Low-Cost, Efficient and Durable High Temperature Wireless Sensors by Direct Write Additive Manufacturing for Application in Fossil Energy Systems

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Project: DE-FE0026170

Agenda

- The Team
- Background
- Research Objectives
- Approach
- Timeline & Deliverables
- Summary

The Team

Rahul Panat – Project Lead PI
Student(s): TBD
Washington State University

Ramana Chintalapalle – Co-PI
Student(s): TBD
University of Texas at El Paso

PIs/Team Kickoff and Project Planning Meeting: October 1, 2015 @ WSU

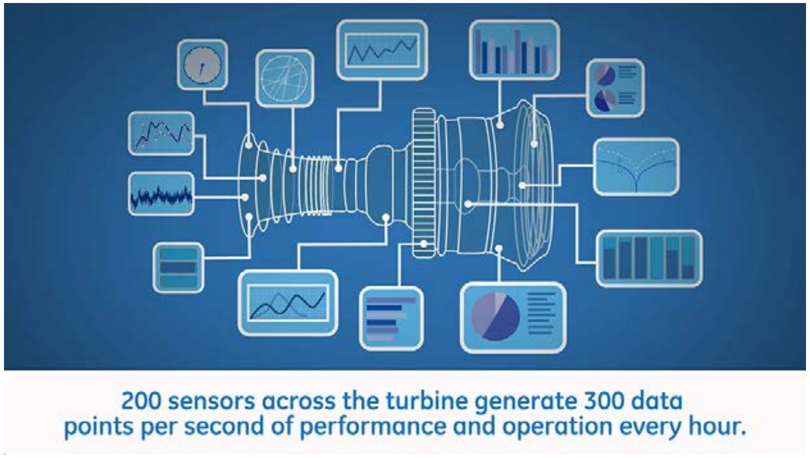
Background

- Wireless Sensors for FE parts are required to
  - Lower fuel consumption through a continuous feedback loop of parameters
  - Improved safety by providing warnings signs by measuring deformation
  - Improved design by obtaining an accurate picture of gas pressure in the combustion engine
  - Understanding of the effect of stresses arising from dynamic factors in an engine
- Challenges
  - Combustion engine surfaces are often curved making it difficult to have conformal strain sensors
  - Harsh environment at high temperature
  - Rotating parts cannot be wired for in-situ monitoring
  - Lithography/MEMs based methods use harmful chemicals, create waste, and may not be compatible with different combustion engine surfaces

Objective

- ❑ Demonstrate the feasibility of low-cost aerosol jet manufacturing for Fossil Energy (FE) systems and develop next-generation sensors, which can sustain high temperatures

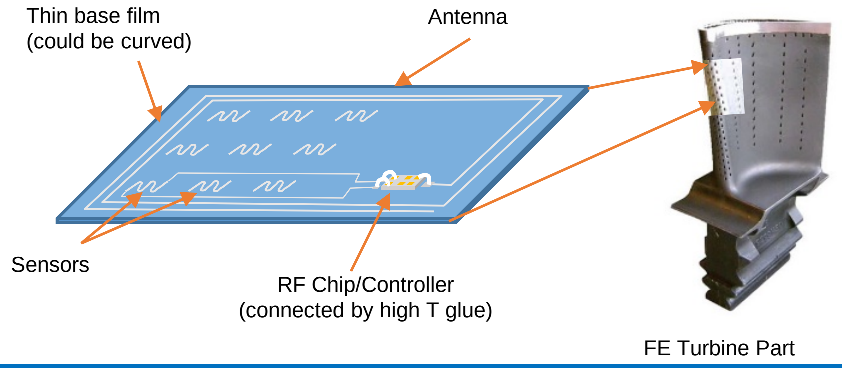
- ❑ Training of next generation professionals as relevant to the DOE mission and goals



