United Technologies Research Center

Printed Electronics for Aerospace and Buildings

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Presented by
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Applied Physics

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Be Curious℠

Direct Write of Electronics and 3D Magnetics

Agenda:

- UTC / UTRC Introduction
- Rub Depth / Wear Sensor
- Thermocouples, RTDs and Heaters
- Printed Electromagnetics
- Structural Electronic Sensor Case Study
- NextFlex Initiative

UTRC Direct Write of Electronics and 3D Magnetics

UTRC INTRODUCTION

Making

modern life

possible

Providing high technology systems and services to the aerospace and building industries.

United Technologies

Our business units

“UTRC is where you bring your toughest problems.”

UTC Aerospace Systems

United Technologies
Climate | Controls | Security

Pratt & Whitney
A United Technologies Company

Otis
A United Technologies Company

UTRC is UTC’s innovation engine

Defining what’s next:

Define new frontiers

Co-develop new technologies

Solve tough problems

Serve as hub for technical interchange

Leverage global network of innovation

Monetize UTC intellectual property

United Technologies Research Center

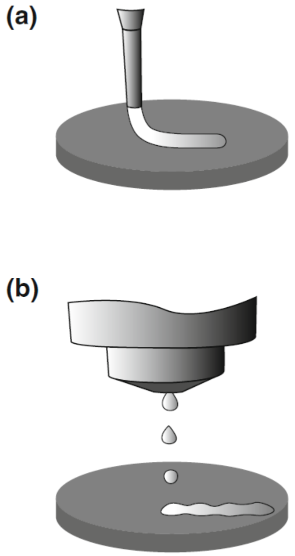
What is Direct Write Printed Electronics?

Technology to create two- or three-dimensional functional structures directly onto flat or conformal surfaces in complex shapes, without any tooling or masks

DW processes

1) Ink-based
2) Laser transfer
3) Thermal spray
4) Beam deposition
5) Liquid-phase
6) Beam tracing processes

direct ink writing techniques



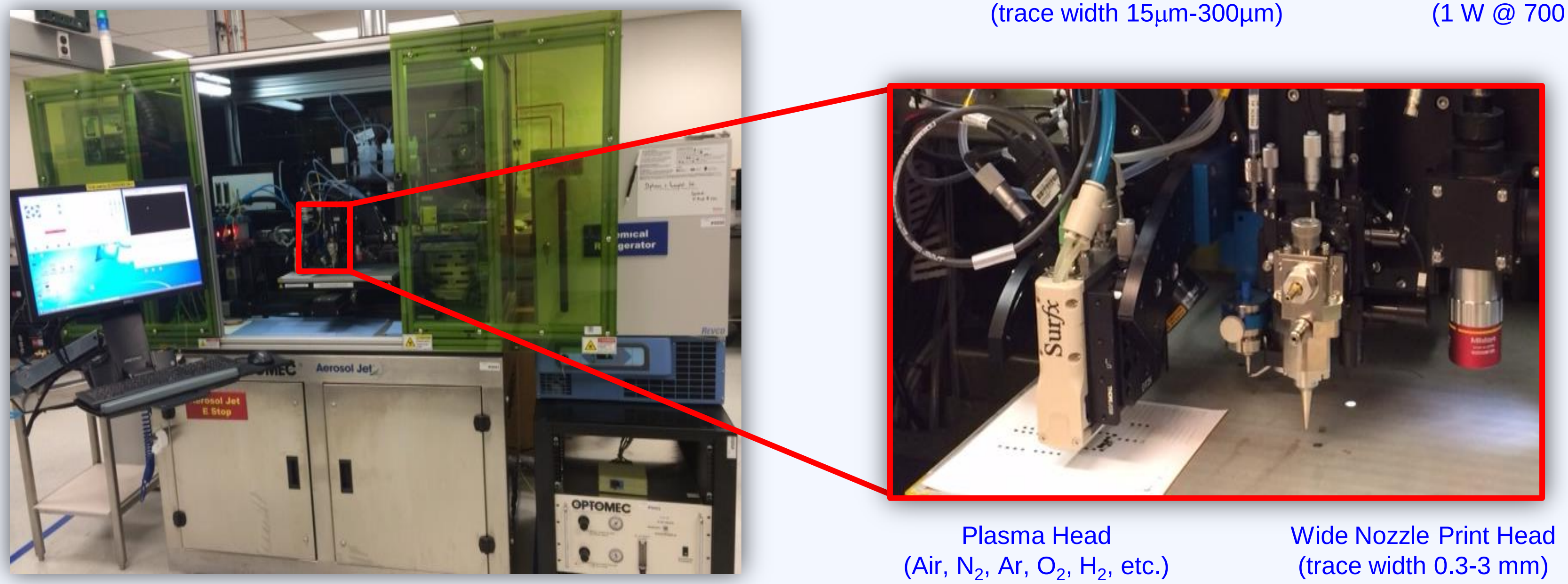
continuous filament writing

droplet jetting

Viscoelastic materials/inks which flow freely under shear through a nozzle but become rigid and set up quickly after that shear stress is released are preferred for electronics manufacturing

Direct Write Equipment Overview at UTRC

Multi-head Aerosol Jet System by Optomec

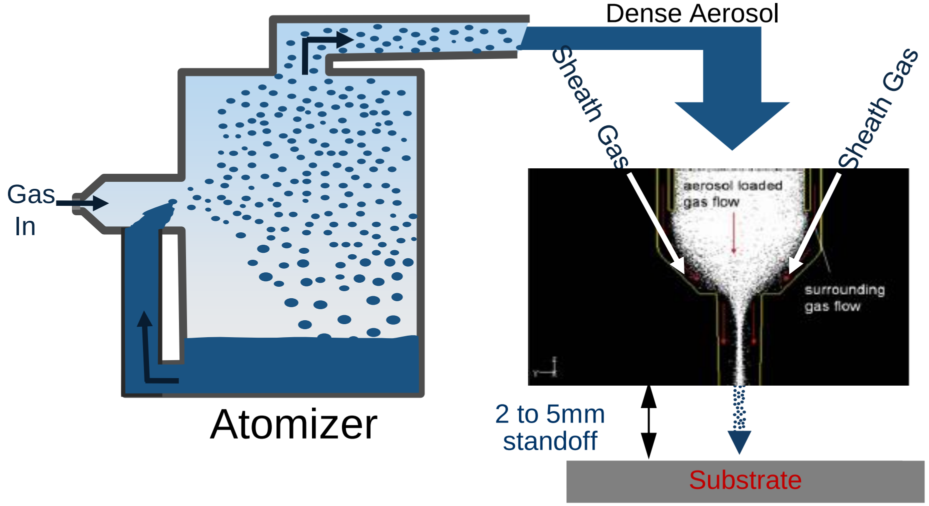


Fine Feature Print Head
(trace width 15µm-300µm)

Laser Cure
(1 W @ 700 nm)

Plasma Head
(Air, N_2, Ar, O_2, H_2, etc.)

Wide Nozzle Print Head
(trace width 0.3-3 mm)



Key benefits

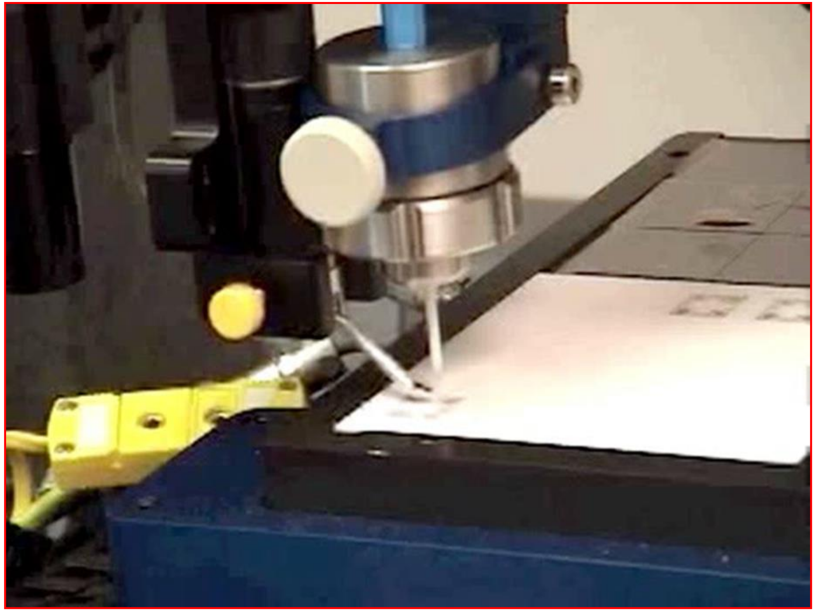
Widest range of working distances and line widths
coaxial laser treatment

Key drawbacks

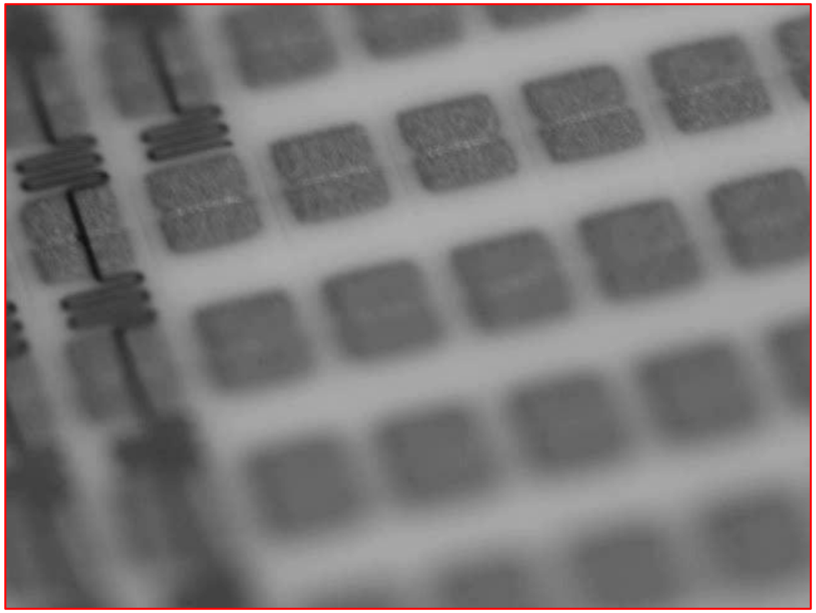
Complex apparatus
Requires inks which can be aerosolized

Aerosol Jet® Process Video

Aerosol Jet Printing head



Printed Resistors Video



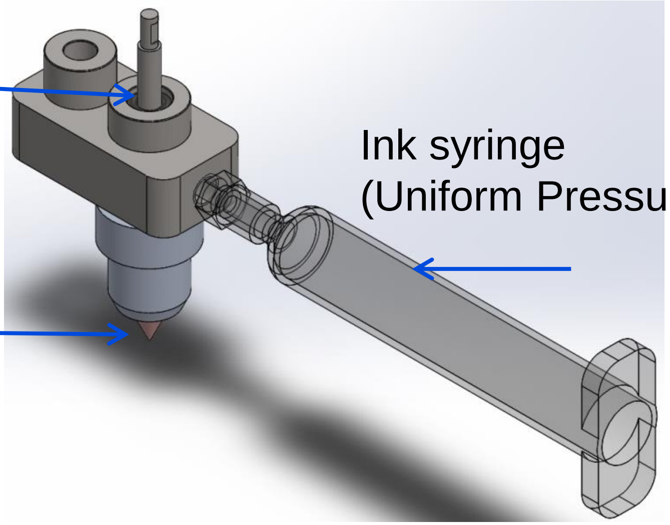
Direct Write Equipment Overview at UTRC

Multi-head Dispensing System by nScrypt

Pick & Place Tool

Deposition Head

3D Surface Mapping



Valve Moving Rod

Conical Nozzle

Ink syringe (Uniform Pressure)

