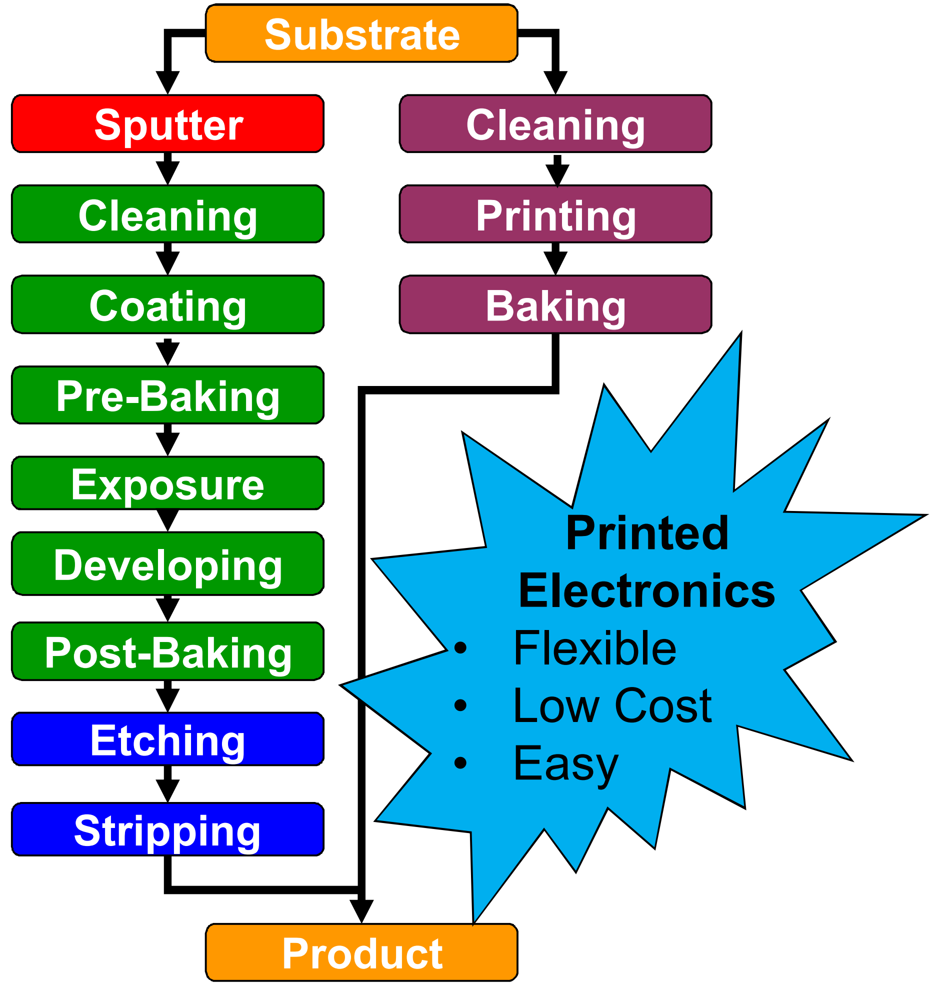
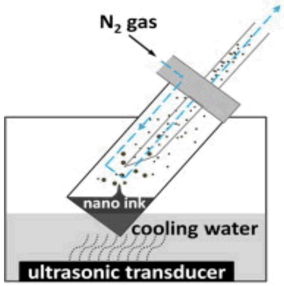
- Printed Electronics
  - Aerosol based droplet printing
  - Goal of work – Improve print quality
    - Minimize overspray at edges
    - Minimize sensitivity to pressure fluctuations
- 3D Metal Printing
  - Powder fed 3D printing processes (LENS, DLF)
  - Goal of work – Improve print process
    - Increase powder capture efficiency
    - Improve part surface finish
    - Provide possibility to transition deposition physics

Promise of Printed Electronics

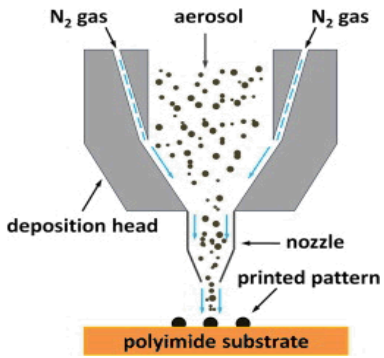
- Flexible Manufacturing Solution
- Fewer Process steps
- Minimize Tooling
- Minimize Equipment Expense
- Customizable – Low Volume/High Mix



Direct Write Printing

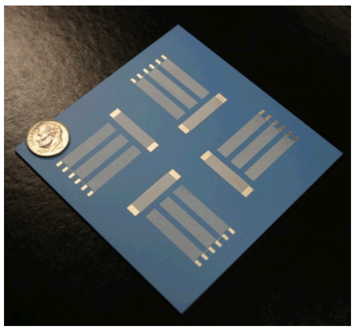


Zaho et.al

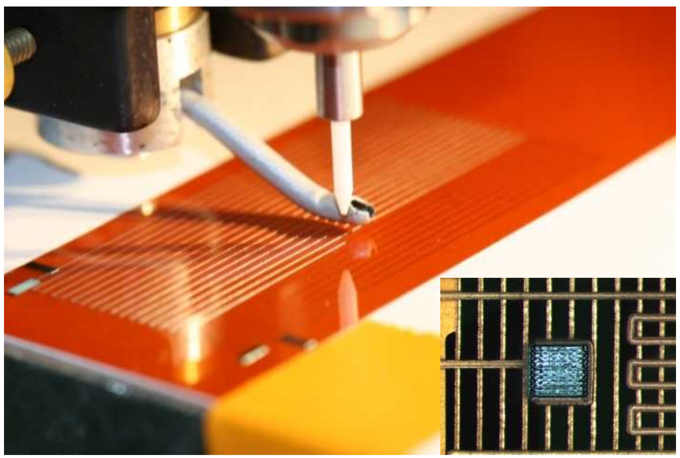


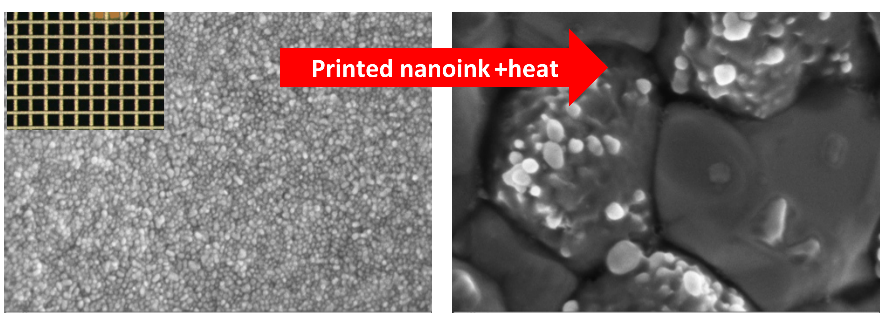
Aerosol Jet Printing Method (Optomec)

- Aerosol can be focused using inert gas streams and a small nozzle
- Atomization of liquid ink to produce a dense aerosol mist
- Line widths as narrow as 10 µm with 0.5-3 µm heights (silver nanoink)
- Broad materials compatibility
- Expanded post processing capabilities
- Rapid design iteration

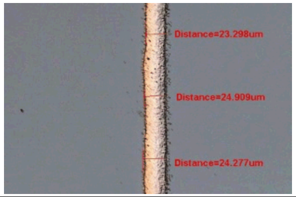
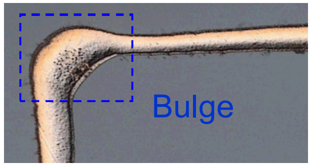
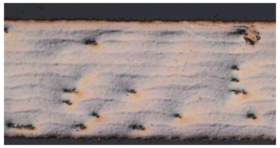
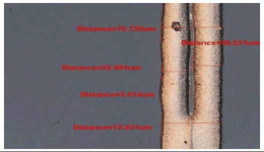


- DC and RF pathways for interconnect and antenna applications on planar or arbitrary surfaces
- Strain and crack sensors for structural health monitoring, resistance temperature devices (RTD)
- Integration of packaged components with external sensing networks for value added functionality