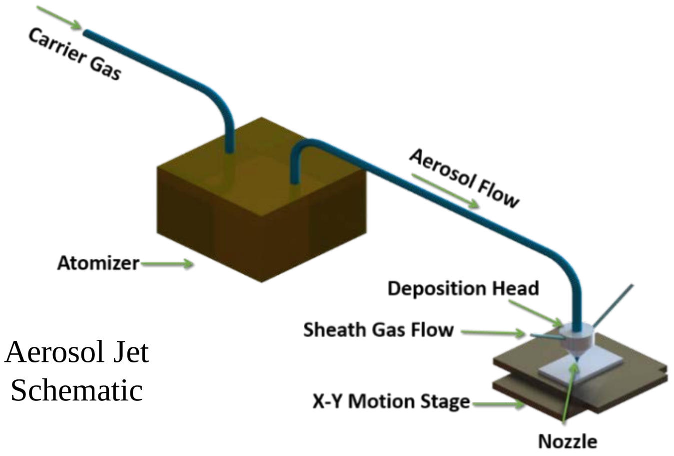
Images courtesy Dr. Mike Renn, Optomec Inc

Approach

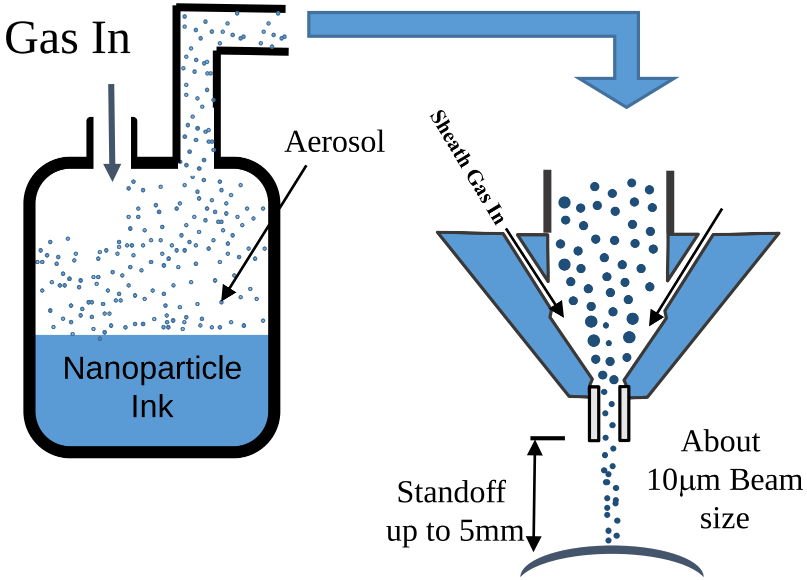
- Direct write Aerosol Jet based Micro-Additive Manufacturing (MAM) of sensors
- Development of materials for MAM process
- Sensor characterization and reliability assessment
- Design of printed antennas and RF chip high for temperature electronics for wireless transmission for in-situ data collection



