Thin Film Ceramic Strain Sensor Development for High Temperature Environments

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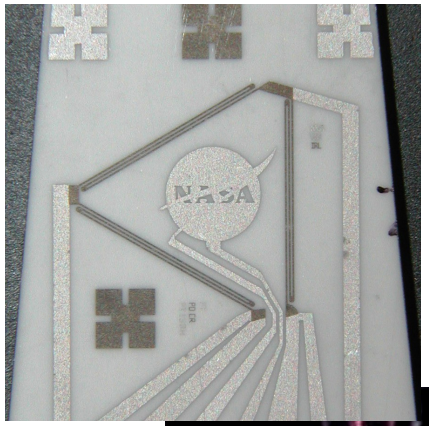
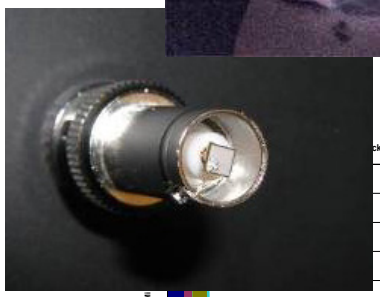
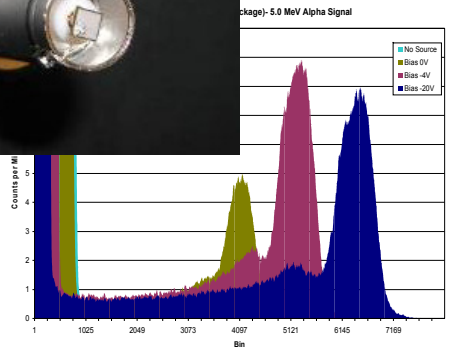
The Researchers

John Wrbanek & Gus Fralick

- Research Engineers / Physicists at NASA Glenn Research Center Sensors & Electronics Branch (GRC/RIS)
- Primarily Physical Sensors Instrumentation Research:
  - Thin Film Sensors
  - Temperature
  - Strain
  - Flow
- Also conduct research in Radiation Detectors, Sonoluminescence & other Revolutionary Concepts