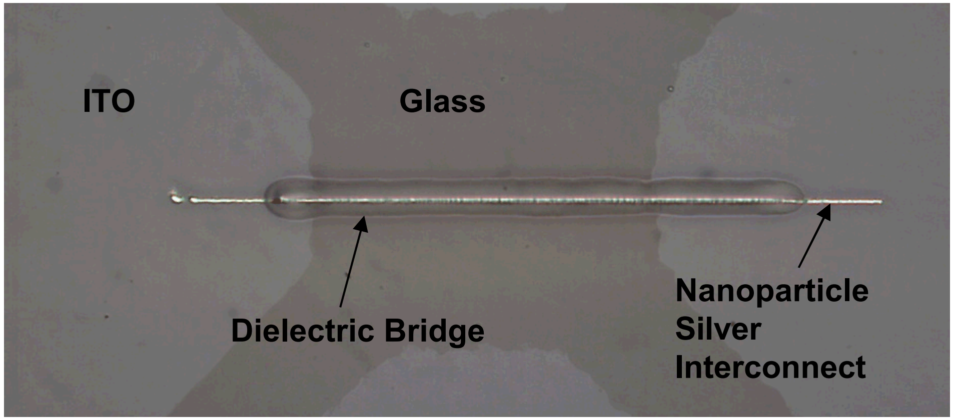
AJ Printing - Customer Expectations

Item	Description	Result Picture	Plan/Action
Resolution	25 µm (100µm Orifice Nozzle)		1.Use 75 or 50 µm Nozzle to check min. line width
Corner Printing	Corner bulged		Mask design 
Large Area Printing	Uniformity Issue		1. Multi nozzle application 2. Printing method ex. concentric circles
Small Line Space	Partial line connect for Line Width / Space : 20/10 µm		design limit for 10um space

Touch Screen Process Example

- Process Report for Bridge Circuit Printing Process. Requirements include:
  - Printing onto a glass substrate with ITO pattern
  - Produce interconnects between adjacent ITO pads
  - 100 µm x 1 mm dielectric layer to isolate interconnect from ITO layer
  - 10 µm x 1.2 mm Ag conductive bridge circuit onto the dielectric to interconnect adjacent ITO pads

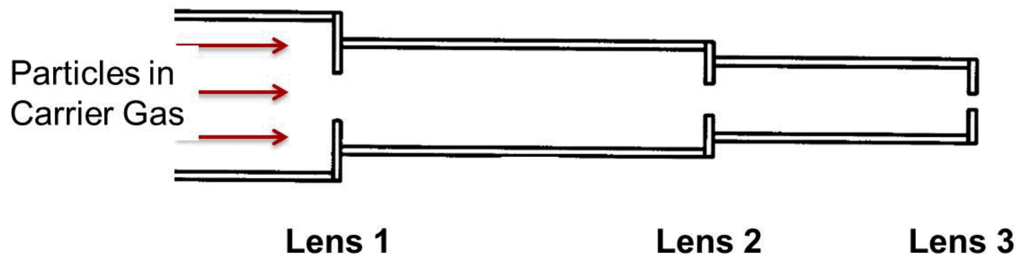
Transparent Insulator, nanoparticle silver interconnects, bridged across glass/ITO boundaries



Adapting Existing Technology

- SNL Experience with Aerodynamic Focusing being Adapted for Electronics Printing Applications (Patent US6348687)
- Particles in Carrier Gas Brought into Lens System
- Each Subsequent Lens serves to Further Collimate Powder Stream
- Series of Lens Also Needed to Collimate Polydispersed Particle Stream

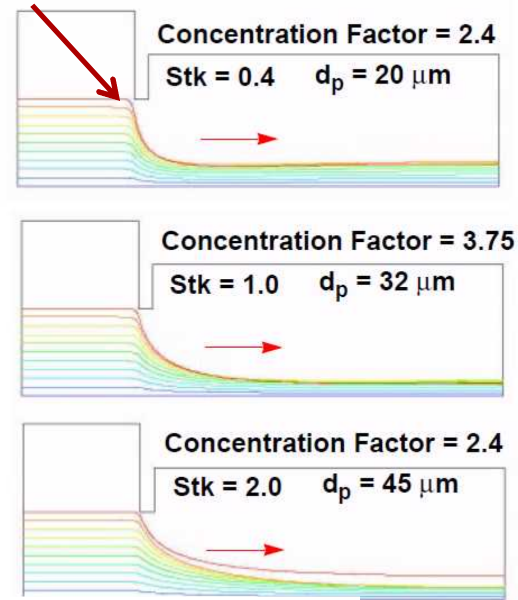
Aerodynamic Particle Focusing Lens System



Aerodynamic particle beam shaping

Conditions

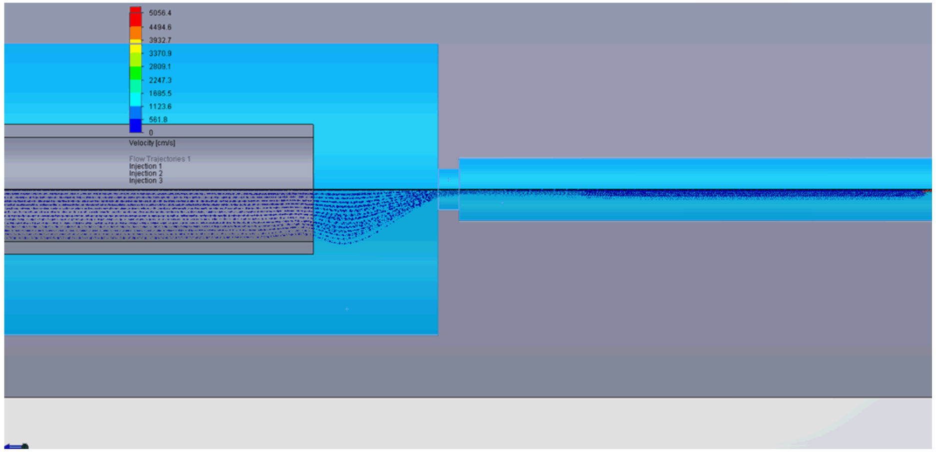
- Flow Directed Down-ward
- Gravity Included in Calculation
- P = 1 atm
- T = 295 K
- U = 86.5 cm/sec
- Re = 300
- D_{up} = 0.533 cm
- d = 0.267 cm
- D_{dn} = 0.40 cm



ck/COLD_SPRAY/IAC98.CS.frm

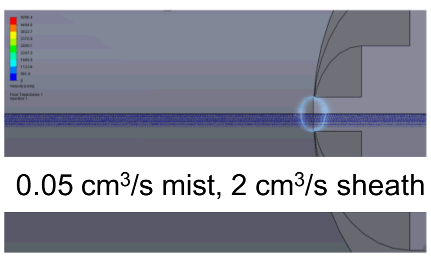
Sheath Gas Minimizes Particle Impaction

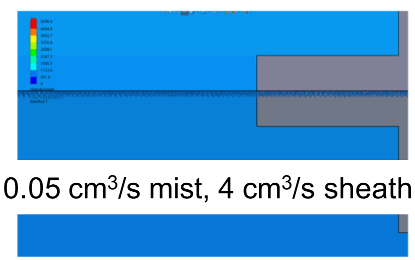
- Sheath Gas Flow is Added to Avoid Particle Impaction
  - Particle Stokes Number >0.213
- Sheath Gas Only Required for 1st Lens

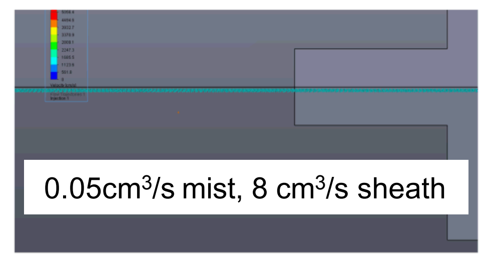


Preliminary CFD Modeling of Aerodynamic Lens

- Monodispersed particle distribution - 1µm droplets
- Sheath gas varied to affect collimation
- Results show improved collimation as sheath flow is increased
- Collimation vs. Focusing