Key benefits

Greatest range of viscosities, simplicity, capable of 3D lattice structures

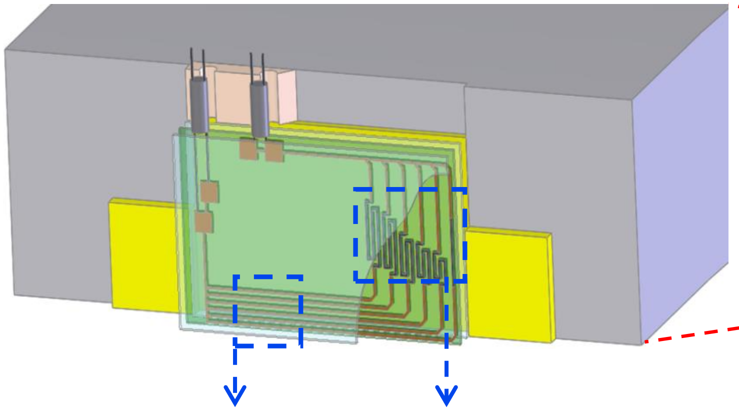
Key drawbacks

Knowledge of surface topography needed to maintain constant stand-off distance

UTRC Direct Write of Electronics and 3D Magnetics

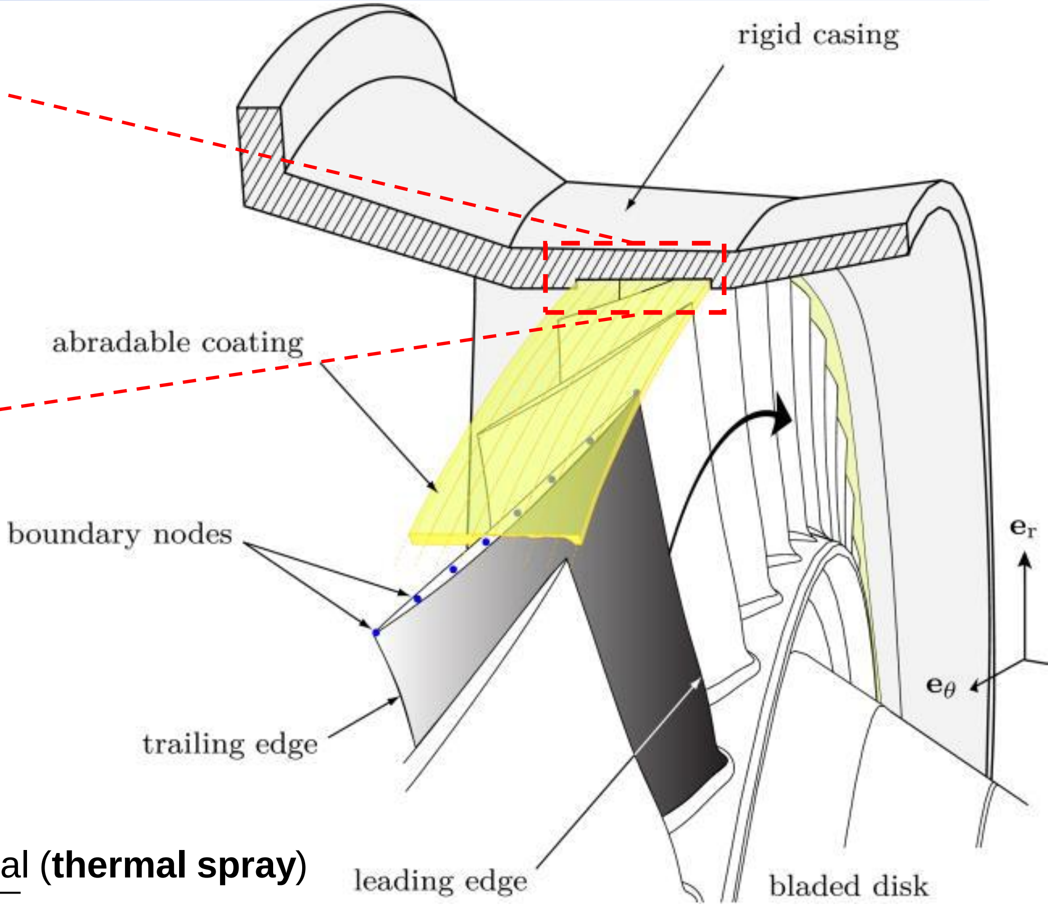
AEROSPACE WEAR SENSOR

Rub Depth Sensor Concept & Design

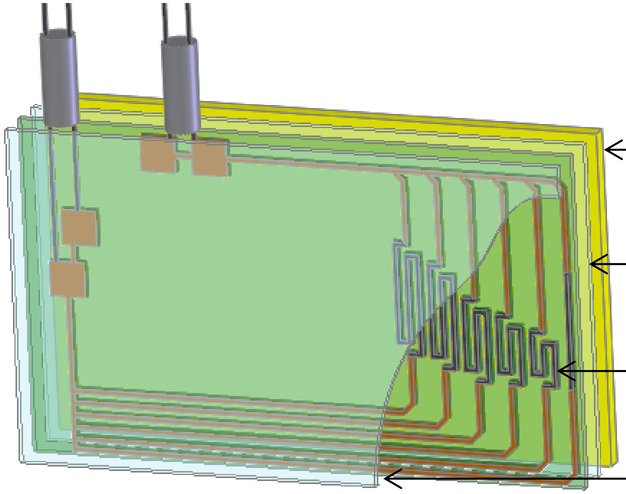


Closely-spaced high conductivity lines

Parallel resistors



4-probe measurement



Abradable metal (**thermal spray**)

Insulating layer (**printed**)

Device layer (**printed**)

Encapsulating glass layer (**printed**)

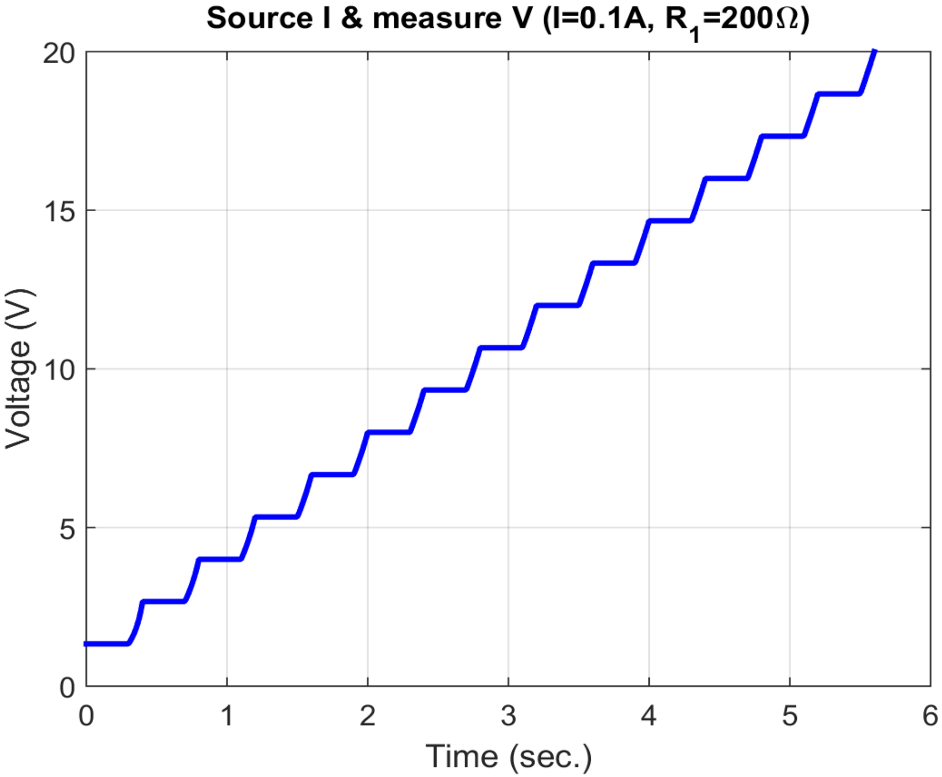
Device Circuit Design & Simulations

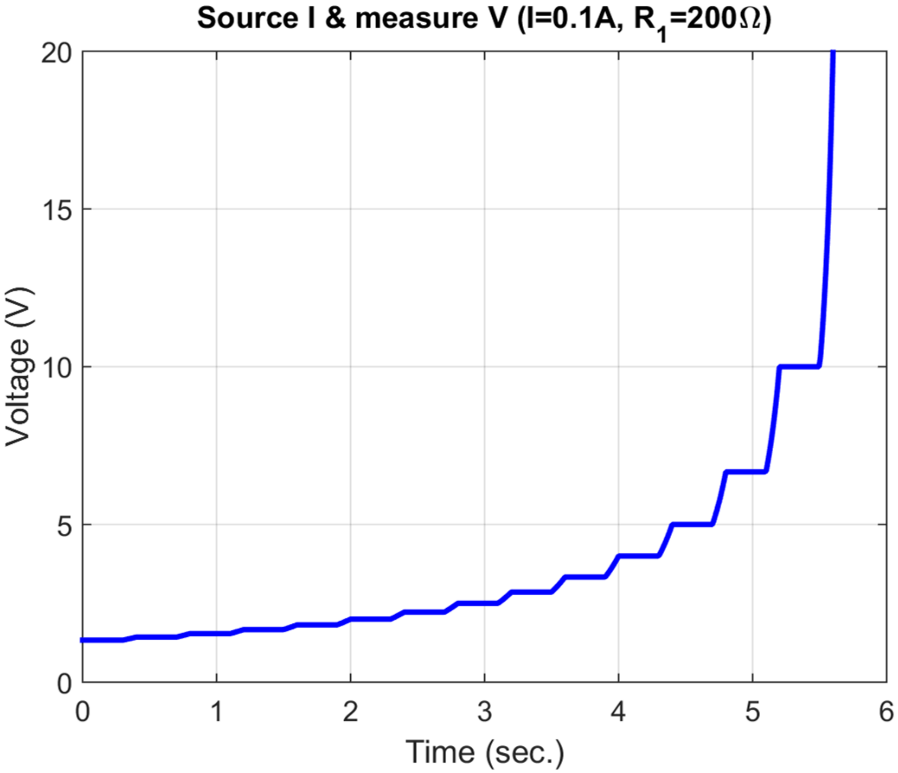
Unequal Value Resistors

1) Equal changes in voltage as blade rubs the coating
2) Change in voltage is higher than noise level
3) Broad range of resistor values needed

Equal Value Resistors

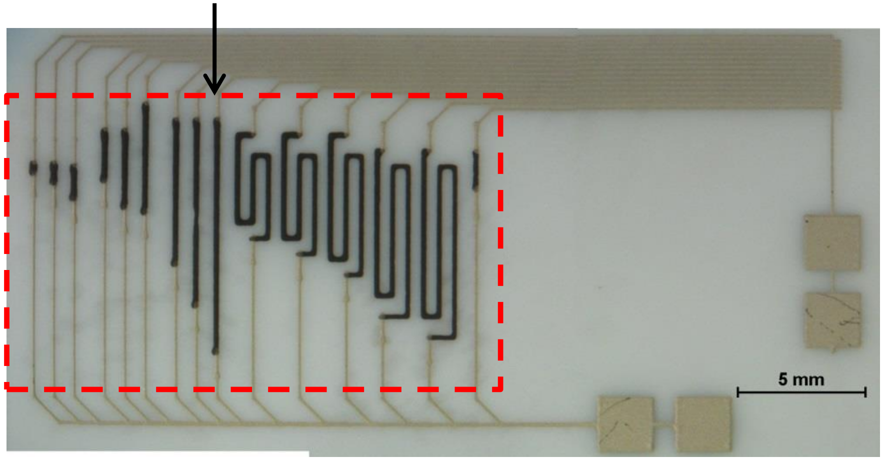
1) Small change in voltage as blade initially rubs the coating
2) Some of the voltage changes could be below the noise level during operation (high temperature)





