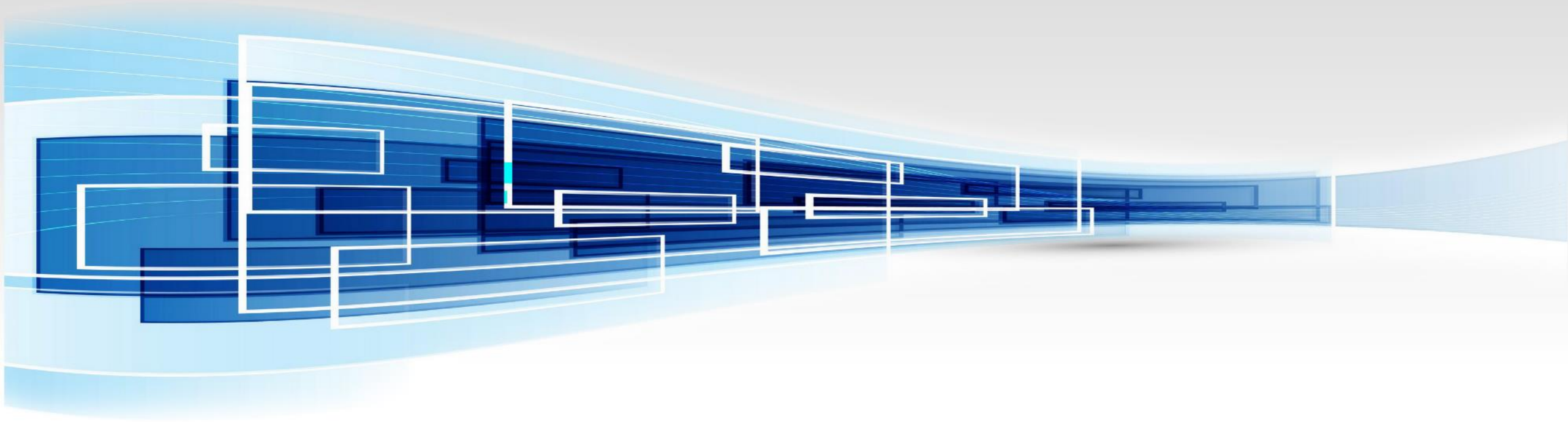
3D Printing of Flexible Circuits and Sensors



OPTOMEC®

Production Grade 3D Printers... with a Material Difference

Presentation Outline

- Company Introduction
- Aerosol Jet Technology Basics
- Material Considerations
- Laser Sintering for Low Temperature Processing
- Strain and Thermocouple Gauges
- Conclusion