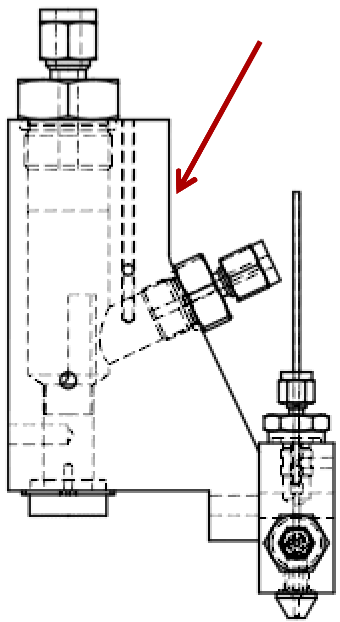


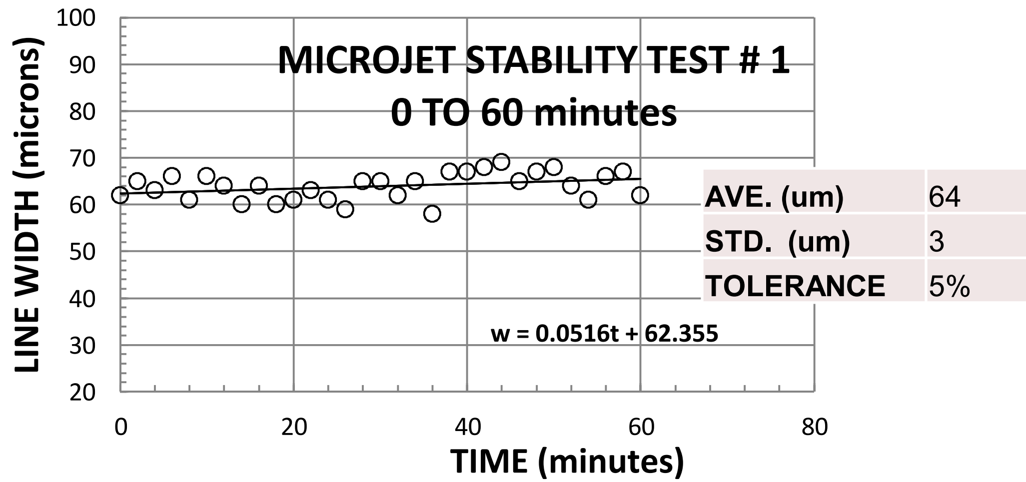


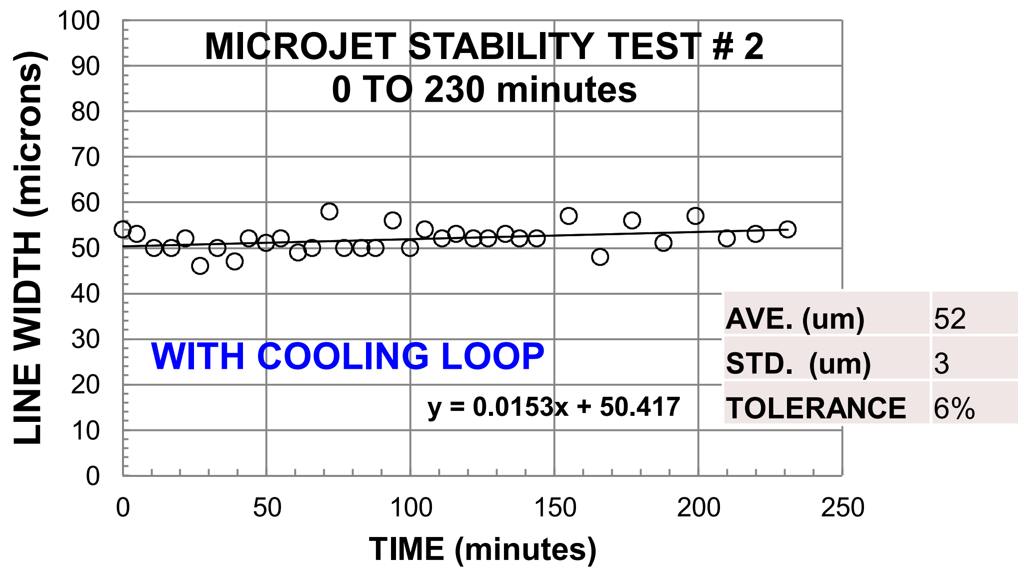
Fluid dynamic modeling results show effect of varying sheath flow rate on focused particle beam diameter (sheath flow rate increased from left to right).

Prototype Print Head and Preliminary Results

- Prototype Direct Write designed and developed for electronics printing applications
- Results show consistent printed linewidth for 4 hours.







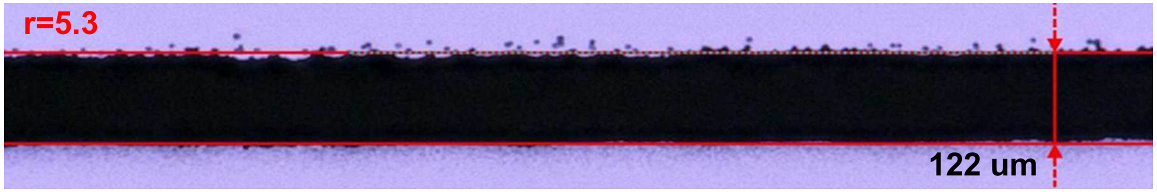
PROCESS CHARACTERIZATION

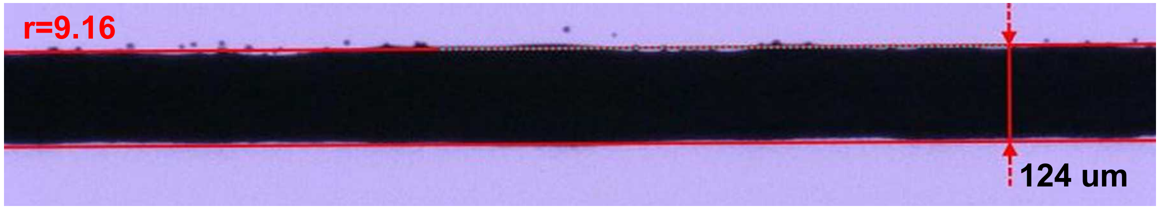
GOAL

Investigation of collimation and focusing of the aerosol distribution

OBSERVATIONS

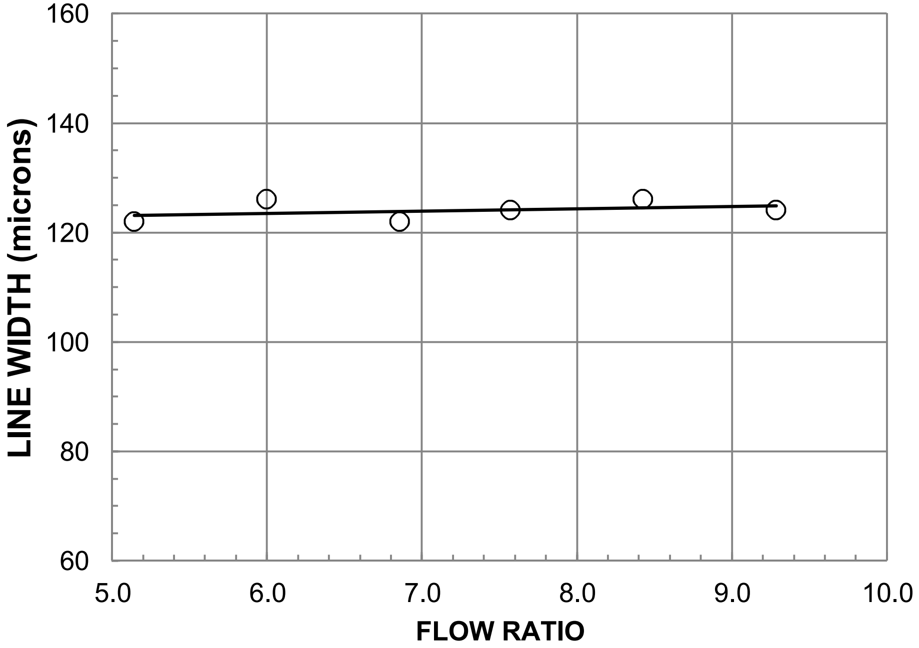
- Medium-size droplets are collimated by the first aerodynamic lens.
- Droplets on either side of the distribution are focused by the sheathed exit nozzle.
- Increased flow ratio (r=sheath/aerosol flow rate) decreases overspray deposition.
- The sheath flow rate has little or no effect on the diameter of the collimated stream.
- Deposited line width is independent of the sheath gas flow.





PROCESS CHARACTERIZATION

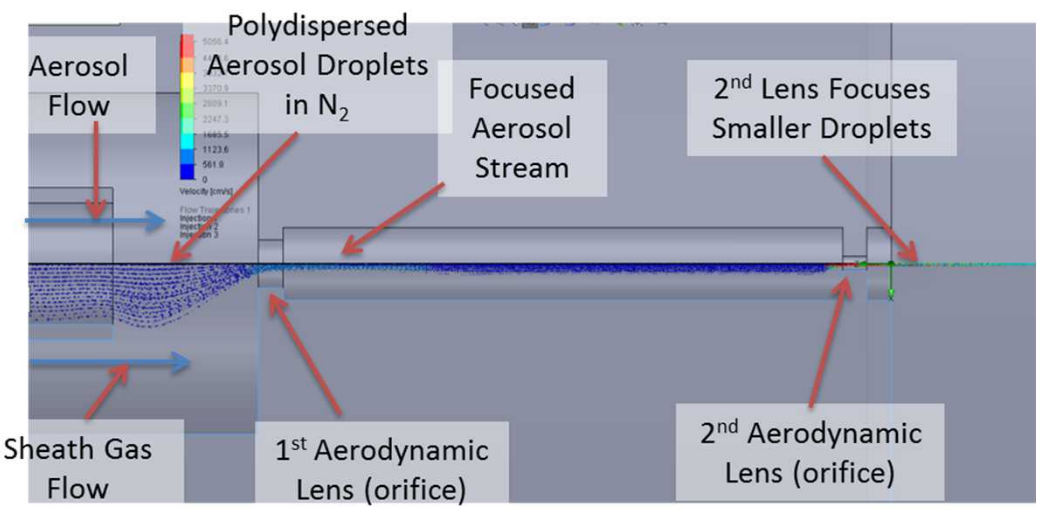
- **Flow Ratio = Sheath Flow Rate/Aerosol Flow Rate**
- **Tolerance = Standard Deviation/Average**