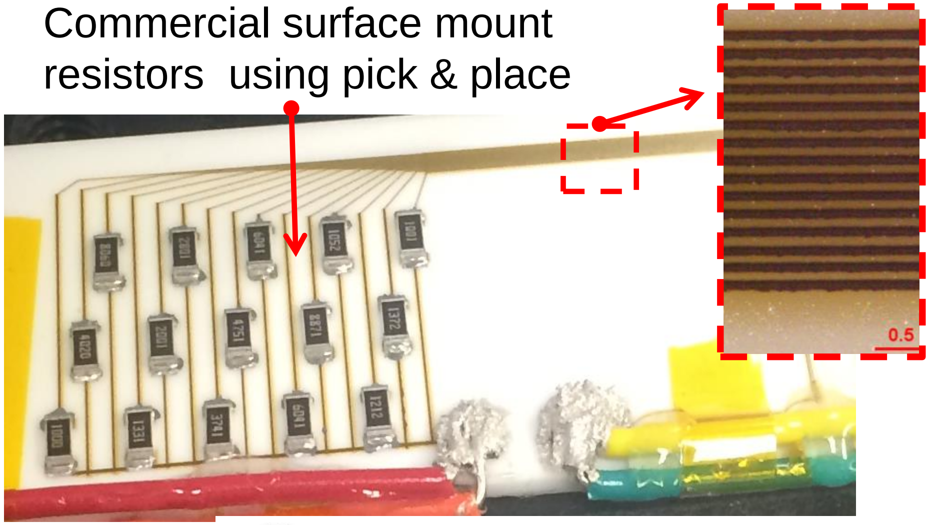
Rub Depth Sensor Manufacturing & Testing

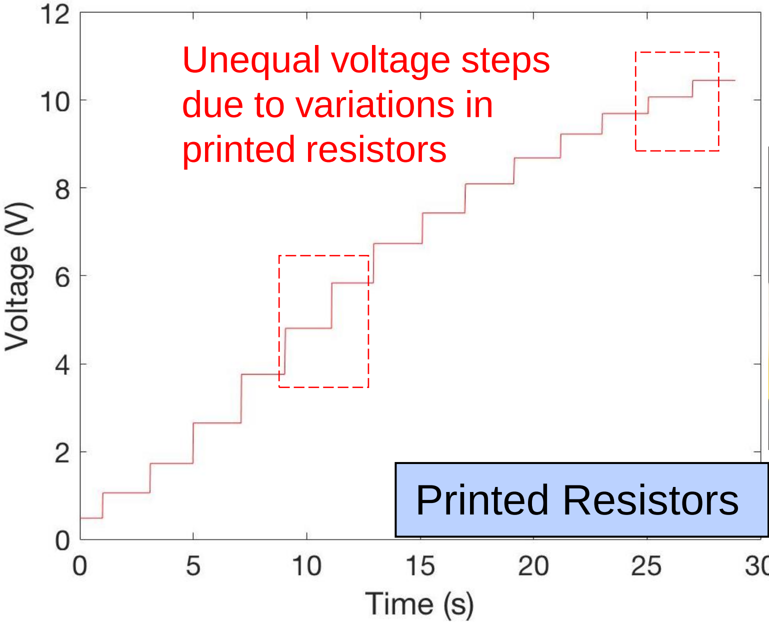
Printed Ruthenium resistors using nScrypt micro-dispensing system