Differentiated Leader in Additive Manufacturing

Power
Healthcare
Aviation

illumina

United Technologies

ALCOA

LITEON

Altaflex

BAE SYSTEMS

xerox

Boston Scientific

300+

Optomec Global Installations

50+ Issued
50+ Pending

Optomec IP

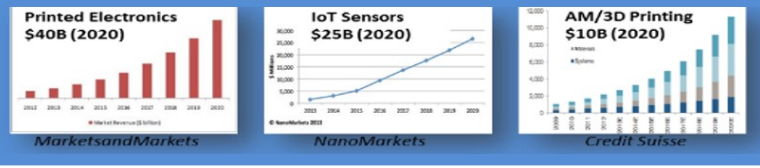
40+

Optomec Material and Automation Partners

75+

Optomec Employees Albuquerque & St. Paul

Targeting High Growth Markets & Applications



Privately Held – Profitable – Recent Investment from GE

BOEING

Nordson

CORNING

Rockwell Collins

Johnson & Johnson

BOSCH

Panasonic

LOCKHEED MARTIN

UNITED ENGINE CORPORATION

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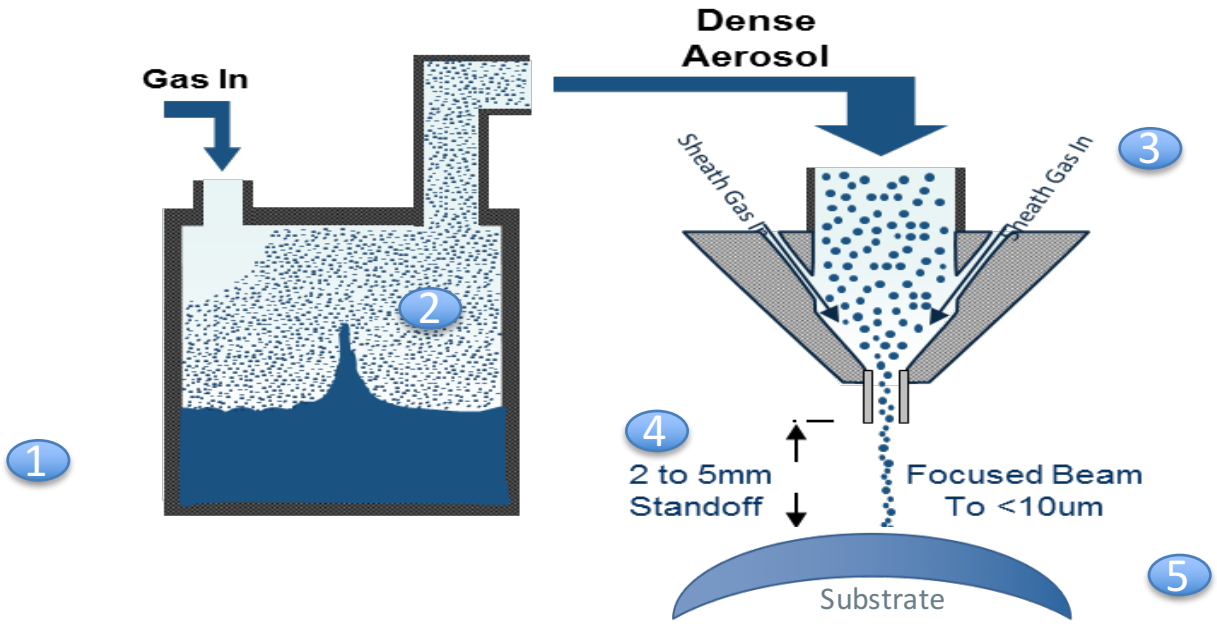
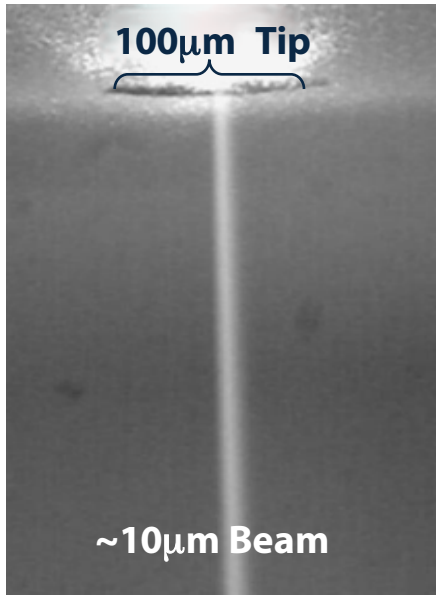
Production Grade 3D Printers... with a Material Difference

3

Aerosol Jet Technology Basics

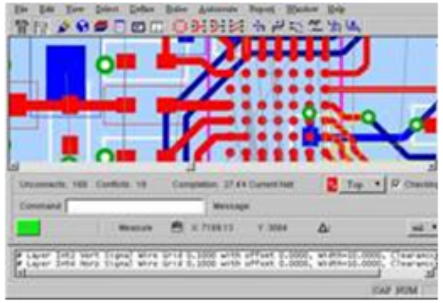




1. Atomize Liquid Electronic Material: conductive inks, dielectric, (1-1,000 cP)
2. Mist of 1 to 5 um Ø highly dense, highly loaded droplets
3. Sheath gas surrounds and focuses particle beam
4. Continuous Flow Exits at 50m/s remains collimated for up to 5 mm
5. Print on planar and non planar substrates