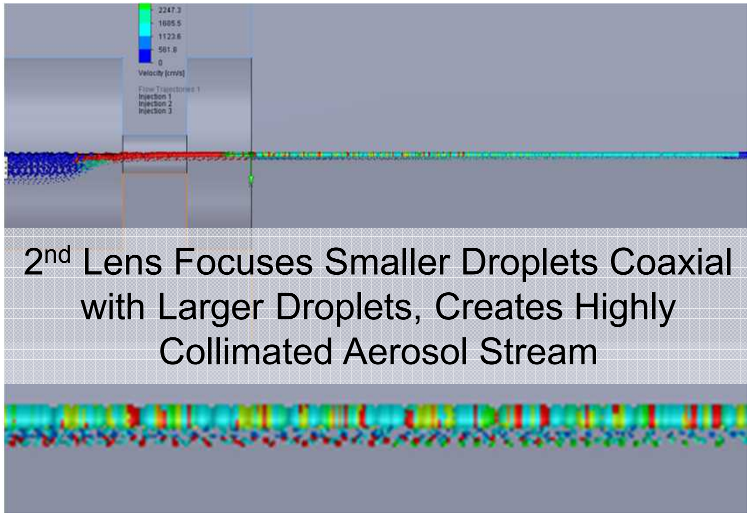


FLOW RATIO	LINE WIDTH (um)
5.1	122
6.0	126
6.9	122
7.6	124
8.4	126
9.3	124
Ave.	124
Std.	1.79
Tolerance	1.4%

Modified Nozzle Design Modeling

- Multiple Aerodynamic lens aerosol focusing
- Poly dispersed aerosol source
  - Droplets range from 500 nm to 3µm.
  - Multiple Aerodynamic Lenses
    - Optimal focusing of all droplets sizes
    - Highly collimated print stream
  - Minimizes overspray/satellites of smaller droplet sizes

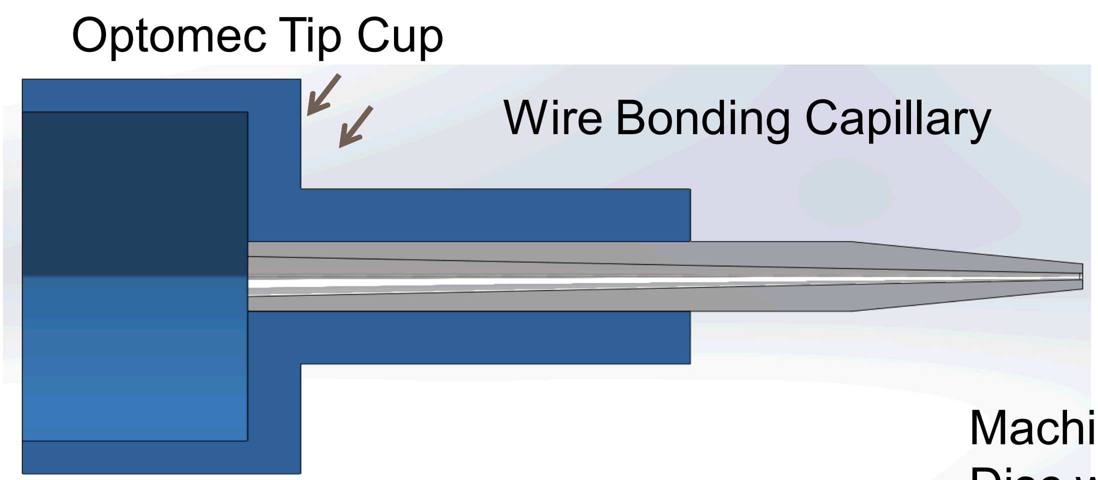




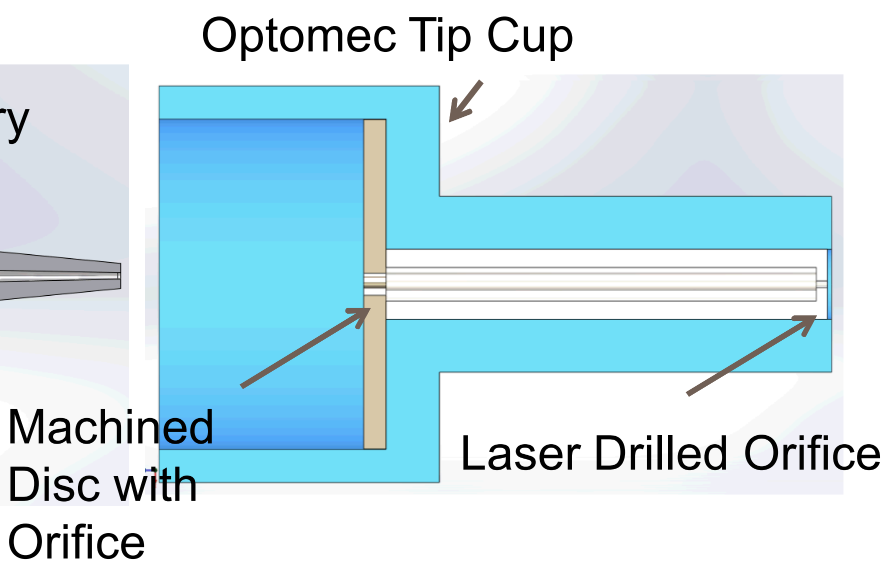
Multiple Aerodynamic Lenses Enhance Focusing for Polydispersed Aerosol

Old Nozzle vs. New Nozzle

- Commercial Nozzle Uses Wire Bonding Tip
  - Not optimized for aerodynamic focusing
- Modified Nozzle Optimized for Aerodynamic Focusing (reduce overspray)
  - Implementing and testing requires 2 parts
    - One machined orifice
    - One commercial orifice