- 100 μm line-spacing
- Aerosol Jet method

Commercial surface mount resistors using pick & place

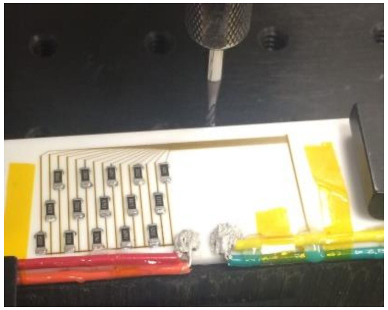


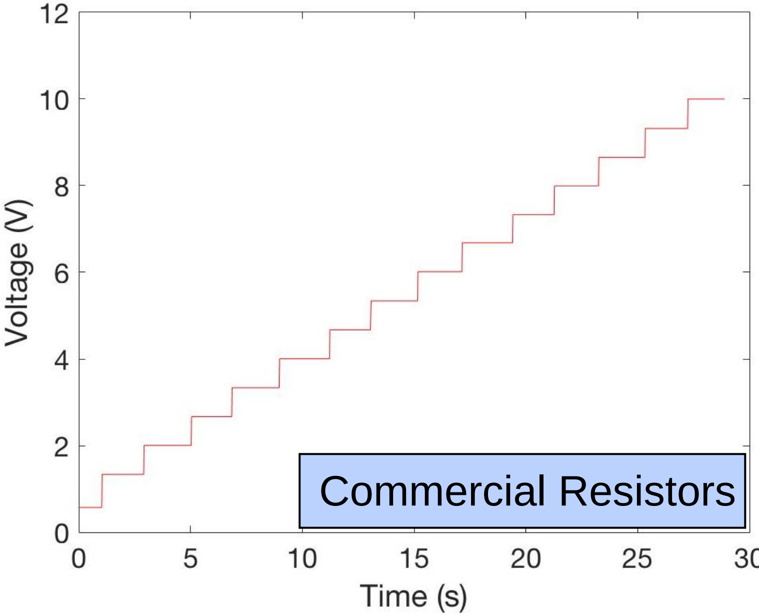


Unequal voltage steps due to to variations in printed resistors

Printed Resistors

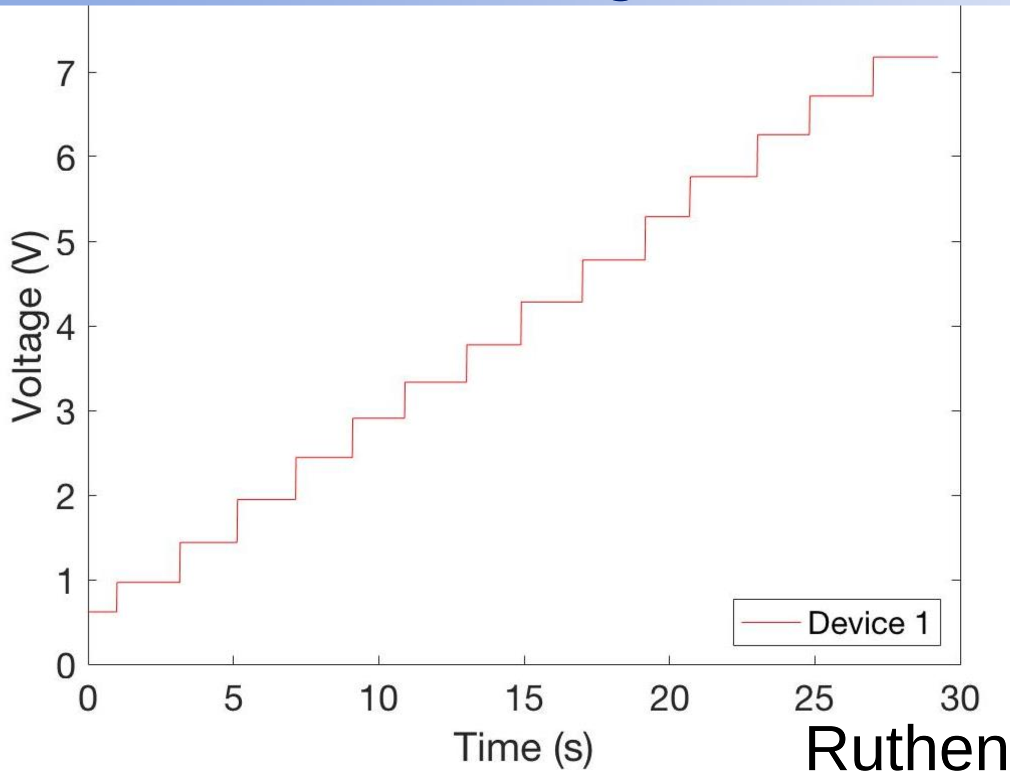
Dremel Bit

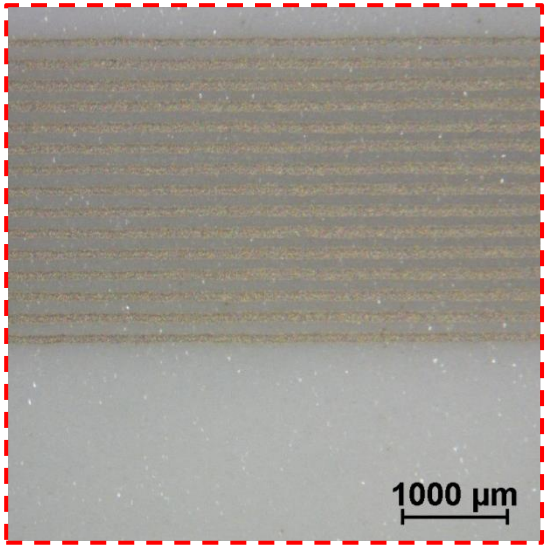




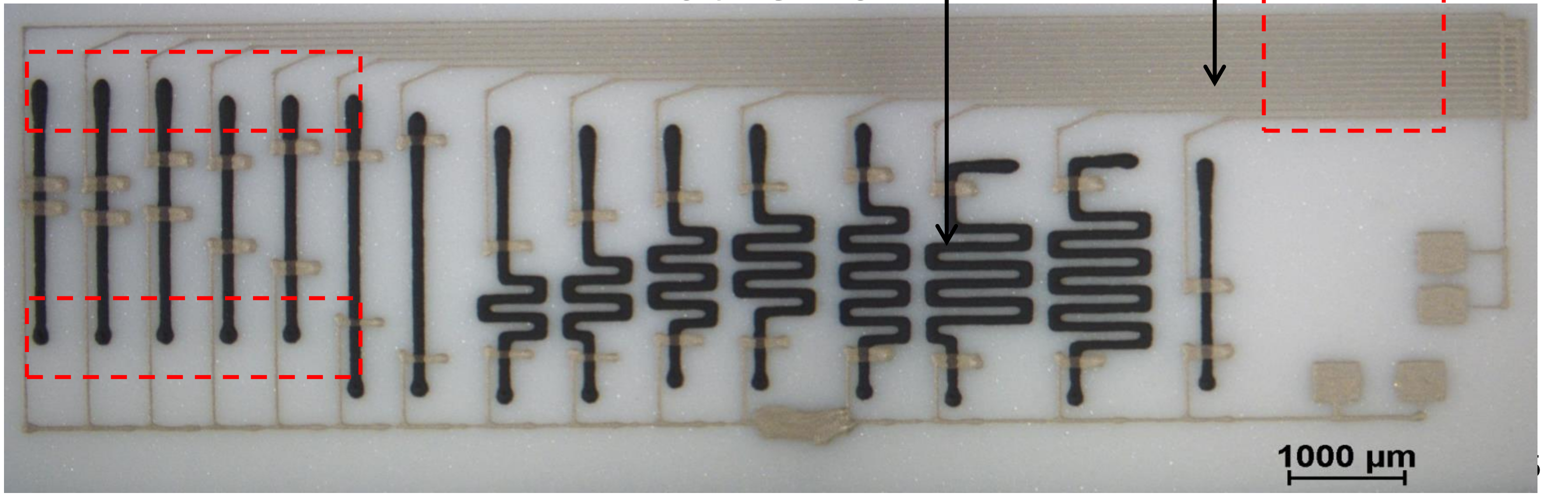
Commercial Resistors

Improved Sensor Design & Manufacturing





End of lines create large variations

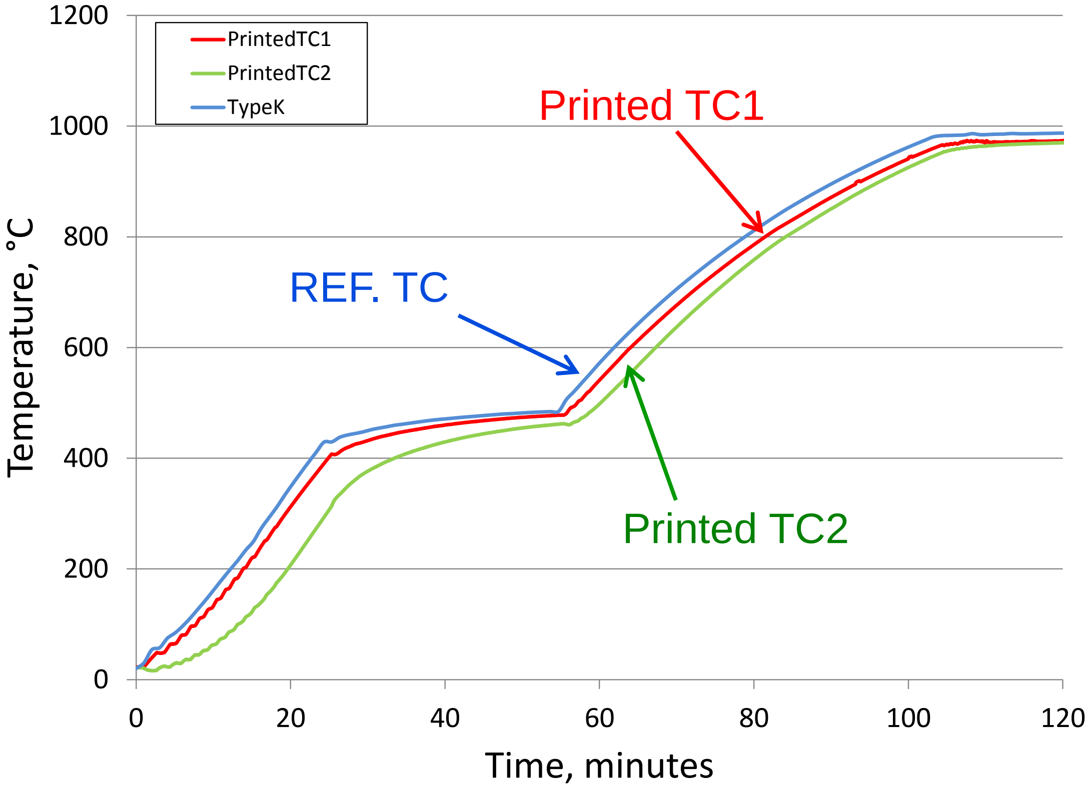


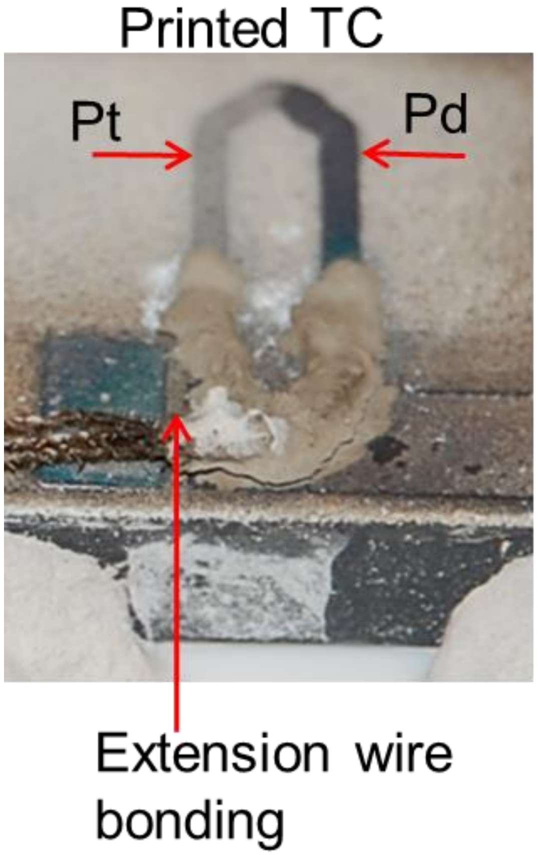
UTRC Direct Write of Electronics and 3D Magnetics

THERMAL SYSTEMS

THERMOCOUPLES, RTDS AND HEATERS

Printed Thermocouples on Ceramic Engine Parts



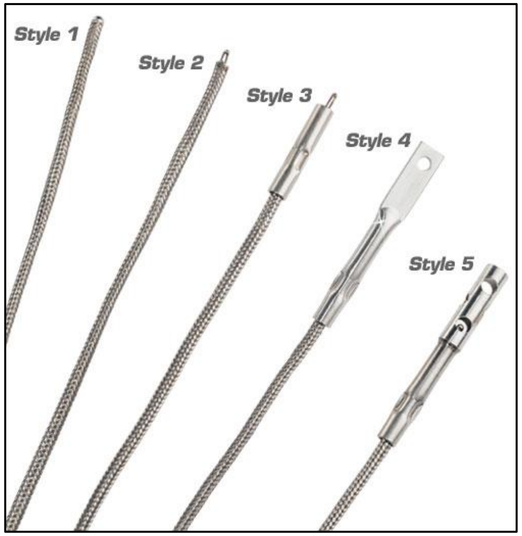


Resistance Temperature Detectors (RTDs) Grid

Hot Surface Temperature Mapping

Current State

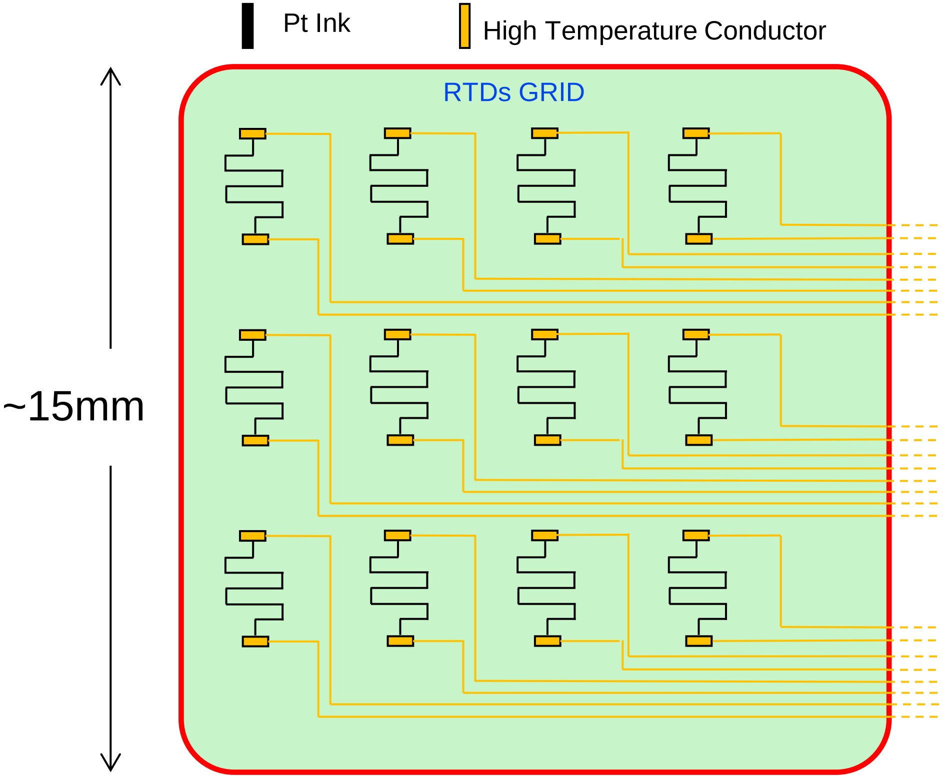
(Commercial Thermocouples)



1. Limited Accuracy
2. Limited in number
3. Large thermal mass
4. Disturbs cooling

Future State

(Direct Write of RTDs Grid)

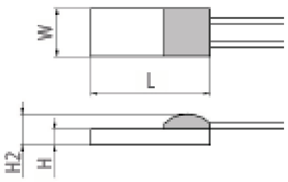


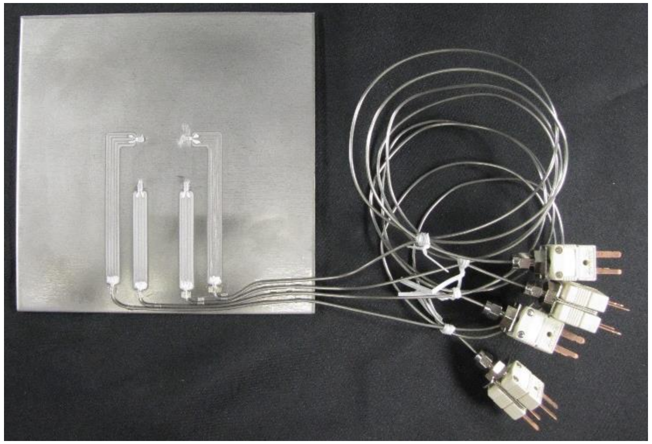
1. Conformal
2. Accurate
3. Low profile
4. Multiple sensors possible
5. Small thermal mass

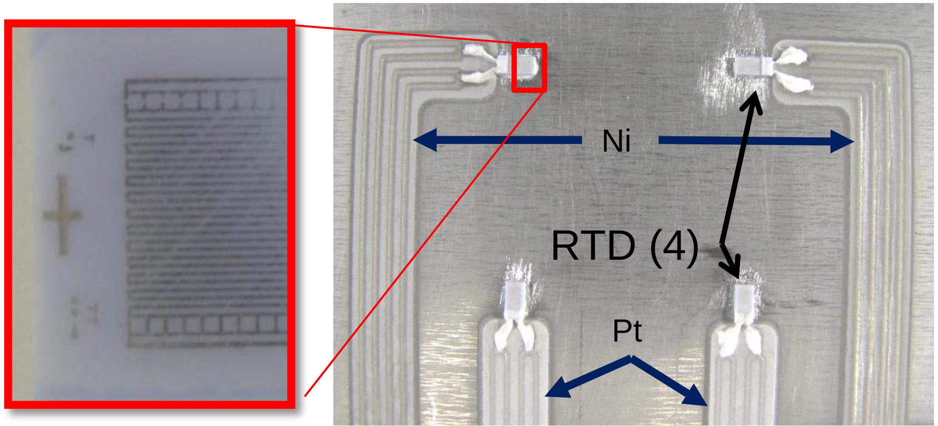
Fabrication of Hybrid RTDs Array

Coatings and Traces Deposited by Mesoscribe on Inconel 625 Substrate (6”x6”)