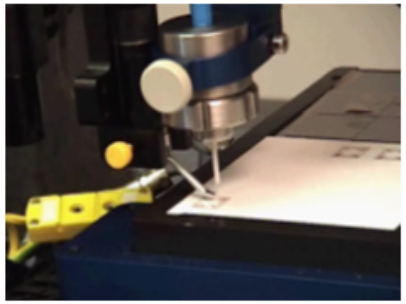
Art to Part Process

Design



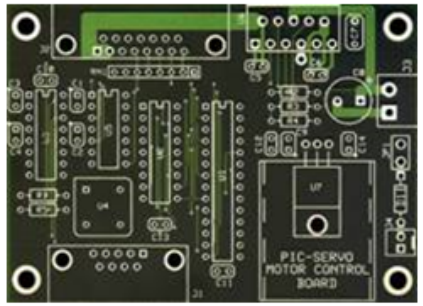
- CAD Model
- Convert to DWG file
- Tool paths generated with Optomec software

Process



- Liquid raw material
- Create fine (femto Litre) aerosol
- Focus to beam (~10µm >)
- Post-process (dry, cure, sinter…)

Part



- 3D Conformal printing
- Interconnects
- Fine line traces
- Embedded passives
- Selective Coatings
- Microfluidic components

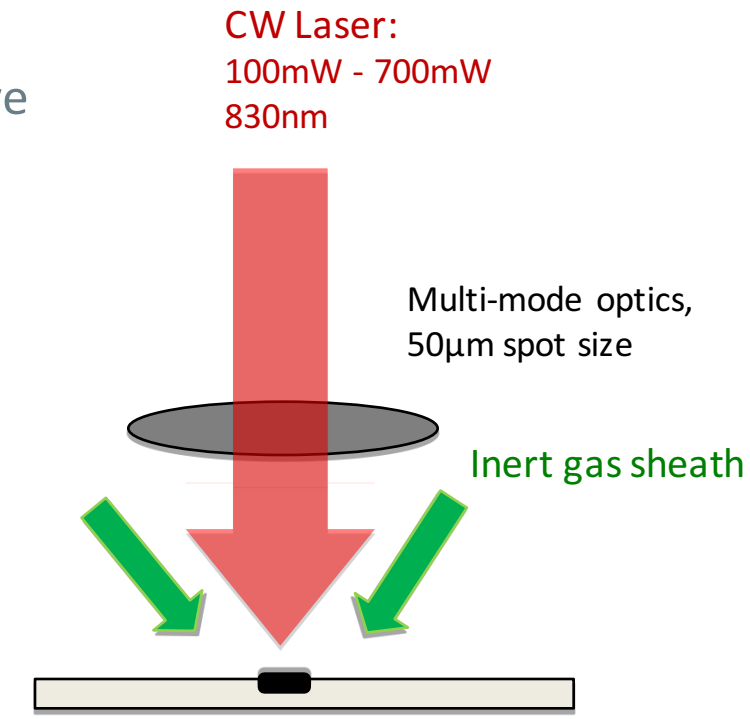
Materials for Sensors and Flex

Material	Resistivity (μΩ·cm)	TCR	Yield Strength (MPa)	Elongation (%)	Sintering (C)	Seebeck Coefficient (μV/K)
Ag	1.6	3.8E-3	55	35	120	6.5
Au	2.4	3.4E-3	205	45	200	6.5
Cu	1.7	3.9E-3	117	40	220	6.5
Ni	7.0	5.8E-3	140-350	40	350	-15
$Cu_{55}Ni_{45}$	49.0	-7.4E-5	140	45	400	-35

- Ag, Cu, Au are best electrical conductors
- Cu, Ni are harder materials with good solderability, low electromigration
- CuNi alloy has low TCR, higher resistance, high Seebeck coefficient