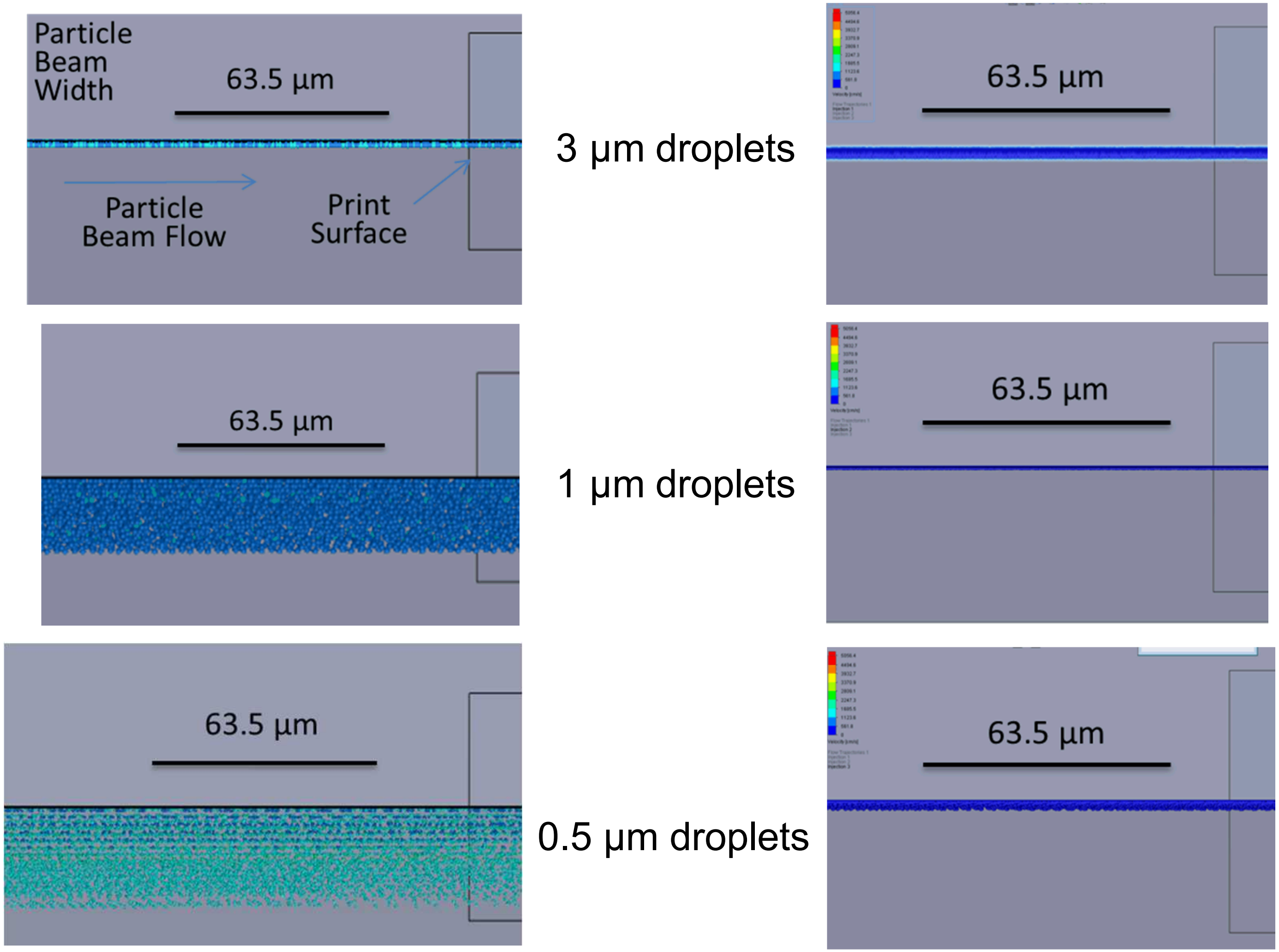


Existing AJ Nozzle



Optimized Nozzle

Commercial Droplet Focusing vs. SNL Technology

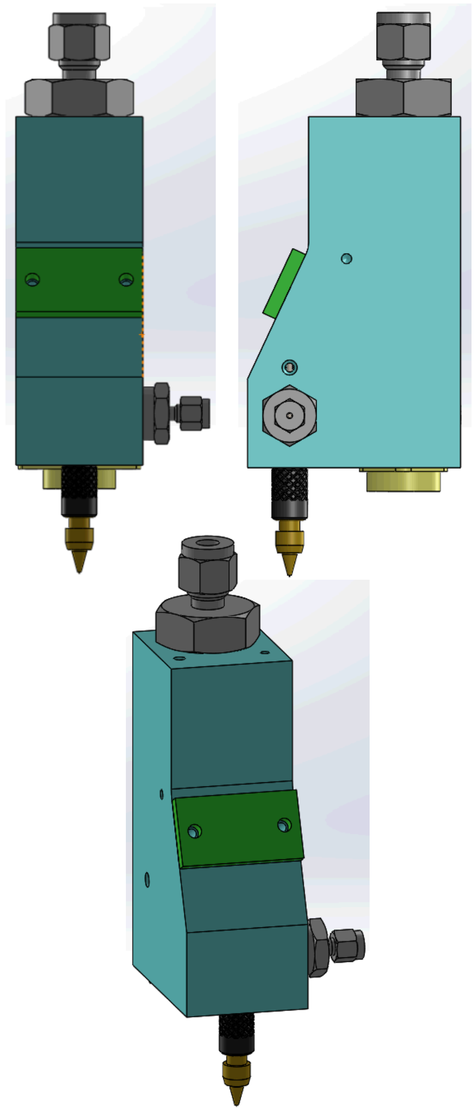


Commercial aerosol jet printing: Largest droplets are focused best, unfocused smaller droplets lead to overspray.

SNL aerosol printing: Multiple aerodynamic lenses allow polydispersed droplet distribution to be collimated.

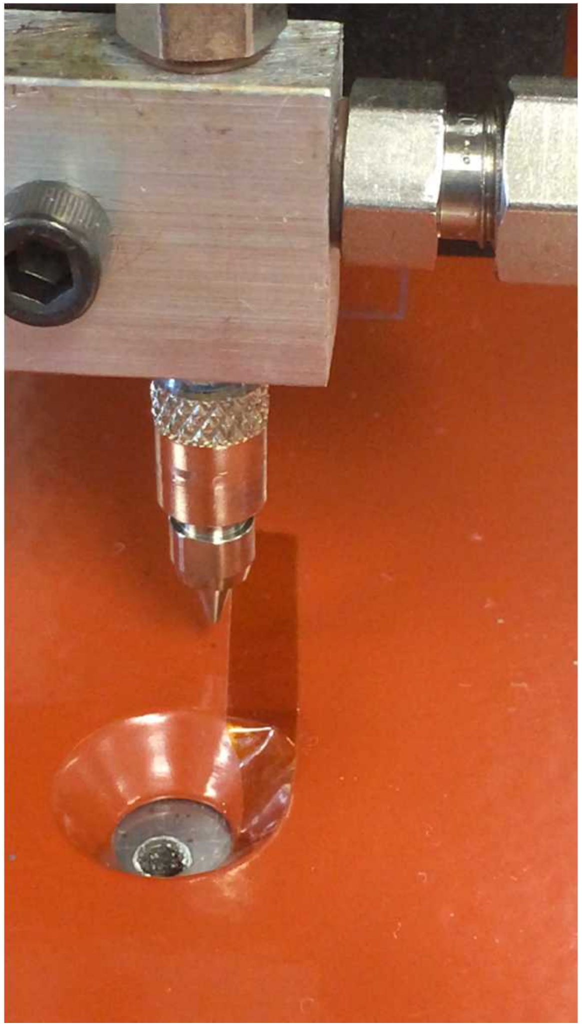
Monolithic Microjet Print Head

- Design based on cold spray technology
  - Provides tightly collimated aerosol stream
- Multiple areodynamic lenses provide efficient collimation of polydispersed aerosols
- Monolithic design provides stable output for many hours of continuous operation
- Cost effective solution is enabling maker community adoption
- Moves technology toward cartridge based system



MicroJet Printing Process

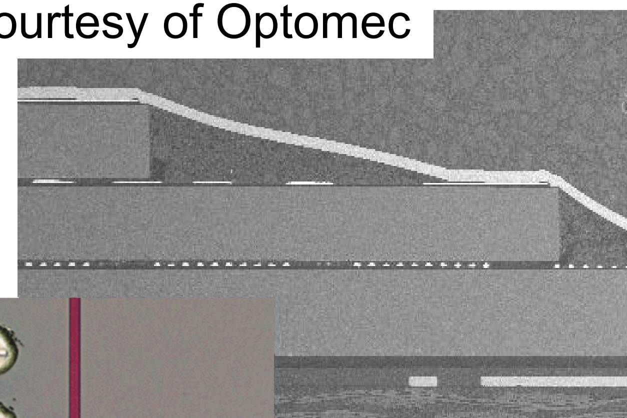
- Standoff from substrate approx. 5 mm
- Plate thickness 6.4mm

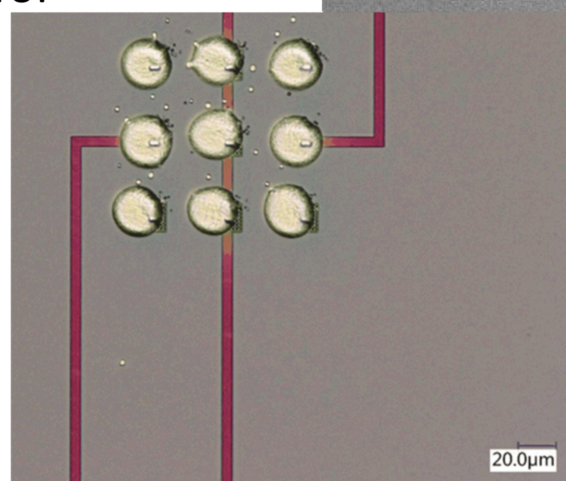


Printed Electronic Application

- 3-D Interconnects
  - Stacked Processor, Display and Memory Chips
  - Minimize Parasitic Effects
  - Increased Speed
  - Alternative to Thru Silicon Via Technology and Wire Bonding
- Micro Bumps for Flip Chips
  - Create reversible interconnects for test vehicles
  - Flip chip packaging