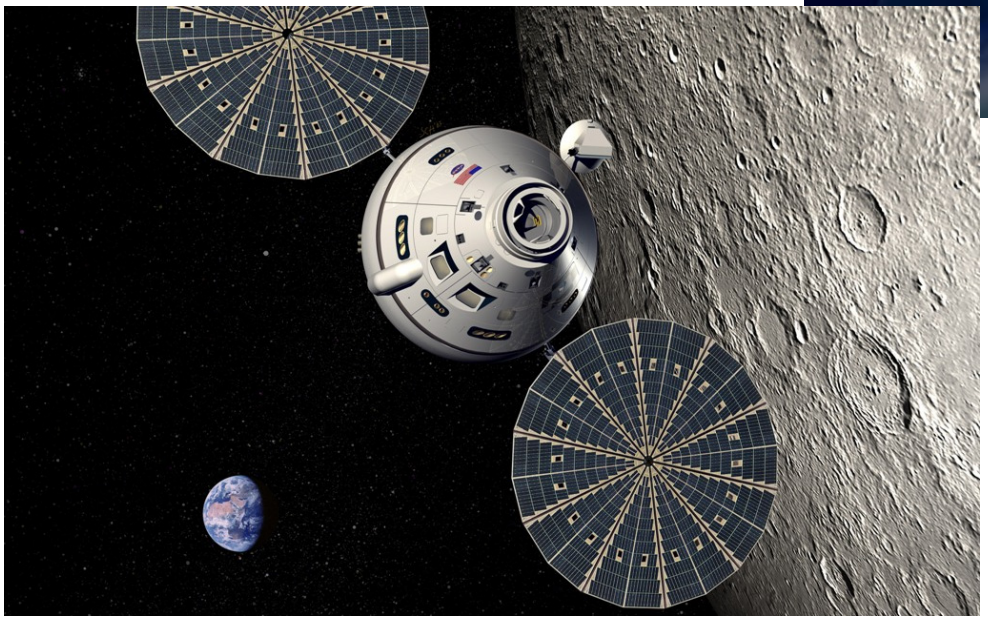






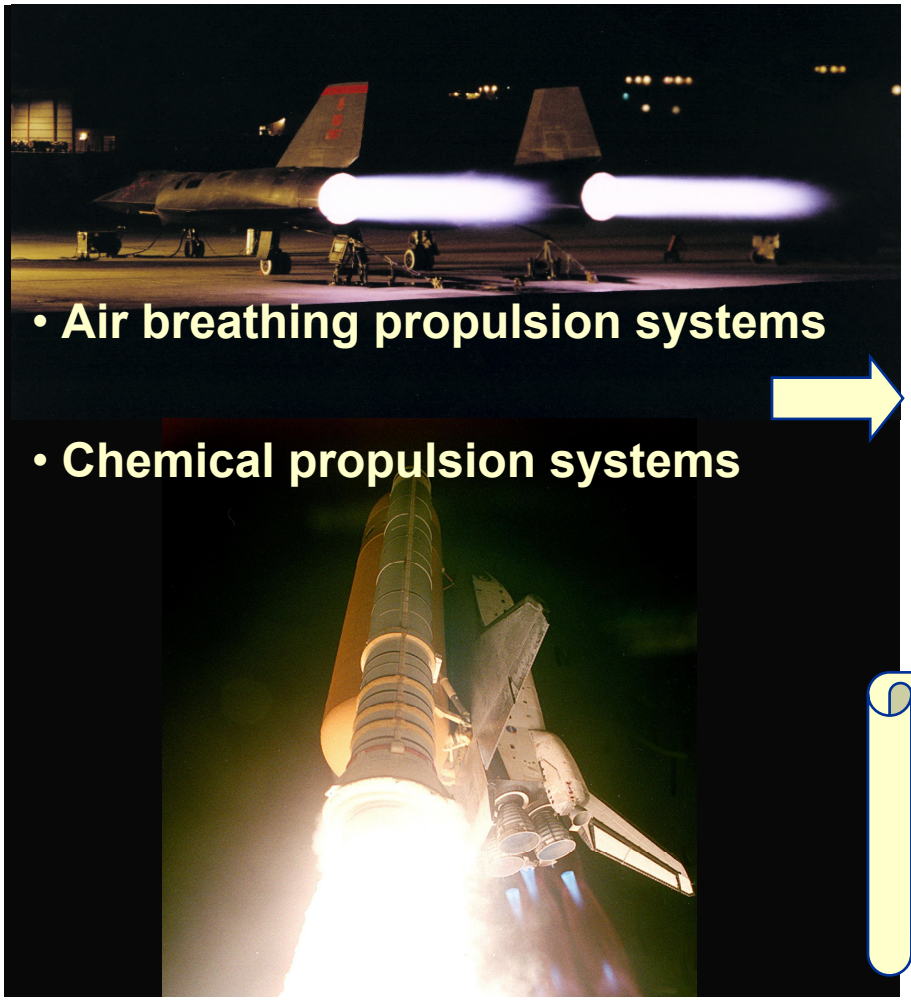
NASA's Mission: To pioneer the future in space exploration, scientific discovery, and aeronautics research

"Advance knowledge in the fundamental disciplines of aeronautics, and develop technologies for safer aircraft and higher capacity airspace systems."
– NASA 2006 Strategic Plan



"Develop the innovative technologies, knowledge, and infrastructures both to explore and support decisions about the destinations for human exploration"
– Vision for Space Exploration

Instrumentation Challenges for Propulsion System Environments



- High gas temperatures
- High material temperatures (>1000°C)
- Rapid thermal transients
- High gas flows
- High combustion chamber pressures