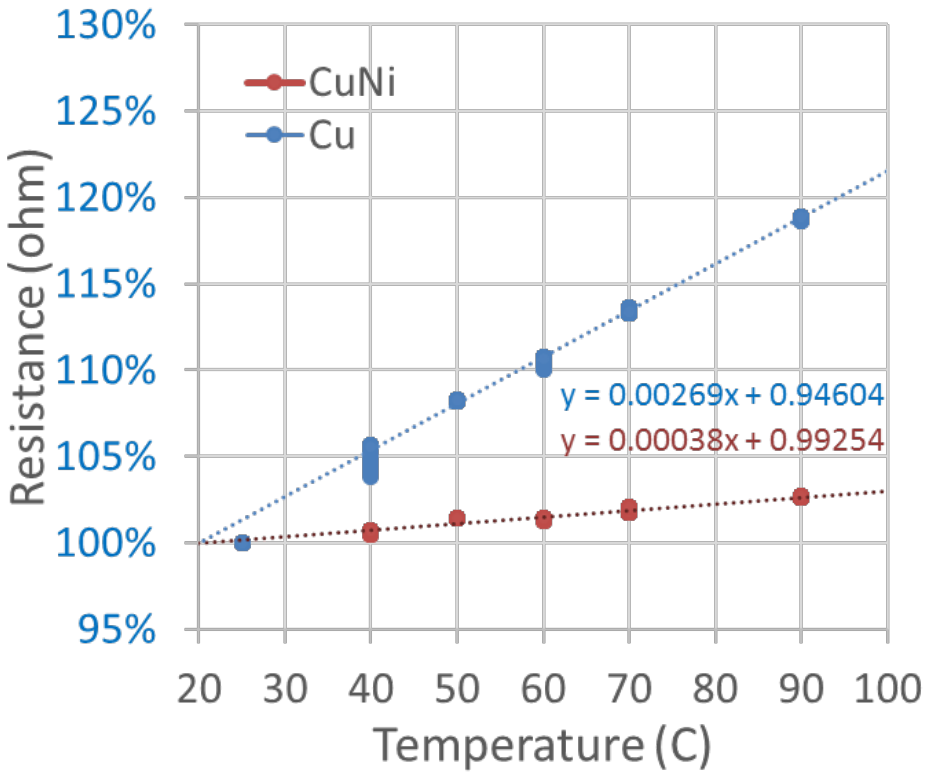
Laser Sintering

- Sintering of high temperature materials on low temperature substrates possible with localized heating
- Inert and reducing cover gas (H5N) inhibits oxidation of air sensitive materials
- Ink samples can be dried with laser at low power, then sintered at higher power
- Scan speeds from 1-20+ mm/s depending on power
- Sintering reactions self-limiting



Temperature Coefficients

- Resistance stability (extrapolated):
  - **Ag [uncoated] = 4.5%(ohm)/yr**
  - **Ag [coated] = 0.4%(ohm)/yr**
  - Cu = 2.75%(ohm)/yr
  - CuNi = 0.06%(ohm)/yr

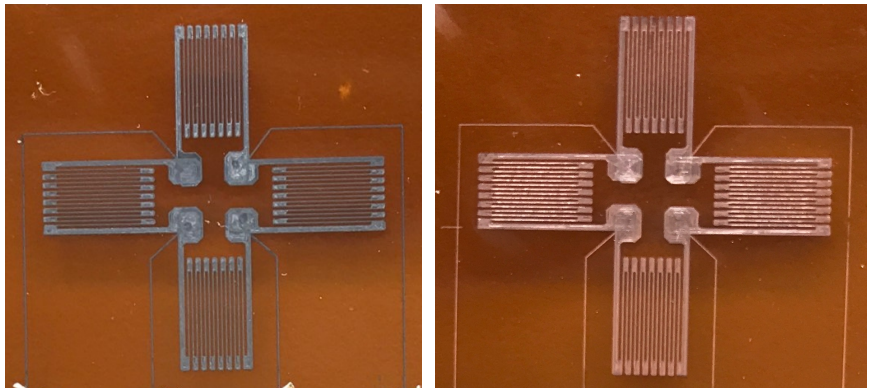


- TCR:

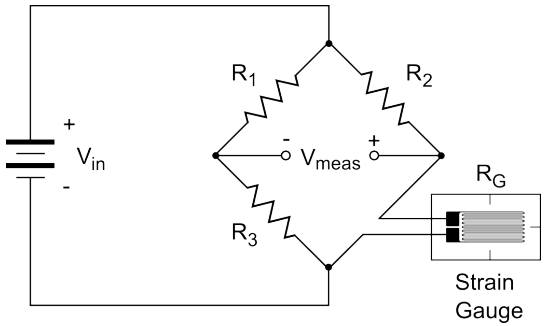
Material	TCR (measured)	TCR (literature)
CuNi	3.7E-4 C^{-1}	7.4E-5 C^{-1}
Cu	2.7E-3 C^{-1}	4.0E-3 C^{-1}
Ag	2.1E-3 C^{-1}	3.8E-3 C^{-1}
Au	1.4E-3 C^{-1}	3.7E-3 C^{-1}