Commercial thin film Pt RTD (1000°C limit) 3.85x1.9x0.45/0.75mm

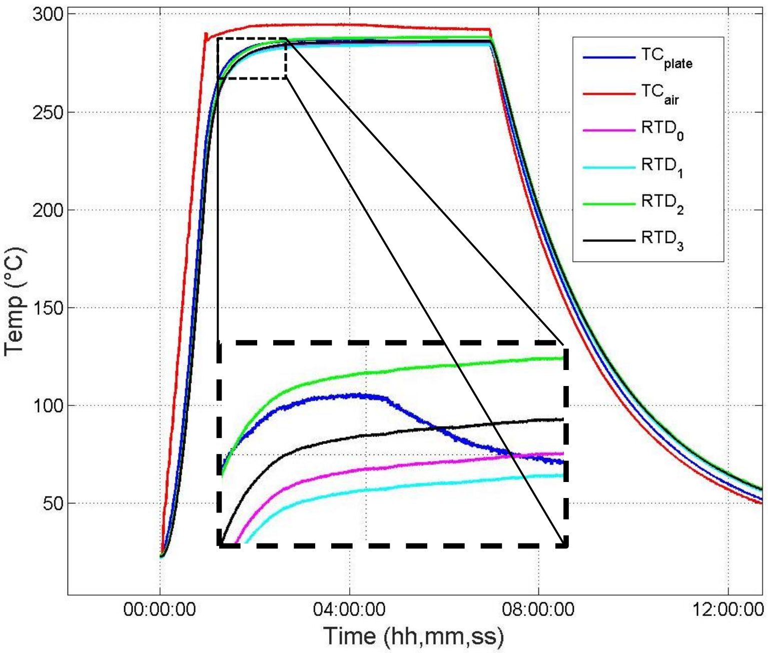


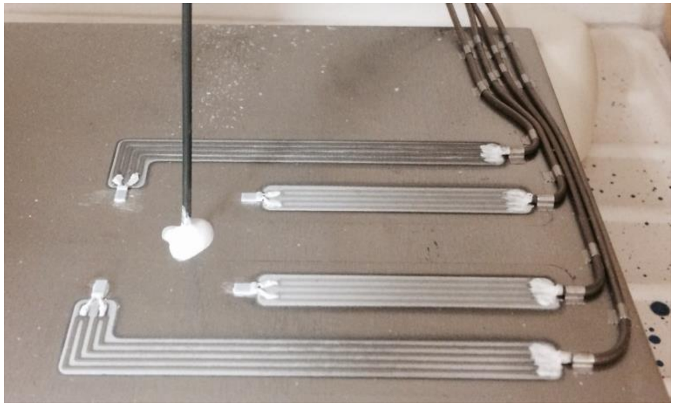




Protective Coating Removed

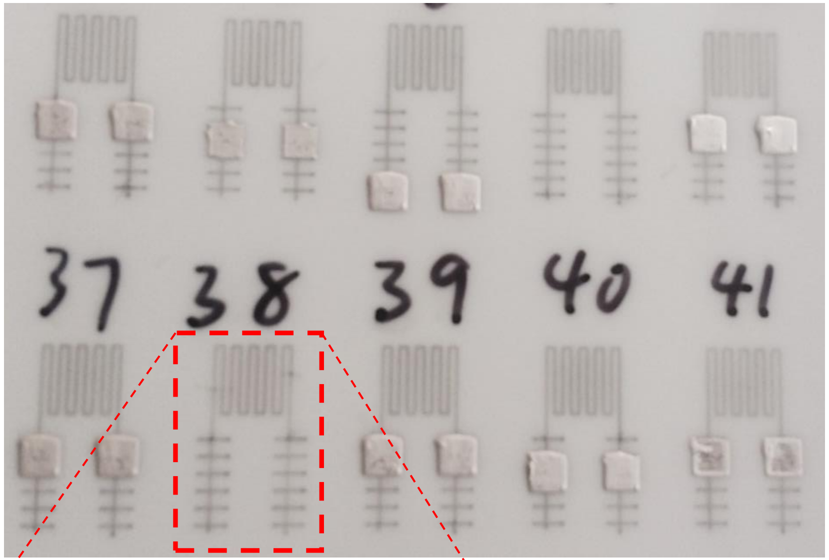
- Bondcoat – NiCr – 1.3 mils thick
- Ceramic – Spinel – 4.0 mils thick
- Traces – Nickel – 2.0 mils thick (outer lines)
- Traces – Platinum – 1.0 mils thick (inner lines)
- < 9 mil thick (< 225 µm)

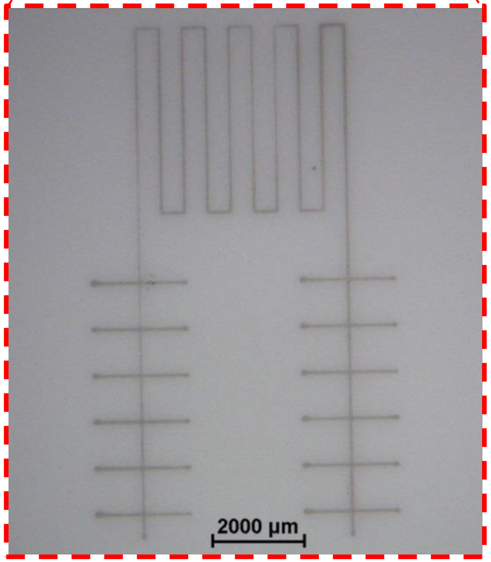


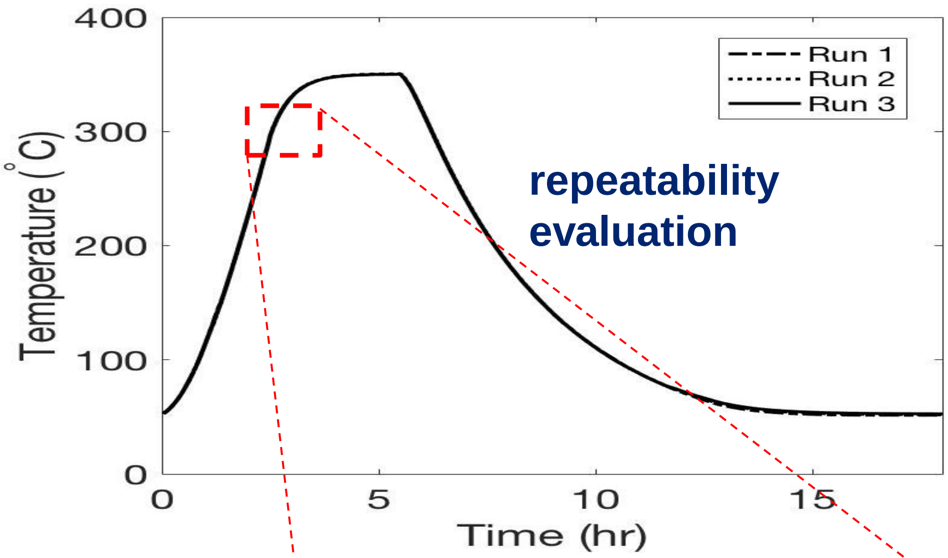


Fully Printed RTDs Array

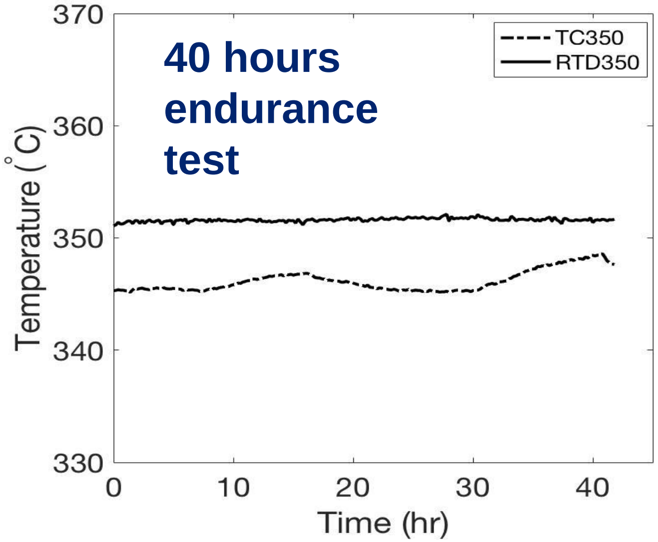
Printed RTDs Grid (Pt Ink on Alumina Substrate)



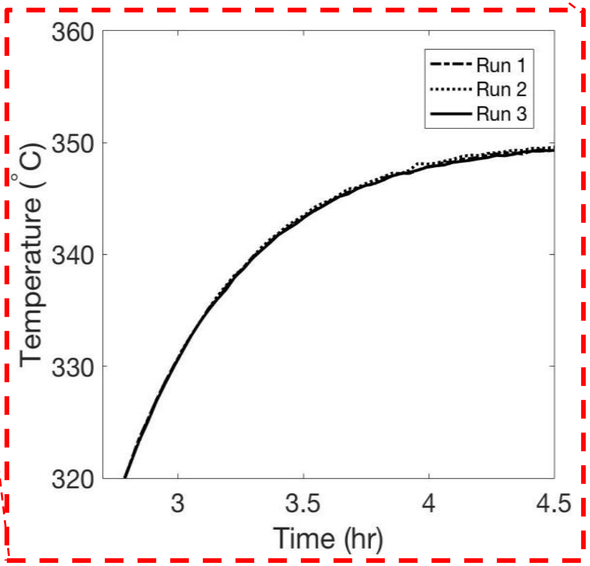




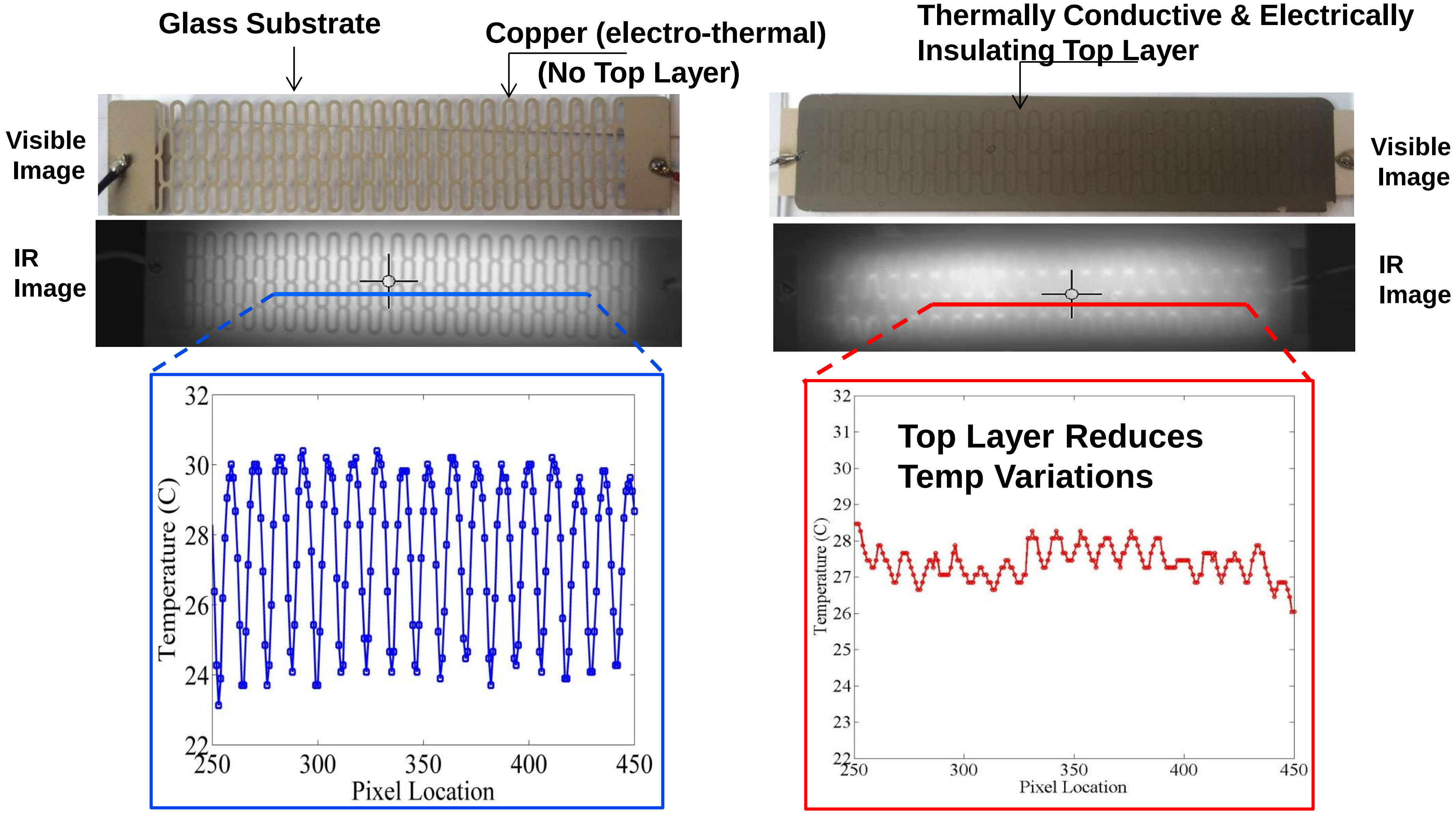
repeatability evaluation



40 hours endurance test



Heating Element with Thermal Spreading Layer

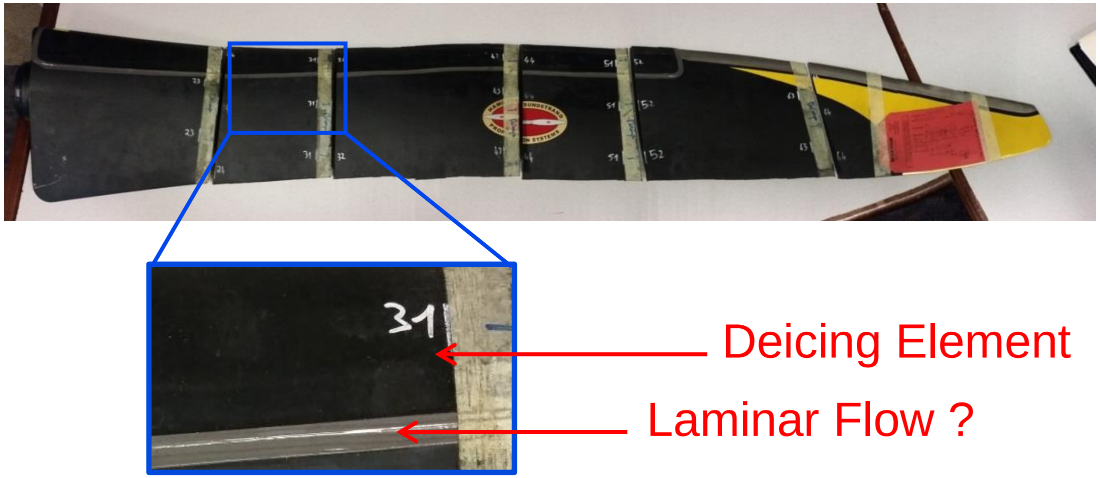


Top Layer Reduces Temp Variations

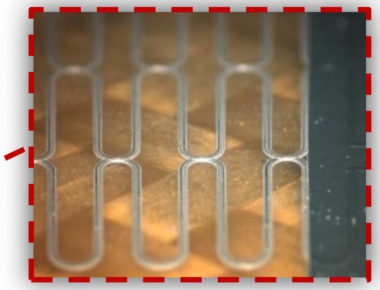
TOP LAYER FUNCTIOS:

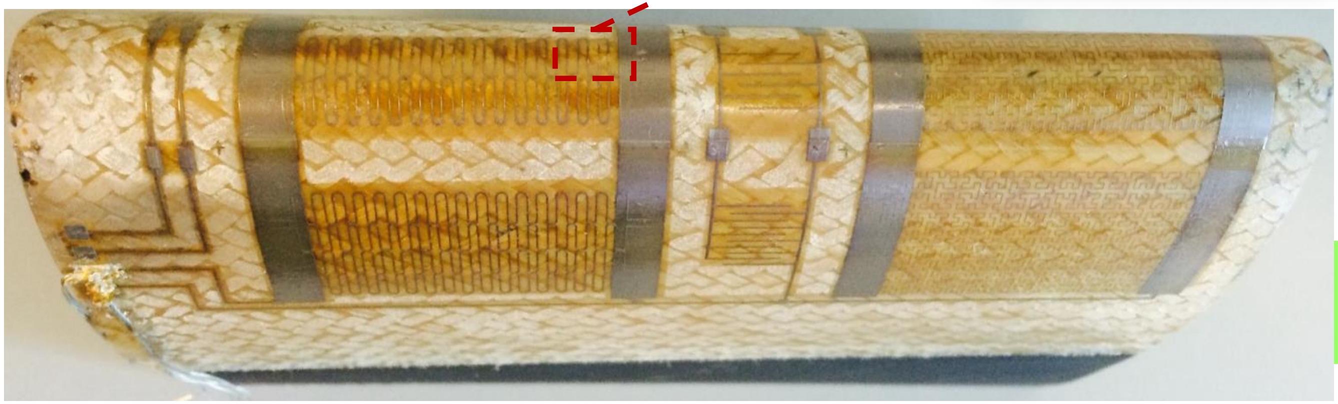
1) **Reduces Temperature Variation (+/-3C to +/-1C)**
2) **Mitigates Failures in Electro-thermal Layer**

Conformal Deicing on the Leading Edge

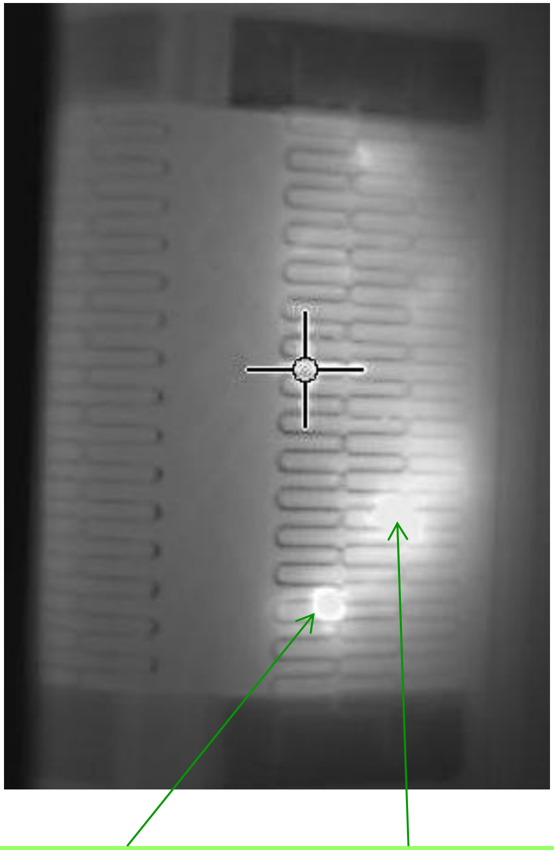


- Electro Thermal Material: Silver Nanoparticles
- Top Coating: Polymide
- Bottom Layer: Polymide
- Method: Aerosol Jet
- Multi-zone & Redundant Design





Performance
(IR Imaging Results)



high resistance areas
(dust or surface roughness)

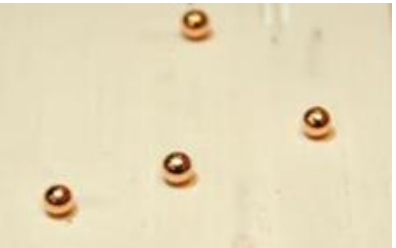
UTRC Direct Write of Electronics and 3D Magnetics

3D PRINTED ELECTROMAGNETICS

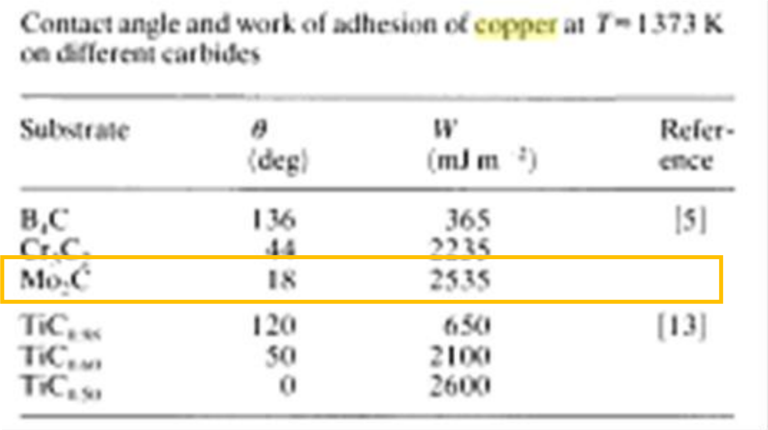
Ink Formulation of High Conductivity Copper

- Copper is non-wetting for Al_2O_3 & other ceramic substrates (contact angle ~ 130-140°)
- Copper found to completely wet Molybdenum Carbide (Mo_2C) and other Metal Carbides
- Potential options to reduce contact angle to <90°
  NiO, Fe_3O_4, Cu_2O, TiO_x, TiC_x, Mo_2C, Cr_3C_2

Cu on Al_2O_3

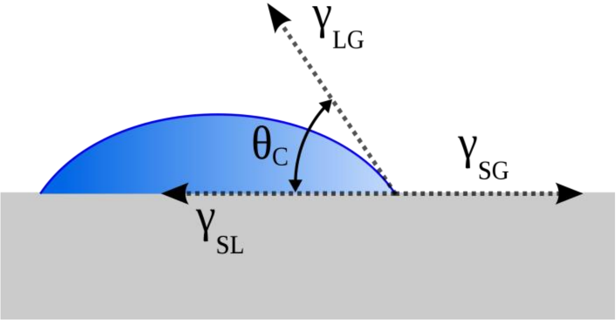


Cu on Mo_2C Coated Al_2O_3



Contact angle and work of adhesion of copper at $T = 1373$ K on different carbides

Substrate	θ (deg)	W (mJ m^{-2})	Reference
B_4C	136	365	[5]
Cr_3C_2	44	2235	
Mo_2C	18	2535	
$TiC_{0.98}$	120	650	[13]
$TiC_{0.60}$	50	2100	
$TiC_{0.50}$	0	2600	



- No commercial Mo_2C ink formulations
- Team developed custom formulations for Aerosol, screen and extrusion printing

Printing of High Conductivity Copper

Mo2C on Al2O3 fired in Ar

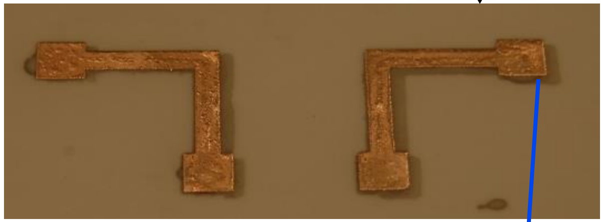
Screen print Cu on Mo2C

Added Cu with a syringe

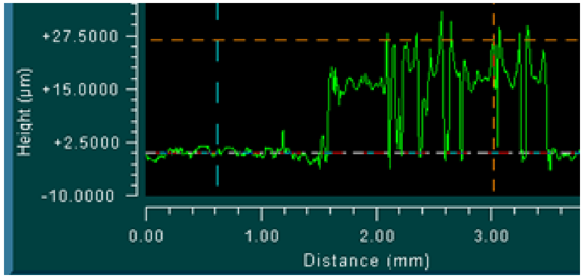
Benefits

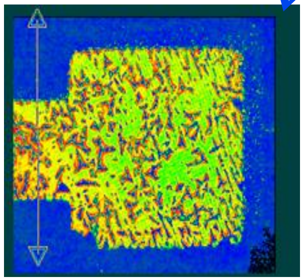
1) Cu only wets pre-printed Mo2C
2) Ability to increase trace thickness
3) Powder/paste as a raw material
4) Glass frit to lower process temp
5) Laser for sintering of copper
6) Bulk-like conductivity