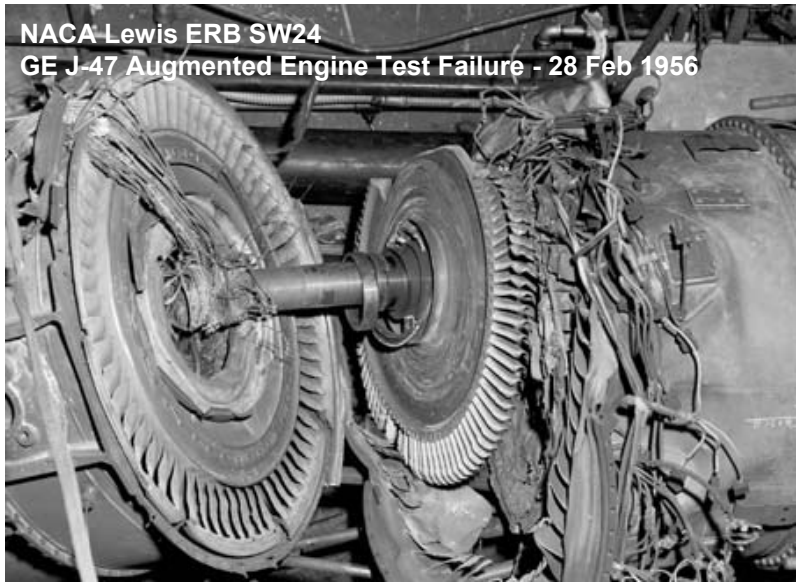
Wire-based sensors are bulky and disruptive to the true operating environment

Physical Issues for Life Prediction of Engine Hot Section

- Centrifugal Stress
- Thermal Stress
- Vibrational Stress from gas flow
- Contact Stresses from different materials (Thermal Expansions, Deformations)
- Blade Clearance (Creep)


Malaysia Airlines Boeing 777-2H6ER
RR Trent 892 Blade Delamination - 03 Nov 2006

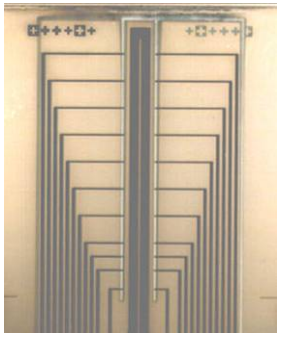

Air New Zealand Boeing 767-219ER
GE CF6-80A In-Flight Failure - 08 Dec 2002


NACA Lewis ERB SW24
GE J-47 Augmented Engine Test Failure - 28 Feb 1956

Thin Film Physical Sensors for High Temperature Applications

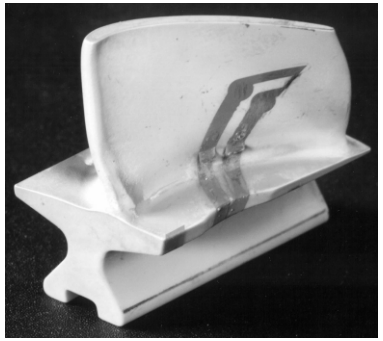
Advantages for temperature, strain, heat flux, flow & pressure measurement:

- Negligible mass & minimally intrusive (microns thick)
- Applicable to a variety of materials including ceramics
- Minimal structural disturbance (minimal machining)
- Intimate sensor to substrate contact & accurate placement
- High durability compared to exposed wire sensors
- Capable for operation to very high temperatures (>1000°C)

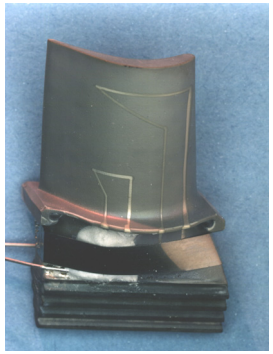


Flow sensor made of high temperature materials

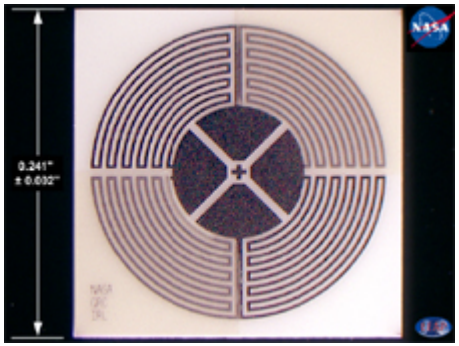
Multifunctional smart sensors being developed