*https://www.allaboutcircuits.com/textbook/direct-current/chpt-12/temperature-coefficient-resistance/

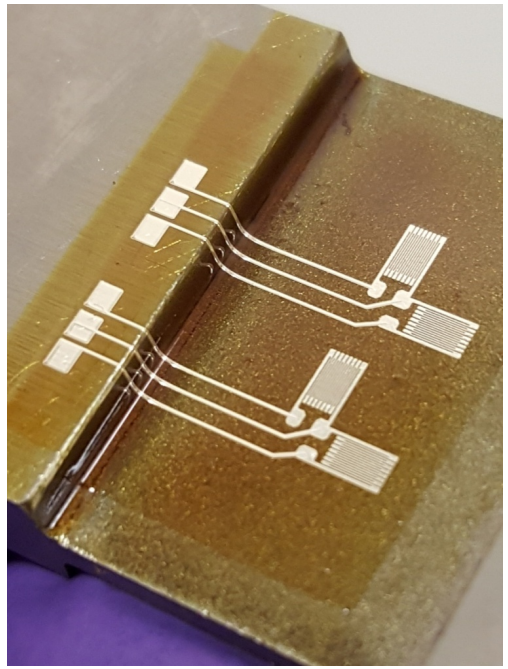
Flex Application: Strain Gauges



Constantan (left) and Copper (right) strain gauge



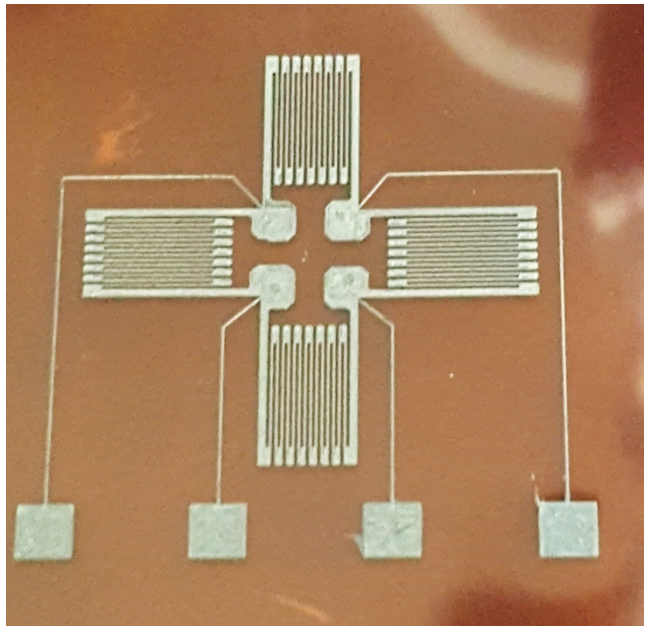
Wheatstone Bridge Circuit diagram



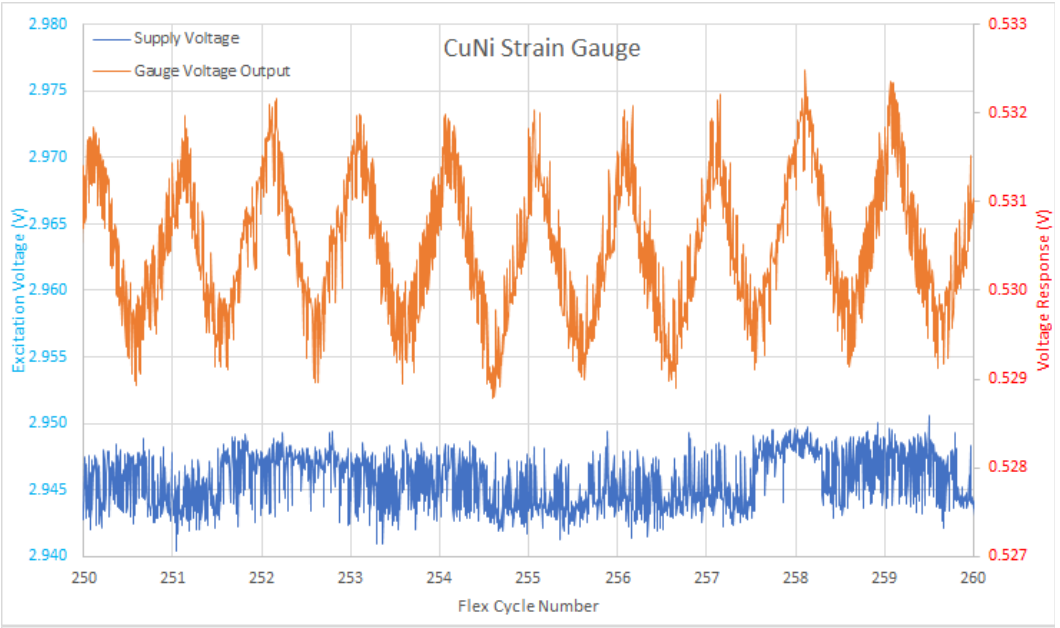
Half Bridge Strain gauge printed on steel beam showing 3D interconnects