Courtesy of Optomec





IMPROVEMENTS TO 3D METAL PRINTING USING PARTICLE FOCUSING

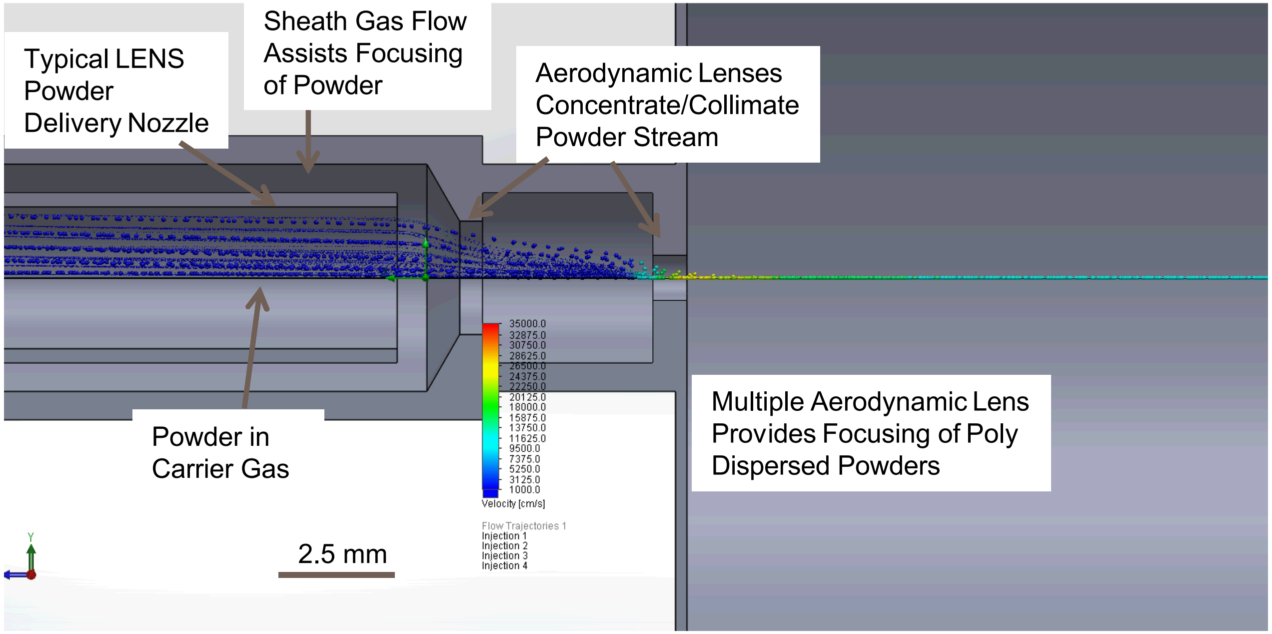
Limitations with LENS Process

- Powder Utilization – Typically 10-15%
- Surface Finish – Partially melted adhered powders
  - Limit finish
  - Limit "as- built" material properties
- Layer Thickness Control
- Material Waste

Improved LENS Processing with Collimated Powder Streams

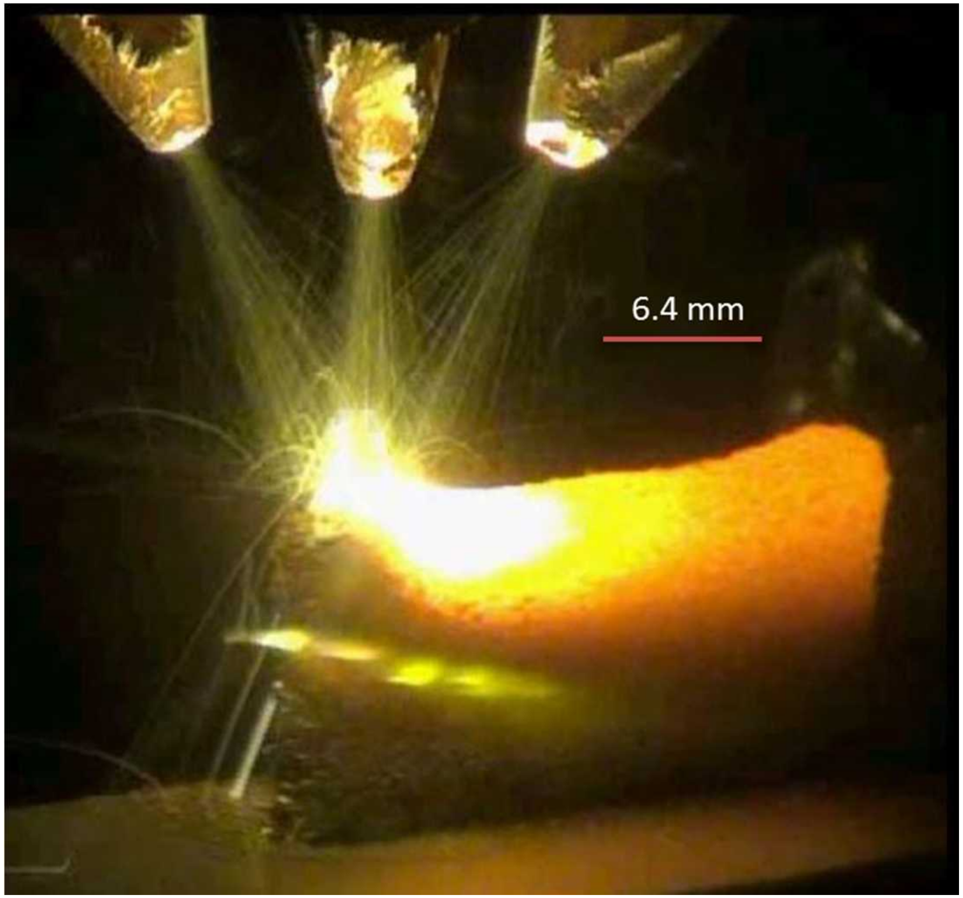
- Collimated Powder Stream Smaller than Melt Pool
  - Enable full utilization of powder
  - Layer height control
  - Minimum powder waste
  - Improved surface finish (no unmelted powder on surface)
- Enable Efficient Gradient Fabrication
  - Fully utilization of powder → Minimal mixed powder waste

Modeled Results for Powder Nozzle Improvements

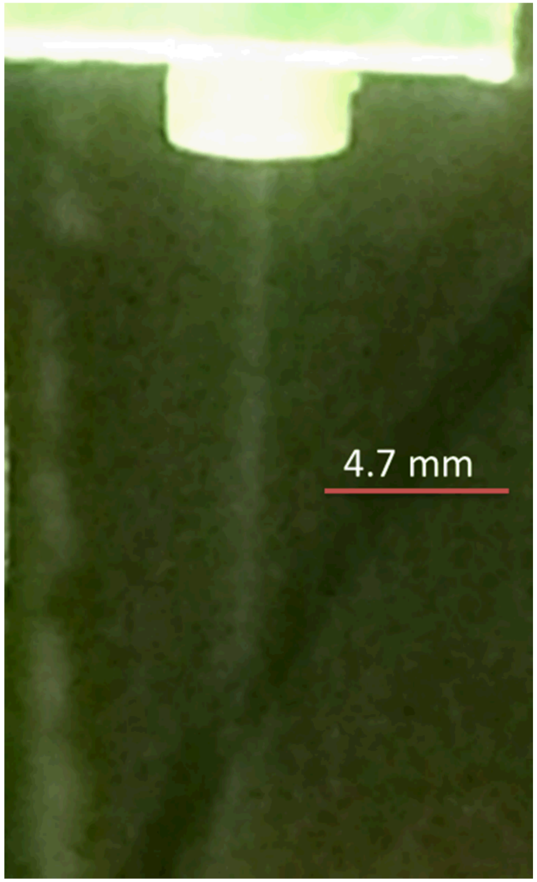


Problem: Typical LENS nozzle provides diverging powder stream to deposition surface limiting powder utilization (typically 10-15%).
Solution: Incorporate SNL IP (Brockman, et.al.) into nozzles to create tightly concentrated, collimated powder streams.

Preliminary Powder Collimation Results



Traditional LENS Powder Delivery



Collimated LENS Powder Delivery

Summary

- Micro Jet Printing Technology
  - Provides improved performance over AJ technology
    - Improved line edge quality
    - Improved working distance
  - CFD analysis supports improved collimation results
  - CFD analysis shows existence of overspray for polydispersed aerosol distribution
- LENS Printing Technology
  - Preliminary results show reasonable agreement between model and experiment
  - Collimation results support ability to significantly enhance LENS process

Thank You

Direct Write & Applications

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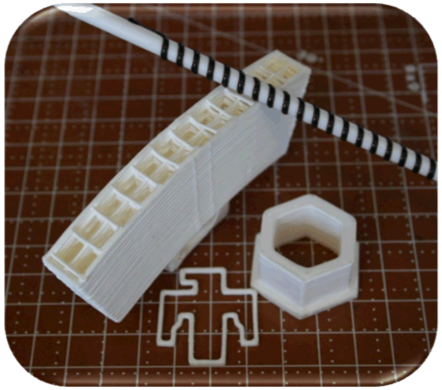