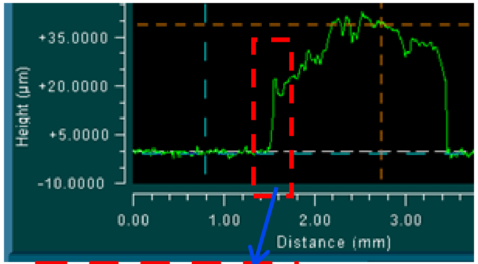
Fired to 1200°C/Ar

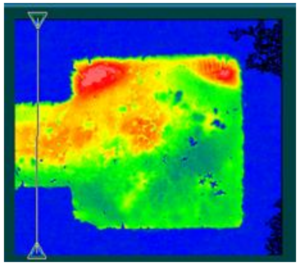


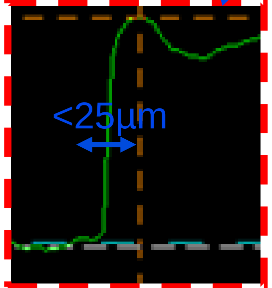
Fired to 1200°C/Ar

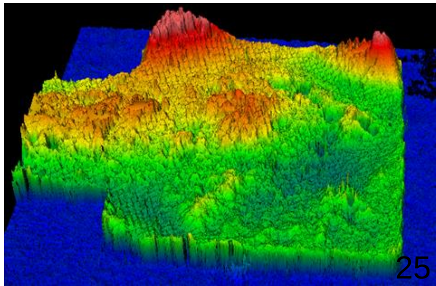






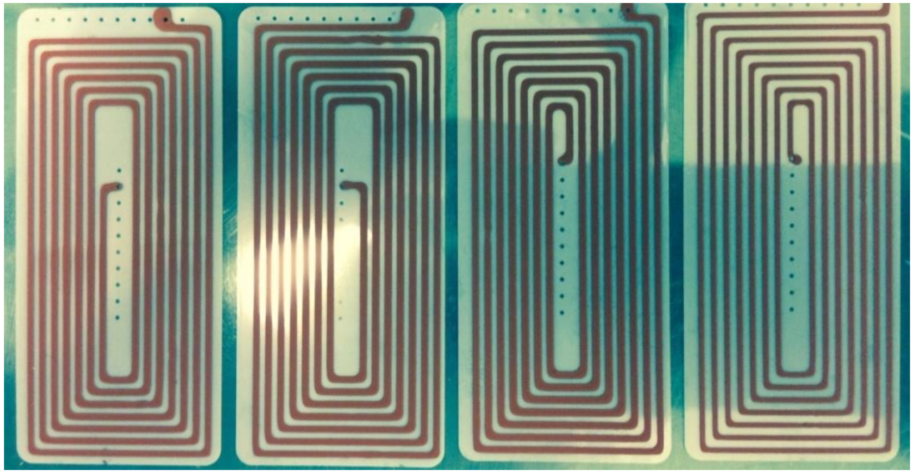




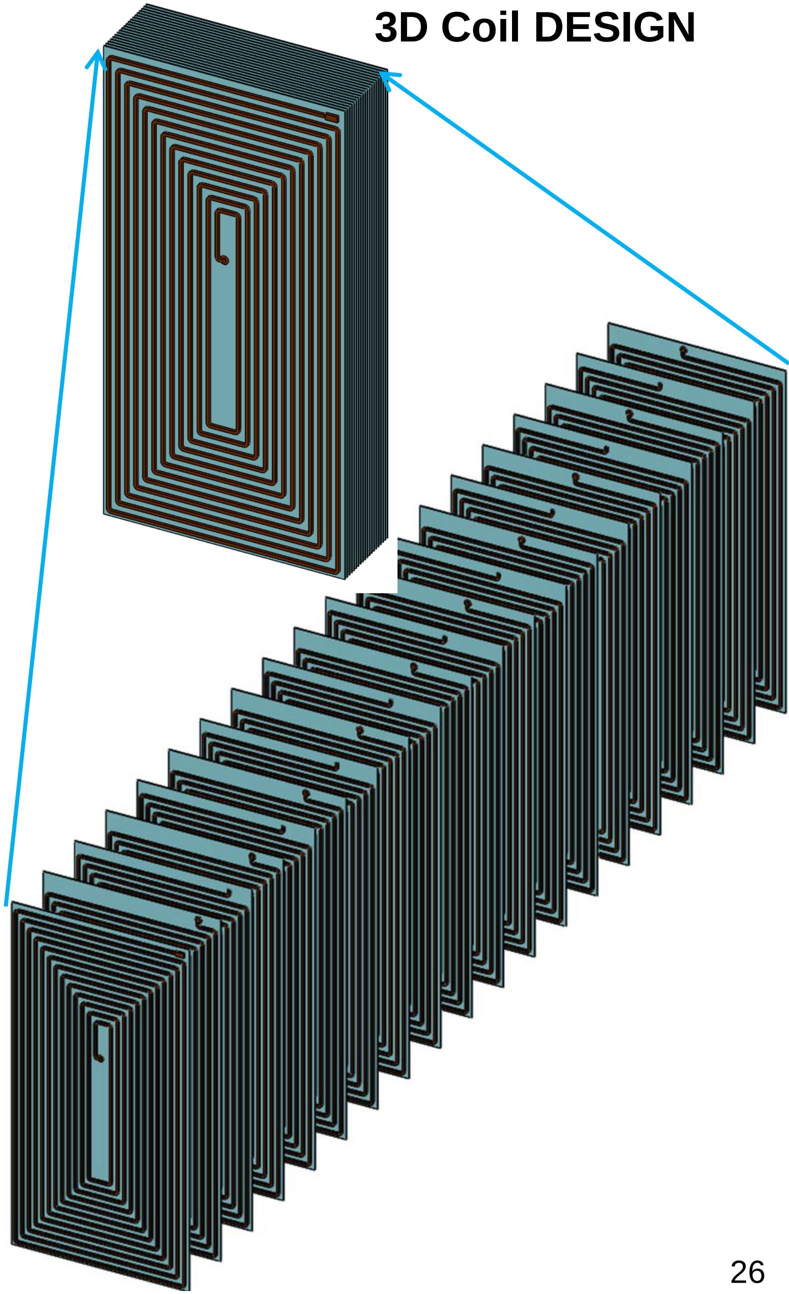


With engineered wetting, Cu is confined to the Mo2C regions which creates edge defined & thick Cu traces

Design and Manufacturing of a 3D Coil

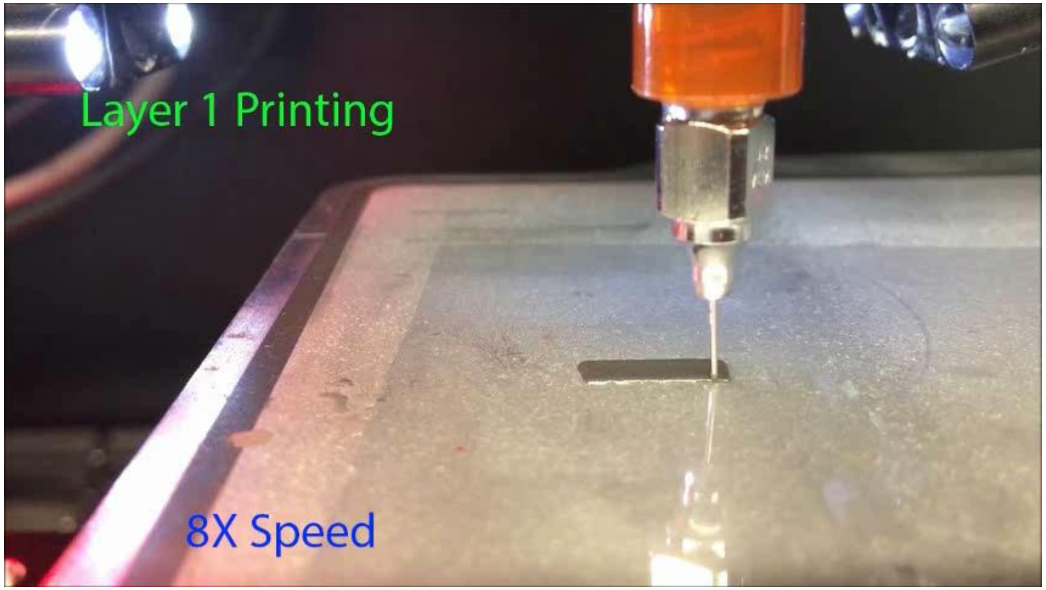


- Copper ink formulation
- Thin ceramic substrate (20 micron)
- Manual stacking
- Through via for interlayer connection
- IP filed

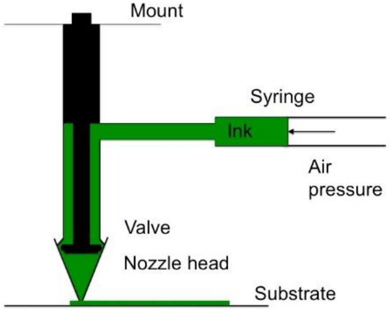


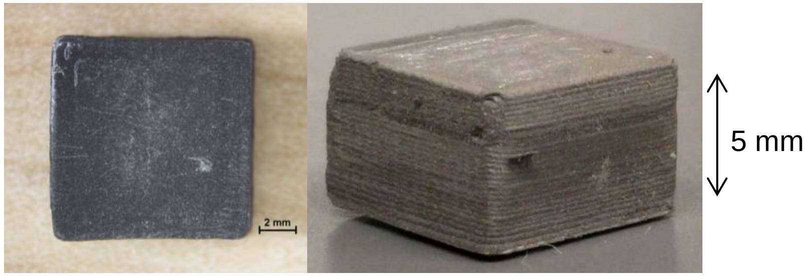
UTRC Method: UV-Assisted Extrusion Direct Write

nScrypt Micro-Dispensing System

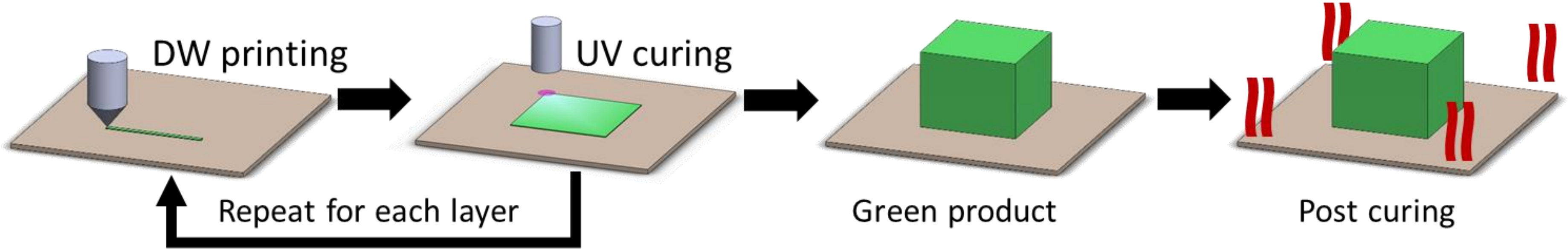


nScrypt Extrusion Mechanism



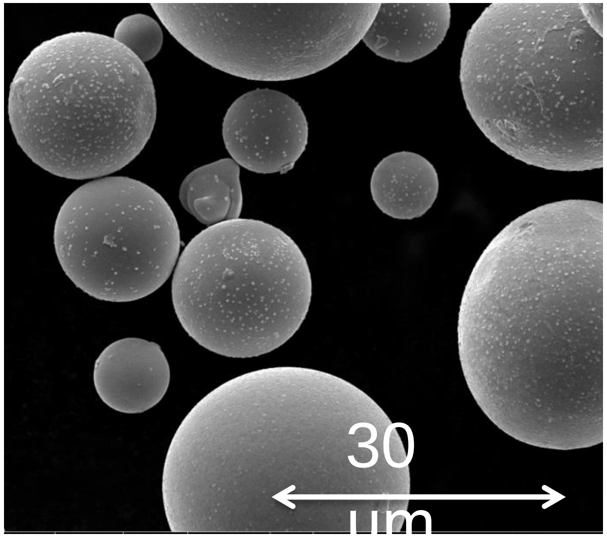


Fabrication Process

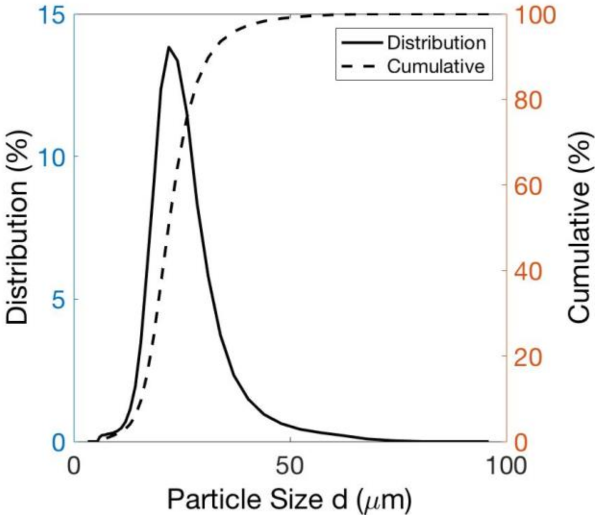


Custom-Tailored Magnetic Particle Suspension

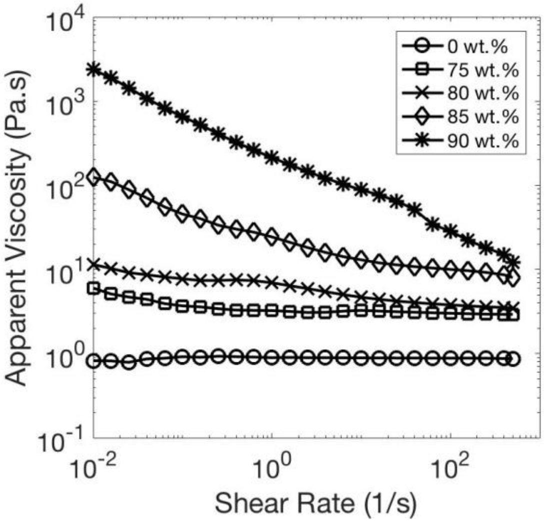
- Magnequench MQP-S-11-9 NdFeB spherical isotropic powder, sieved by size 500 mesh (<25 μm).
- Custom ink fabrication: methacrylate photopolymer resin + NdFeB powder at different weight ratio.