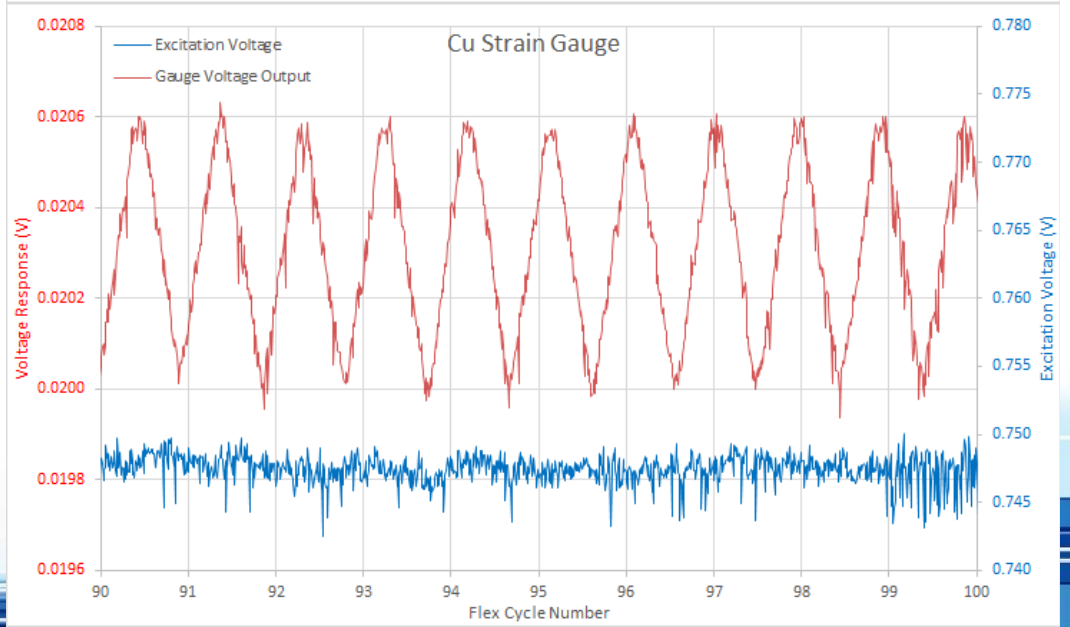
Strain Gauge Performance

- Cyclic bending over 60 mm diameter pipe (0.6% strain)
- >5,000 flexes without signal degradation