Aerosol Jet Micro-Additive Equipment

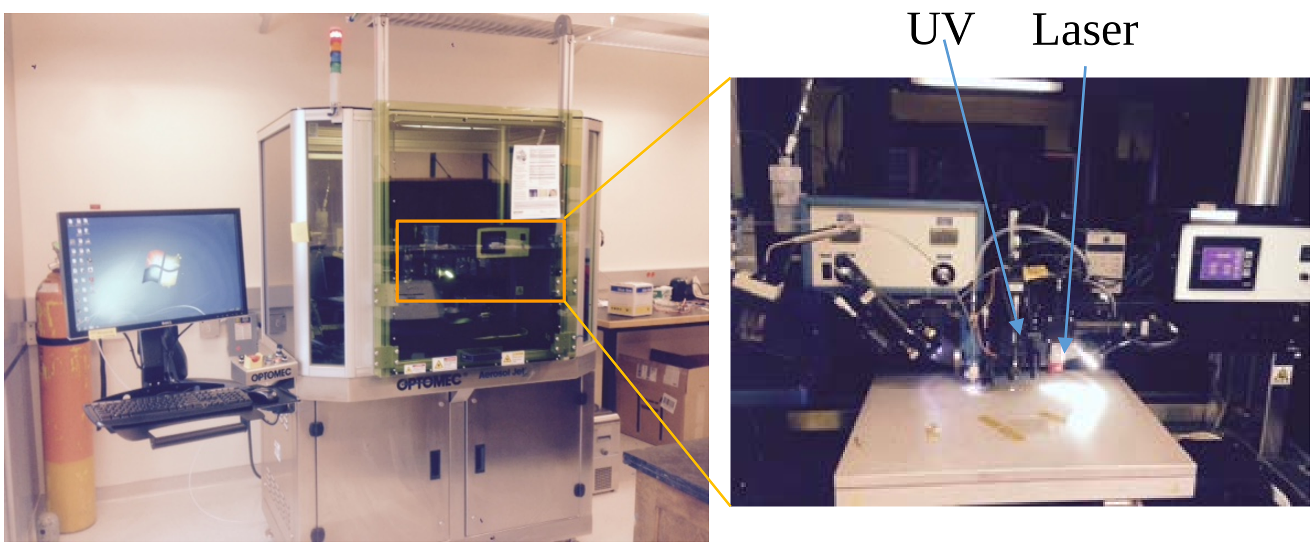


Aerosol Jet Schematic



- ❑ Operates by creating aerosol mist of 1-5 µm droplets, each containing nanoparticles
  - Stand off height about 5mm
  - No restriction on substrate type
  - Minimum feature size down to 10 µm
  - Printing accuracy of ± 2 µm stdev
- ❑ Clog resistant nozzles
- ❑ Ultrasonic and pneumatic atomizers allow nanoparticle ink with viscosity up to 1000 cP