SEM image of Raw Particles



Particle Size Distribution by Microtrak



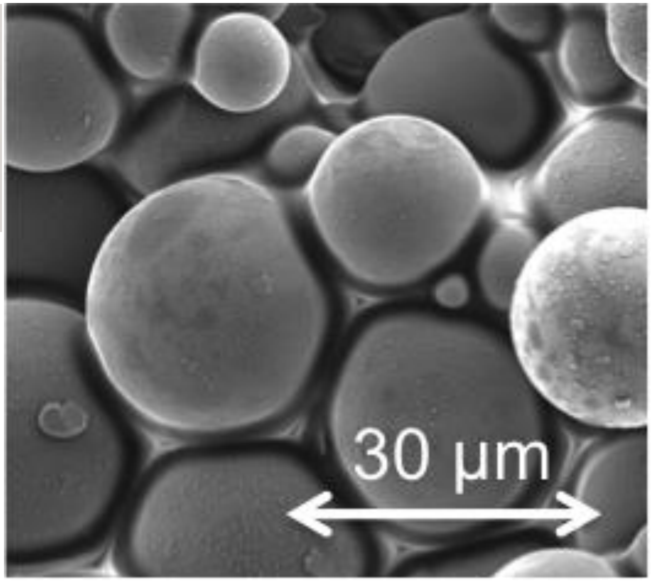
Steady Shear Experiment

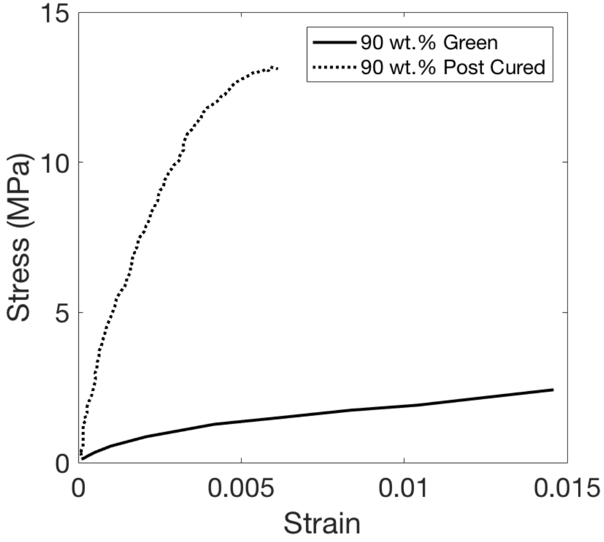
Mechanical Properties

- Post-curing improves maximum tensile strength and Young’s modulus but reduces maximum elongation.

	Solid loading volume	Max. Strength/ MPa	Young's modulus/MPa	Elongation at Failure
DW Green	57%	2.43	577	1.7%
DW Post-Cured	57%	10.4	5200	0.6%
BAAM	60%	6.60	4290	4.1%

*Li, L., Tirado, A., Nlebedim, I. C., Rios, O., Post, B., Kunc, V., … Paranthaman, M. P. (2016). Big Area Additive Manufacturing of High Performance Bonded NdFeB Magnets. *Scientific Reports*, *6*(1), 36212.





Green VS. post-cured

UTRC Direct Write of Electronics and 3D Magnetics

STRUCTURAL ELECTRONIC OPTICAL SENSORS

Structural Integration of Printed Electronics

Leverage established manufacturing methods with emerging capabilities

Established Methods → **Integrated Electronics**

- Insert Molding

Enabled by low-pressure molding systems

- In-Mold Decoration

- Membrane Switches

.

Enabled by conductive, dielectric, semiconducting, and other functional inks

Lighter, Less cost,
Assembly time reduction,
Design and functional freedom

Structural Electronics Manufacturing Impact

In-Mold Electronic Value Proposition and Future

- Reduced Manual Insertion and touch time by labor force
  Operators/space reallocated to increase volume
- Flexibility and acceleration in design, prototyping, development
  "Complexity for free" additive manufacturing
- Scalable, automated lines allow distributed production
  Reduced shipping costs / on-shoring
- Nearly limitless addition of integrated functionality
  Wireless, multi-sensor, aesthetics (labeling, logos), part authentication, etc.

UTC Optical Sensor Comparison:

Current State
> 19 parts
5 mold pairs
5-7 assembly stations

In-mold electronic Demonstration:
7 parts
2 mold pairs
1-2 assembly stations

Near 60% Reduction in Parts, Molds and Assembly Steps

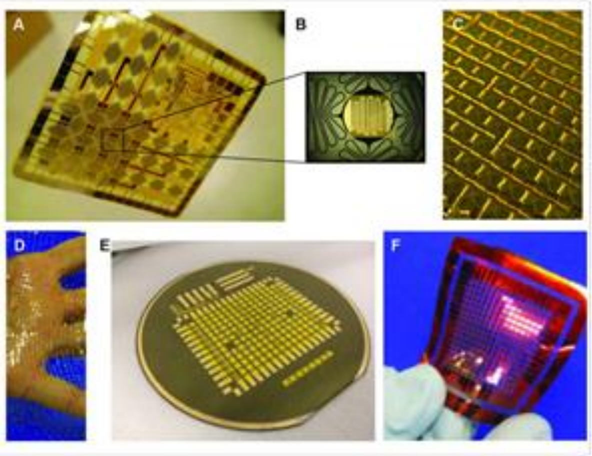
UTRC Direct Write of Electronics and 3D Magnetics

NEXTFLEX INITIATIVE

NextFlex - External Collaboration

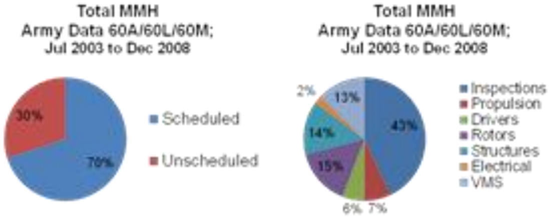
- **NextFlex Project Call 1.0 Proposal**
- **Selected for $2.6M award**
- **Distributed and Stretchable Hybrid Asset Monitoring Platform**

DEVELOPMENT, MATURATION, TESTING



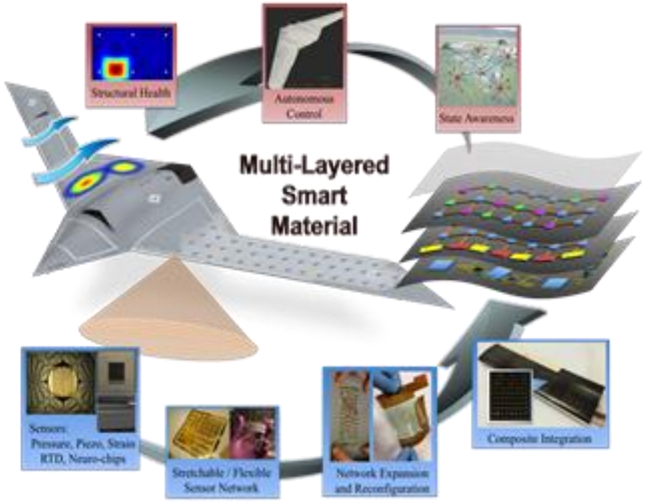
COST SAVINGS

Maintenance Man-Hours (MMH)



- Reduced scheduled maintenance
- Reduced MMH for inspections and structures

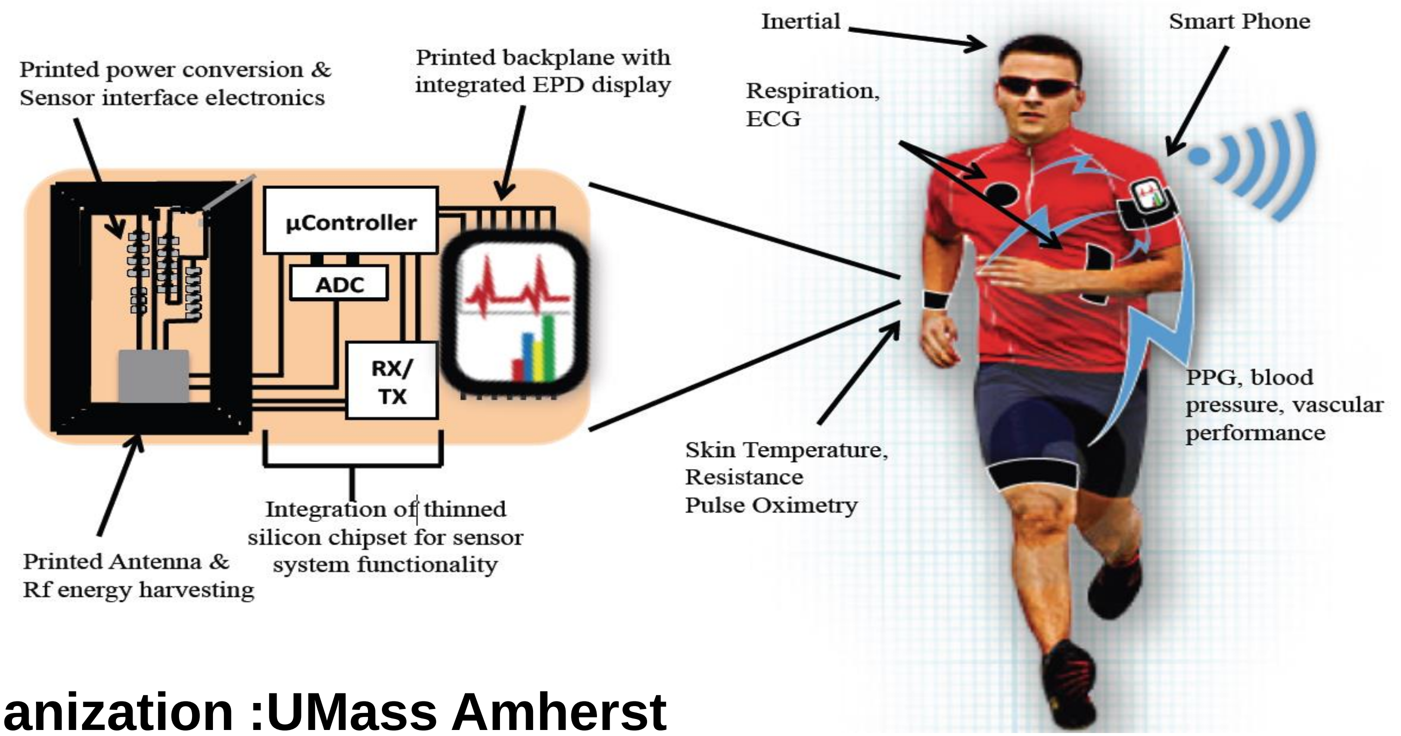
SCALE-UP, FULL-SCALE TESTING, IMPLEMENTATION



- **Lead Organization :UTRC**
- **Team Members: Stanford University & Acellent Technologies**
- **50% Cost Share**
- **Development Agreement in Discussion**

NextFlex - External Collaboration

- **NextFlex Project Call 1.0 Proposal**
- **Selected for $2.6M award**
- **Scalable Manufacturing for a Wearable, Integrated Human Performance Monitoring System**



- **Lead Organization :UMass Amherst**
- **Team Members: UTRC ($300K), Si2, Uniqarta**
- **50% Cost Share**
- **Development Agreement in Discussion**

Printed Electronics for Aerospace and Buildings

THANK YOU!