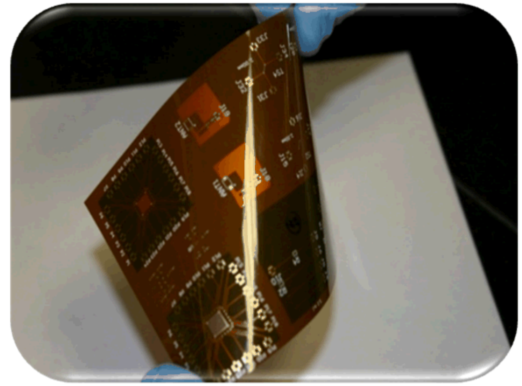
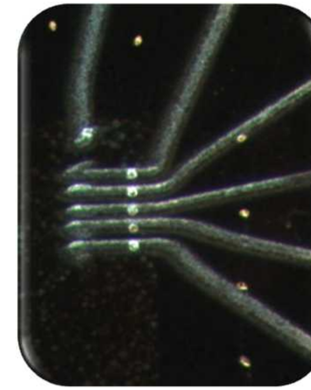
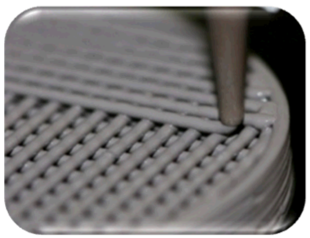
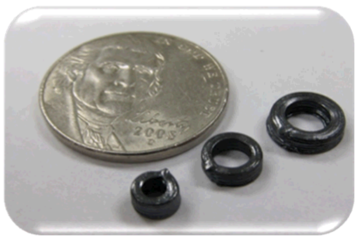
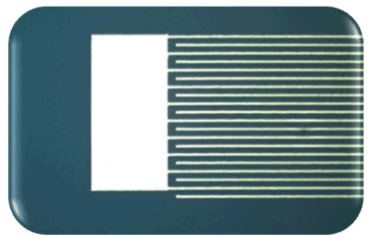

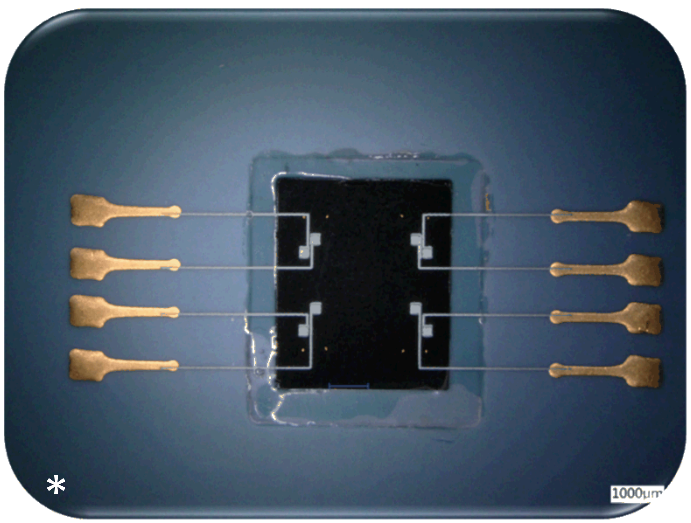


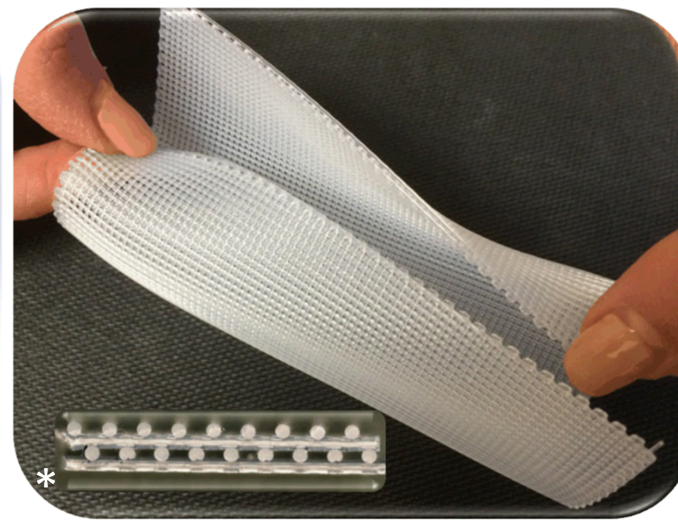

* Collaboration with KCP

Collimated Powder Streams Enabling for Hybrid Deposition Process

- High Velocity Powder Enhances Deposition Rate
  - Powder velocity > 200 m/s should enable laser assisted cold spray AM process
    - Heating of deposition area will enable deposition of broader range of materials
    - Solid state deposition process with heating will minimize residual stress

Materials Synthesis and Processing for Direct Write

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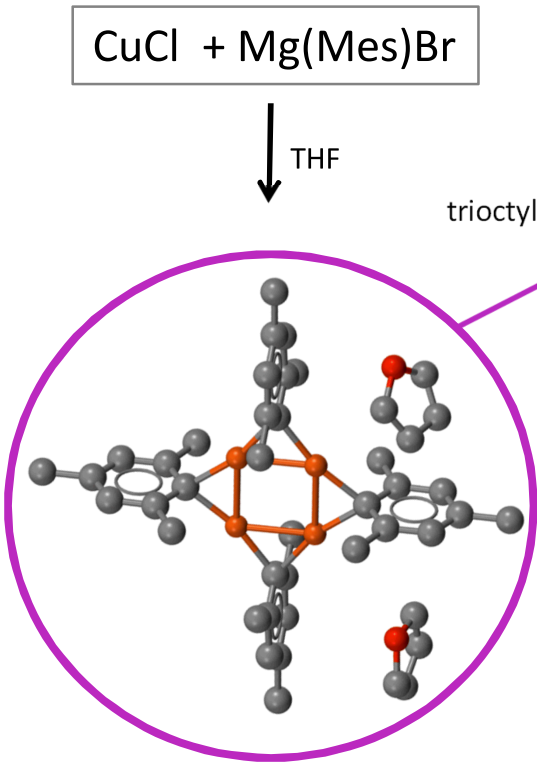
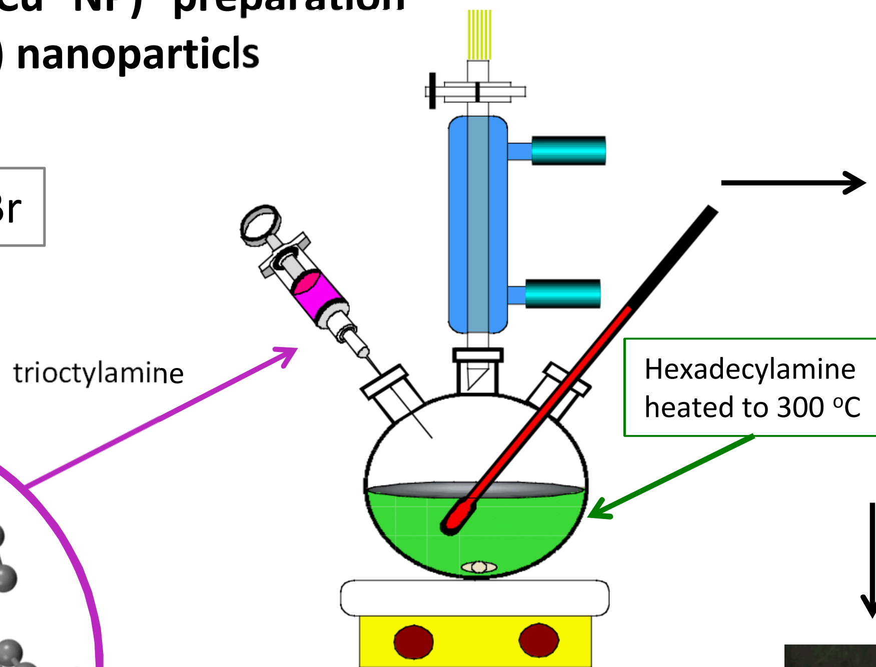
Copper nanoparticle (Cu NP) preparation yields high quality Cu(0) nanoparticls

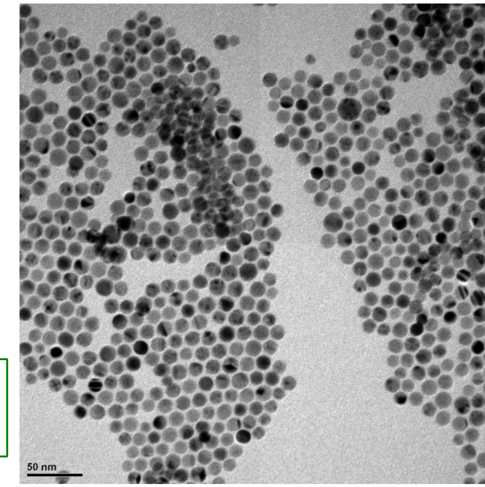


$[Cu(Mes)]_4$•2THF

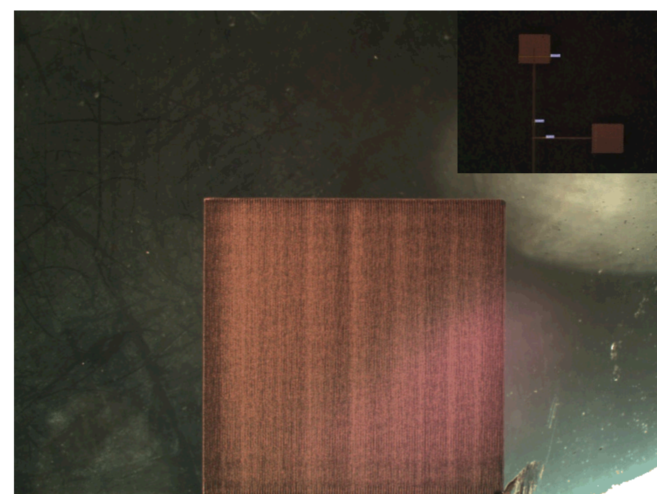
A. Extensive washing with hexanes and extraction with toluene leads to high purity $[Cu(Mes)]_2$ which is critical for high quality Cu NP



B. Following a solution precipitation synthesis,[1,2] [Cu(Mes)] dissolved in trioctylamine was injected into hexadecylamine at 300 °C. After 5 min, the reaction is removed from the heat, allowed to cool. Cu NP are isolated by centrifugation of a toluene:methanol mixture. Repeated washing with methanol ensures ‘clean’ Cu NP.