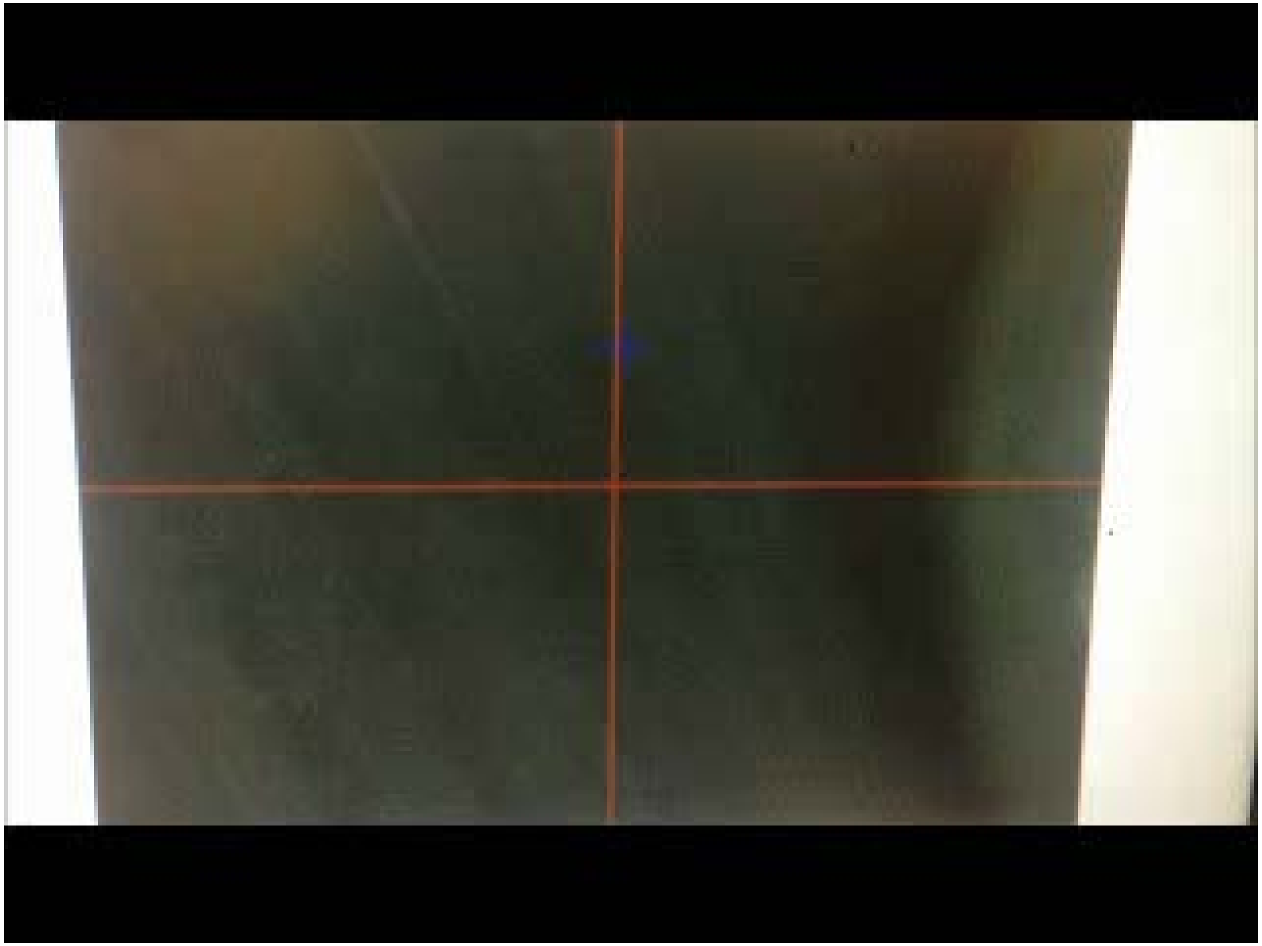
Aerosol Jet Micro-Additive Equipment



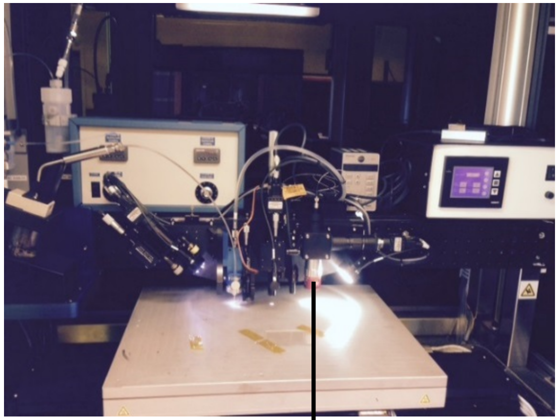
Aerosol Jet AJ300

- PI's lab has recently Aerosol Jet AJ-300 MAM system
- Includes both pneumatic and ultrasonic atomizers
- Also includes UV (for UV curable inks) and laser attachment for sintering

Video: AJ-MAM Printing and Nanoparticle Sintering