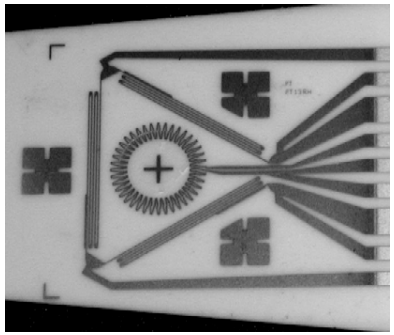
PdCr strain sensor to T=1000°C



Pt- Pt/Rh temperature sensor to T=1200°C



Heat Flux Sensor Array to T=1000°C



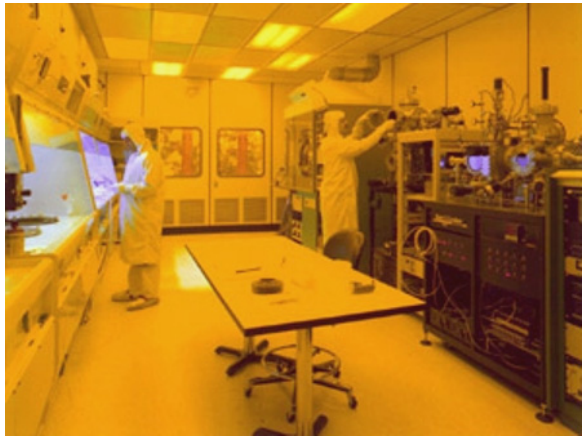
Multifunctional Sensor Array

Physical Sensors Facilities

Sputtering PVD Systems

Sensing Film layers are fabricated with physical vapor deposition methods (sputter deposition, e-beam vapor deposition)