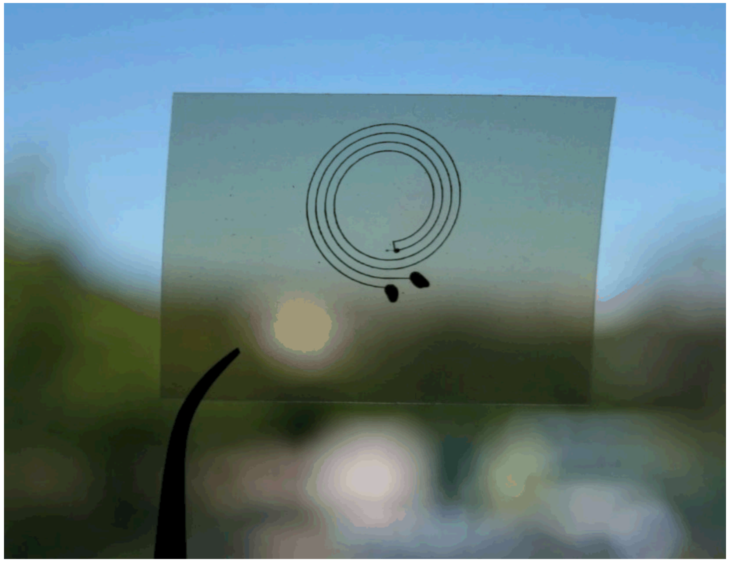
C. TEM images of 10-15 nm Cu NP; some larger present. Scale Bar = 50 nm.



Printed Cu Ink (unprocessed)

Low Temperature Curing

- Photonic Curing
  - Laser based curing
  - Optical light pulses
- Room Temperature Curing
  - Identified a mechanism that enables room temperature curing for nanoparticle inks
  - Seeking to understand phenomenon behind room temperature curing
  - Goal: Develop coating to be used in conjunction with printing to provide method to enable room temperature curing to broad range of substrates

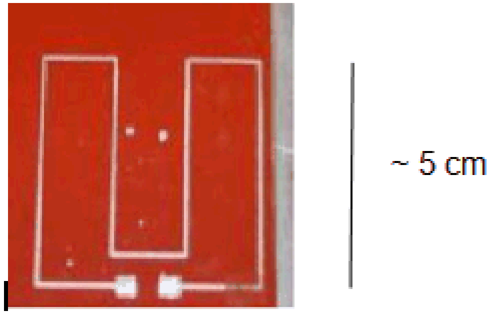


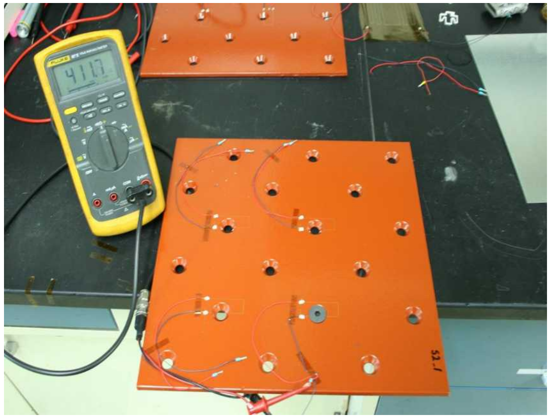
Direct write Ag spiral on PET. Conductive as printed

Large Area Sensors

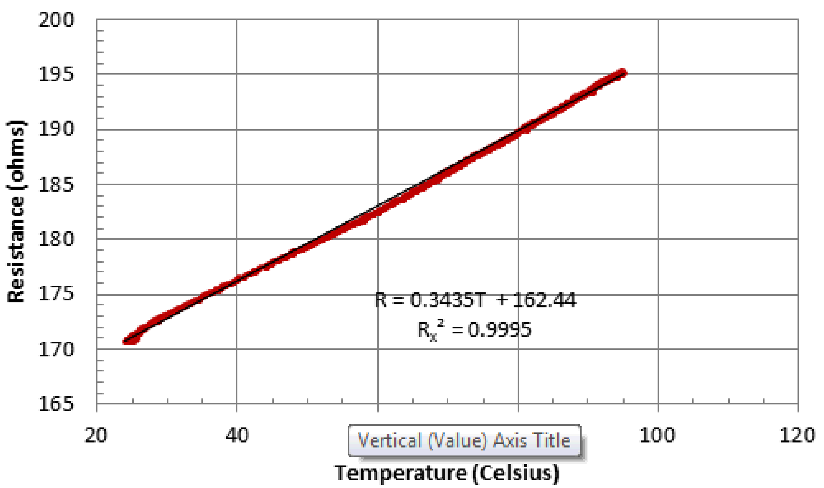
Sandia National Laboratories

- Proof of Concept Effort
- Multi-Layered Structures Created to Isolate and Embed Sensors
  - Stainless steel substrate
  - Powder coating for 1st dielectric
  - Printed Ag traces to create sensors
  - Over-coated with 2nd dielectric to isolate and protect
- Application
  - Structural health monitoring
  - Intrusion detection

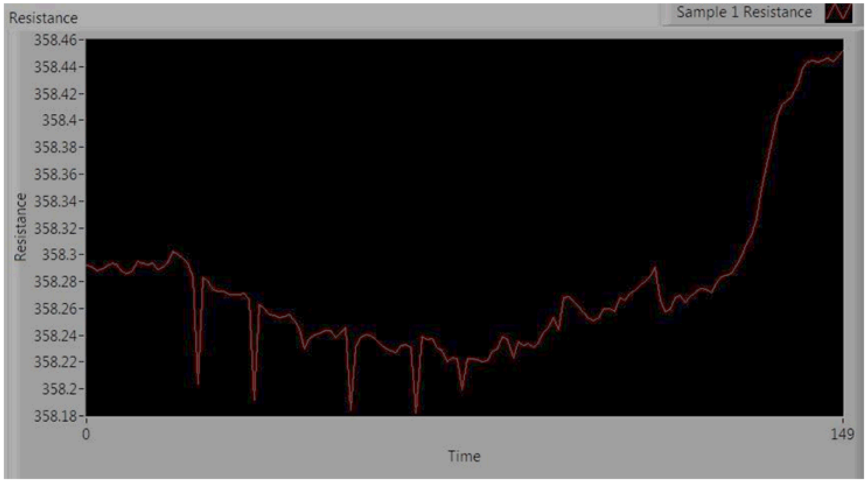




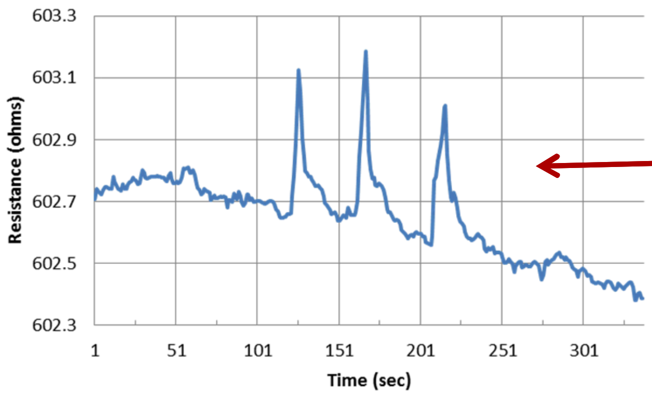
Test Results – Large Area Sensors



Temperature response of a sensor on a flexible substrate.



Strain response of a sensor on a flexible substrate.



Response of a proximity sensor circuit as a downward facing hand is placed near the circuit and removed. The test was performed three times. Each test is recorded as an upward spike in the response curve.