Nanoparticle Sintering



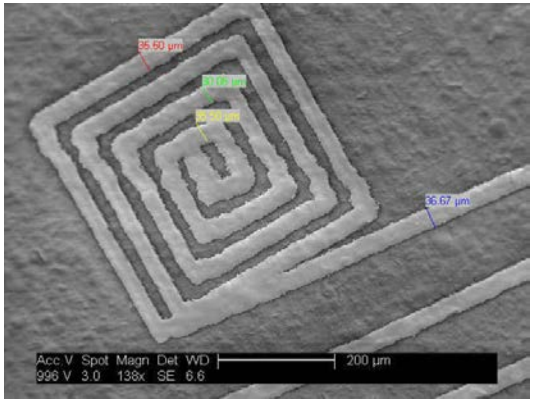
In-situ Laser Curing
** Power: 0-700 mW

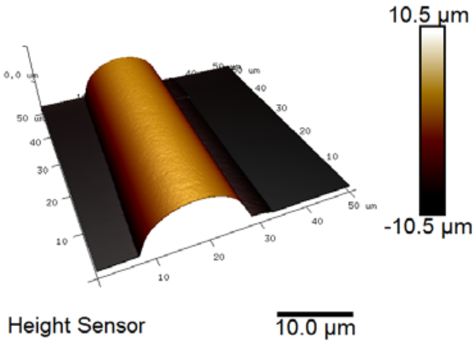
Photonic Curing
** Energy: 500-2000J

Thermal Curing
Max: 1100 °C

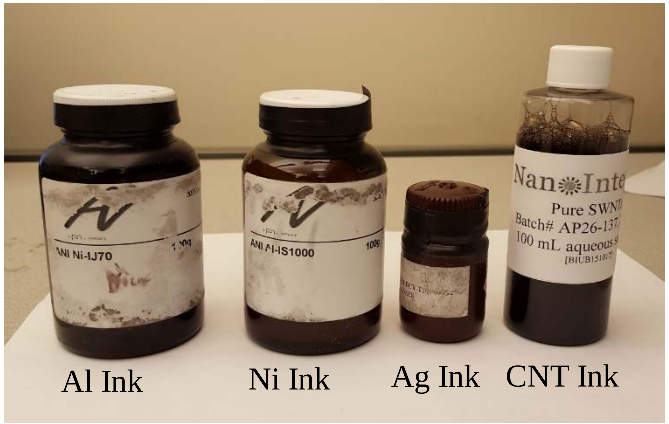
- ❑ Three sintering methods available to create additively manufactured sensors