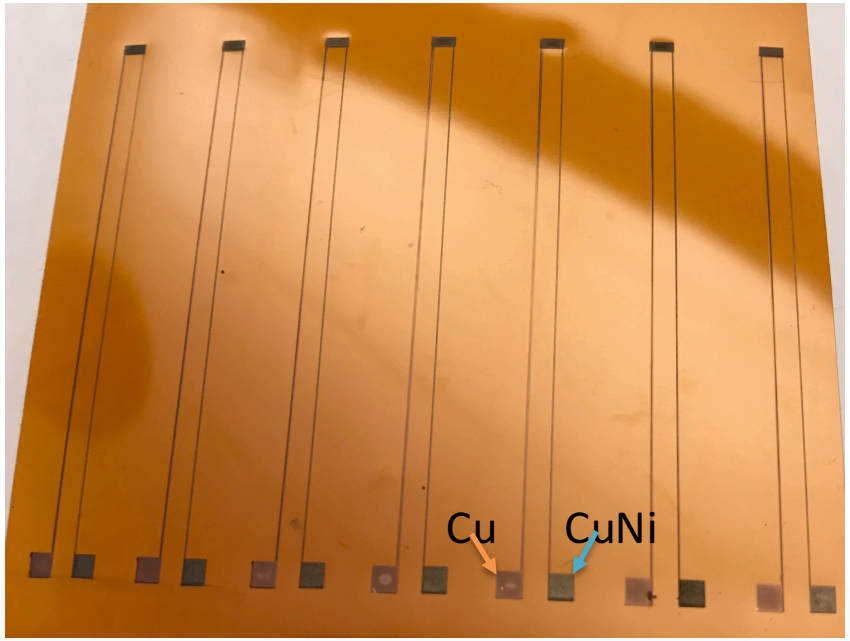
CuNi gauge on 0.005” Kapton

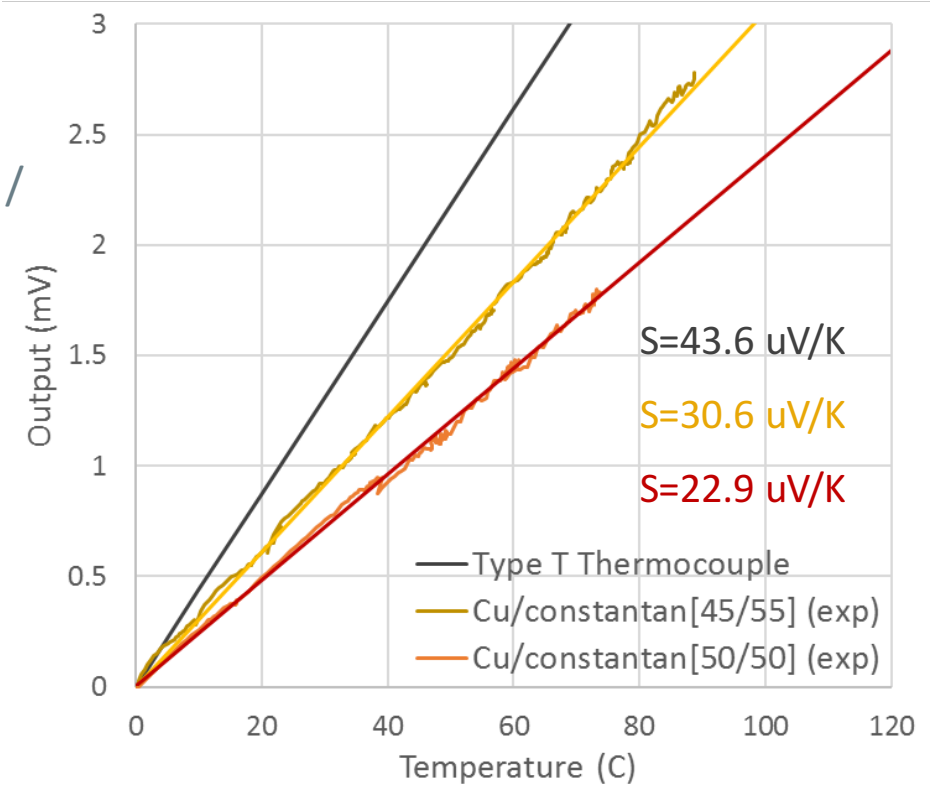




Copper–Constantan Thermocouples

- Two different CuNi formulations
  - $Cu_{55}Ni_{45}$
  - $Cu_{50}Ni_{50}$
- Seebeck coefficient approaches type T thermocouple (Cu / $Cu_{55}Ni_{45}$)
- Pad to pad resistance ~2kOhm





Summary

- Air sensitive copper-based materials printed with Aerosol Jet
- Local sintering with Laser inert shield gas results in high conductivity
- Laser sintering allows low-temp substrates to be used with sintering
- Copper and Copper alloy strain gauges cycled over 5,000 times on Kapton
- Copper-Constantan printed thermocouples demonstrate linearity

Thank You…

Questions?

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