Thin Films using AJ-MAM and Sputter System



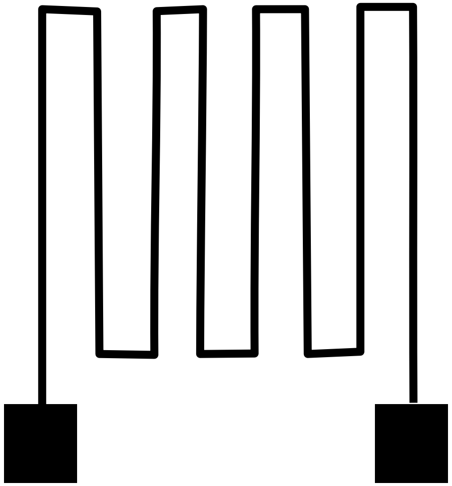


- AJ-MAM machine acquired at WSU in March '15 and is already being used for several sensor related works
  - Three papers on 3-D antennas and sensors over the last 6 months
  - Several inks already available for the DOE project
- UTEP has sputtering system and tube furnace available
- UTEP has electrical characterization equipment available

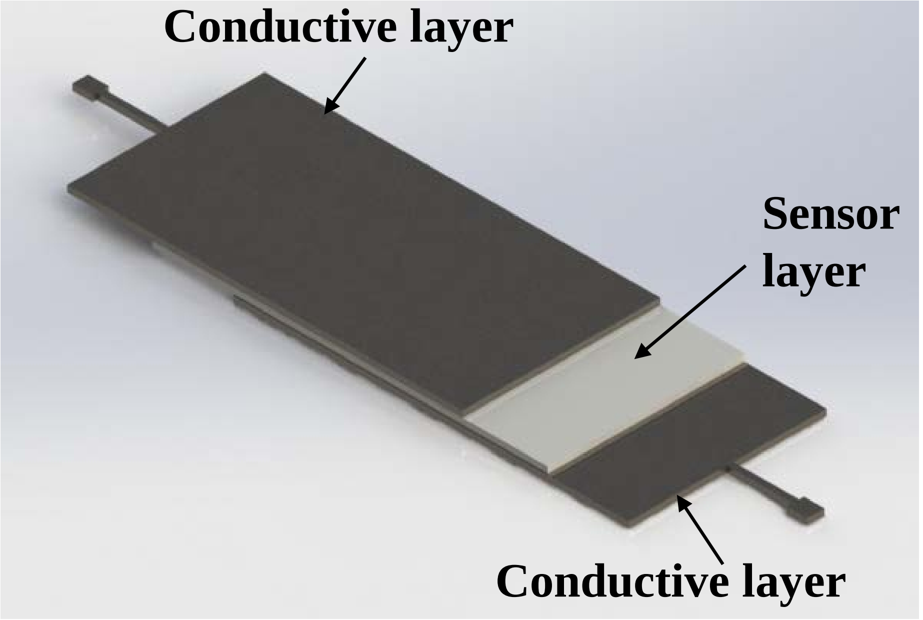


Sensors being Considered

Strain Sensor



Pressure Sensor

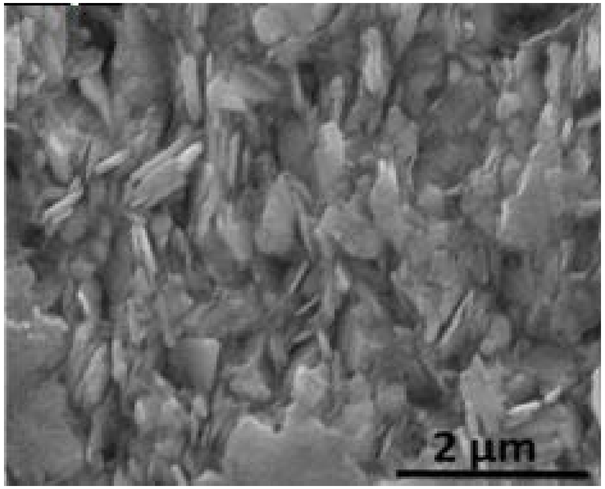


Materials for MAM Strain Gauges

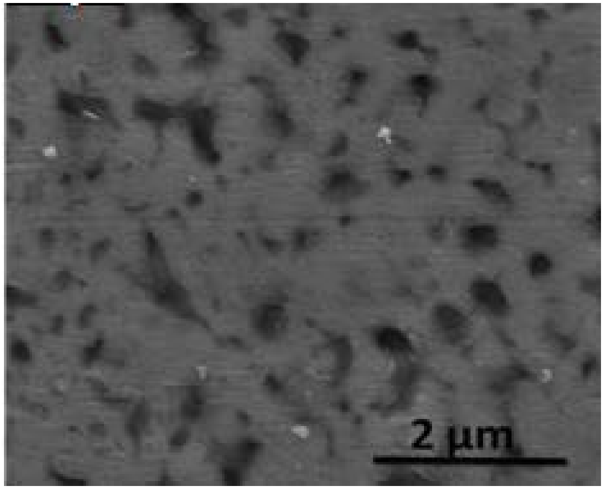
- Metal nanoparticle inks and MW-CNTs
  - Use of commercially available inks
  - Expected gauge factors unknown (will be evaluated)
  - Important considerations will include oxidation resistance, TCR, creep, adhesion to substrate etc.

Materials Challenges

- Oxidation resistance to 350-500 C
  - Strategy: Use various material, including known oxidation resistant materials
- Compensation method for TCR
  - Strategy: Measurement of TCR part of characterization/fundamental studies
- Encapsulation strategies
  - Strategy: High temperature cement will be explored with matching CTE to substrate
- Manufacturability
  - Strategy: AJ-MAM with various sintering methods

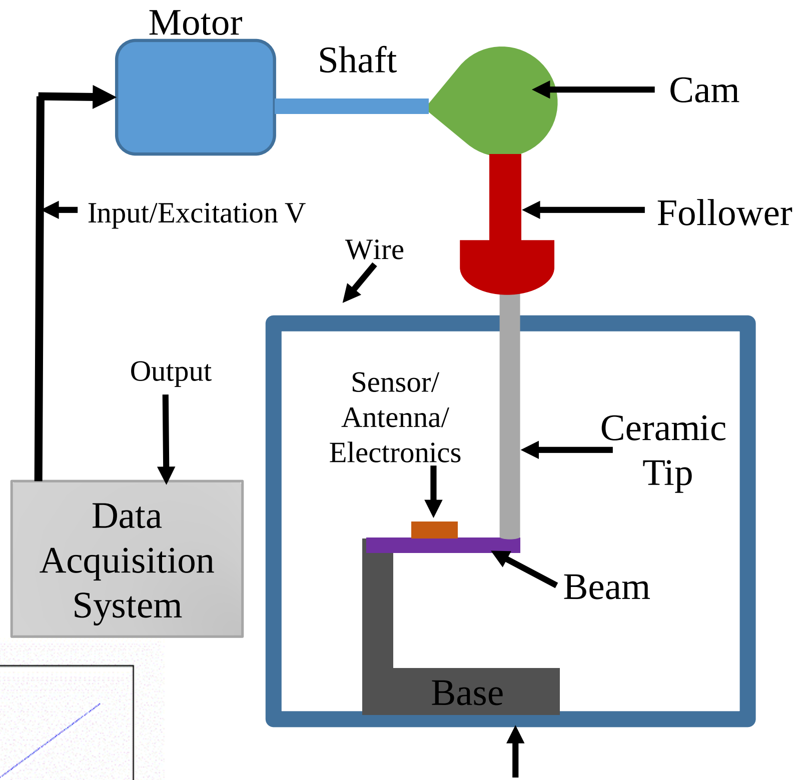


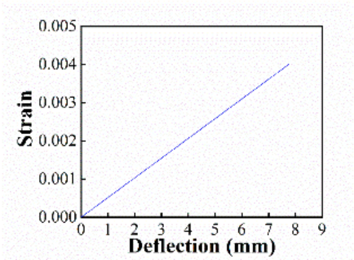
Silver unsintered

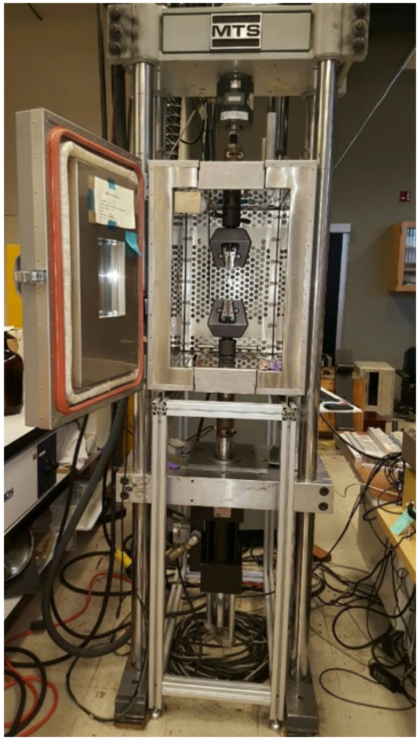


Silver sintered

Strain Sensor Testing Design







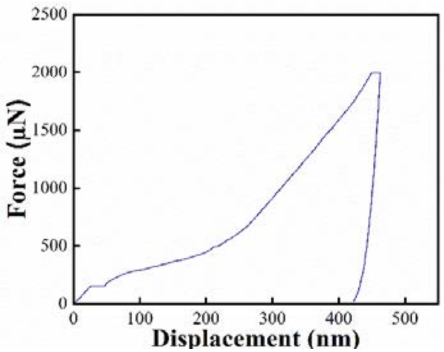
MTS system

- ❑ High temperature apparatus will be ready by third quarter of the project (design underway)
- ❑ Design in works –MTS system available for temperature up to 150 C until the high temperature apparatus is ready

Material Characterization

- ❑Nanoindentation
  - Modulus and hardness change with temperature
- ❑Transmission Electron microscopy vs temperature cycling observations
- ❑Evaluation of TCR/CTE for printed nanoparticle traces
- ❑Manufacturing Characterization
  - Printing variability
  - Statistical analysis of resistance change

Hysitron Nano Indenter



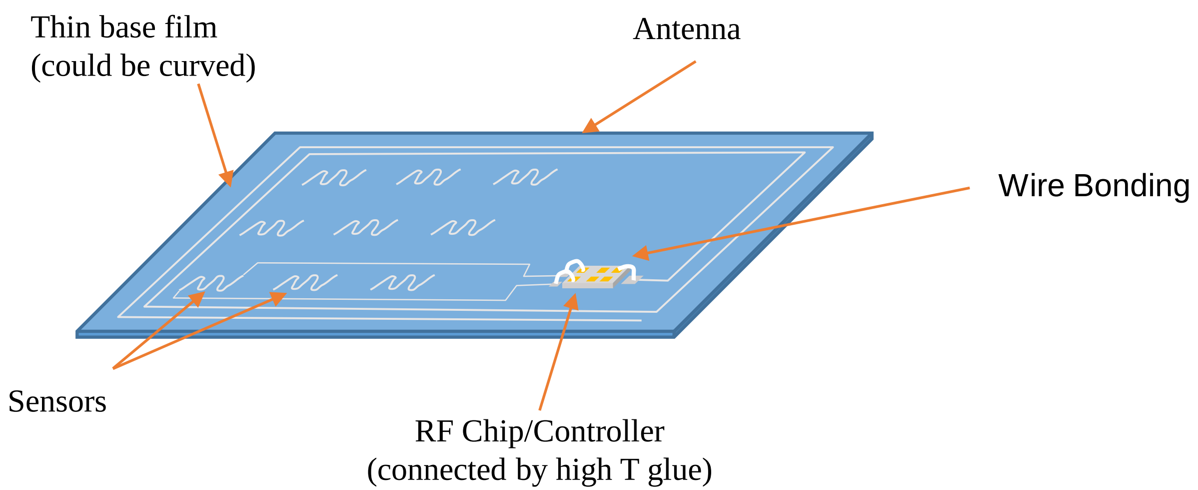
Force vs Displacement Curve at RT for Ag

Pressure Sensors

- Printed metal layer as a potential conductive layer
- Piezoelectric films deposited by PVD required for pressure sensitive layer
  - Various printed materials will be explored
  - Will also explore the pressure sensor by printed resistive elements over a diaphragm

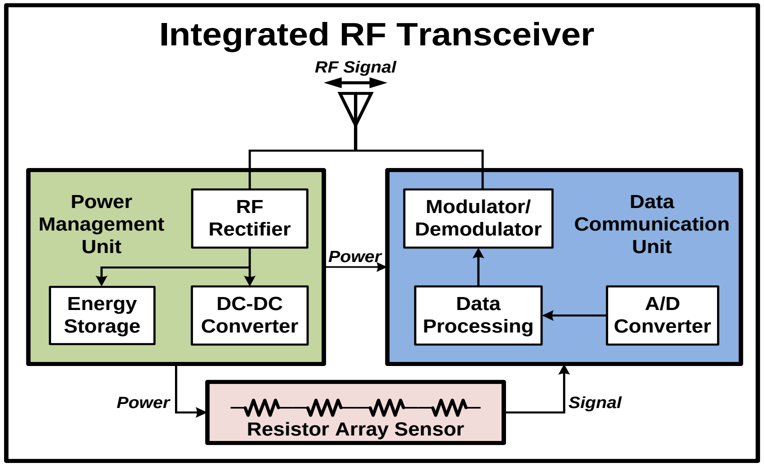
Sensor Array and Wireless Mechanisms

- WSU to fund one graduate student for a year PI's startup funds for the design of wireless module. The graduate student will work in the second year of the project with the PIs and Dr. Heo or EECS on this part of the project (design, fabrication at external vendor: year 2, Testing: year 3)



Sensor Array and Wireless Mechanisms

- Work to involve
  - Printed antennas characterized for impedance at high temperature
  - Design of integrated RF transceiver
  - Fabrication of the chip at external vendor on SiC or GaN
- Initially we will test/demonstrate wireless signal transmission to an external data reader at high temperature using a outside power source such as a battery
- The wireless power from an external energy transmitter (AC voltage signal) will then be designed with power management unit and an antenna
- The antenna will be designed by using an Electromagnetic (EM) solver tool such as Momentum or High Frequency Structural Simulator (HFSS). PMU and DCU circuits will be designed by using a software Cadence and Advance Design System (ADS).
- Chip, sensors, antennas will be integrated over a substrate for final demonstration



Budget/ Personnel Training

- Budget: $400k for 3 years for DOE + $88k WSU cost share

- Personnel Development
  - One PhD student at WSU for the project duration
    - One MS/PhD student will be supported for 1 year to support wireless design by WSU cost-share
  - One PhD student at UT-EP for the project duration

- Training
  - Students will get trained in the interdisciplinary areas of materials, manufacturing, and electrical engineering
  - Student visits to conferences to disseminate the research findings
  - PI visits to each other’s institutions

Tasks/Milestones/Timelines

	Year 1												Year 2												Year 3											
	Q1			Q2			Q3			Q4			Q1			Q2			Q3			Q4			Q1			Q2			Q3			Q4		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
Task 0.0: Project Planning	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Task 1.0: Single Sensor Elements - Material System and Manufacturing Methods	■	■	■	■	■	■	■	■	■	■	■	■																								
Task 2.0: Single Sensor Design and Testing					■	■	■	■	■	■	■	■	■	■	■	■	■	■																		
Task 3.0: Reliability of Sensors at High Temperature					■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■												
Subtask 3.1: Work of Adhesion and Nanoindentation					■	■	■	■	■	■	■	■	■	■	■																					
Subtask 3.2: Interfacial TEM observations											■	■	■	■	■	■	■	■	■	■	■															
Task 4.0: Wireless System Design and Fabrication													■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Subtask 4.1. Design of High Temperature Wirelessly-Powered Integrated RF Transceiver													■	■	■	■	■	■	■	■	■	■	■	■												
Subtask 4.2.Manufacturing of the Sensor System and High Temperature Testing																					■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■

Summary

- In this collaborative project, low cost additive manufacturing will be used to realize high temperature wireless sensors for FE applications
- The project will develop materials, manufacturing processes for the sensors along with fundamental understanding of material properties and reliability at high temperature
- The work will also involve training of next generation of scientists and engineers in interdisciplinary areas in line with the mission of the DOE

Thank You