Sensors are patterned by photolithography methods and/or stenciled masks



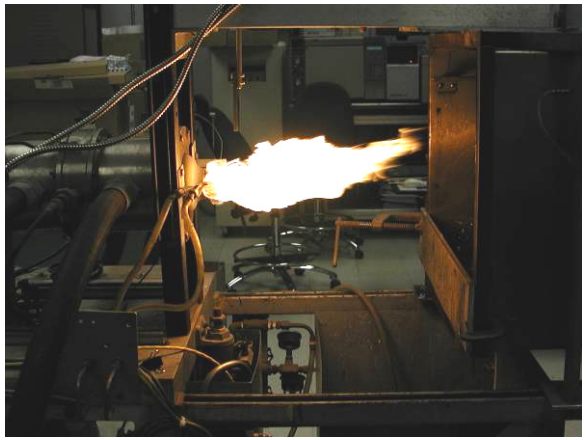
Microfabrication Clean Room

Evaluation of thin films with in-house Materials Characterization Facilities

Testing of films with in-house high-temperature furnaces & burn rigs

SEM/EDAX

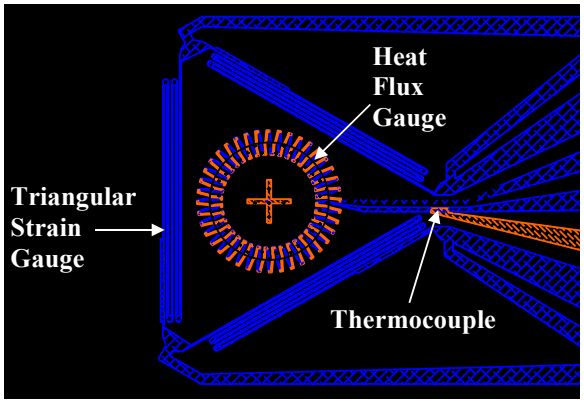
Thin Film Characterization Lab



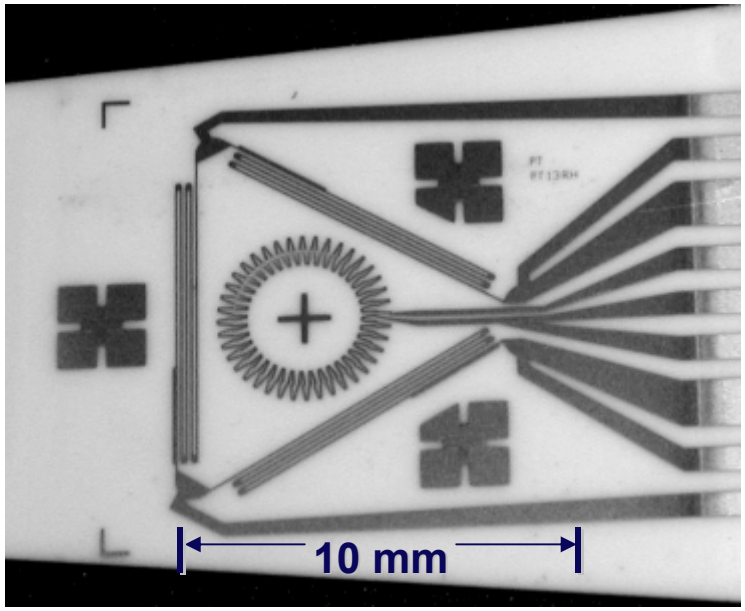
ERB Burn Rig

Multi-Functional Sensor System

- Multifunctional thin film sensor designed and built in-house (US Patent 5,979,243)
- Temperature, strain, and heat flux with flow all in the same microsensor
- Fine-line patterned sensing elements of Palladium-Chromium alloy (PdCr), Platinum-Rhodium alloy (PtRh) and Platinum (Pt)
- Enables measurements on component surfaces, and reduces boundary layer trip on metals compared to wires or foils
- Weldable shim designed to simplify sensor mounting
- Dynamic measurements demonstrated in lab



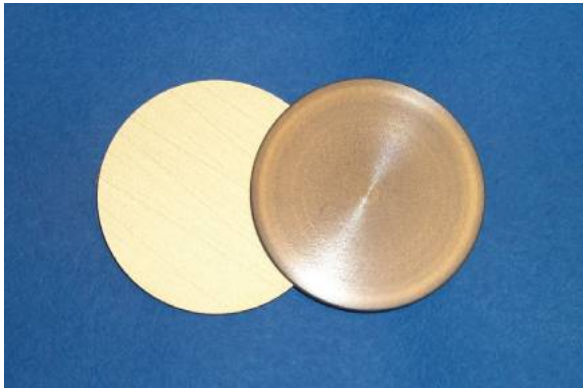
Schematic of Multifunctional Sensor



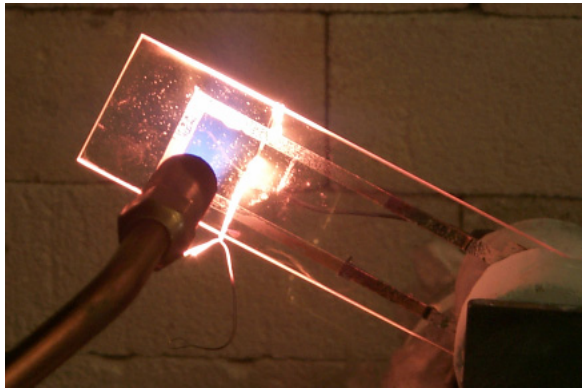
Multifunctional Sensor Prototype

Application of Ceramics as Thin Film Sensors

- The limits of noble metal thin film sensors of 1100°C (2000°F) may not be adequate for the increasingly harsh conditions of advanced aircraft and launch technology (>1650°C/3000°F)
- NASA GRC investigating ceramics as thin film sensors for extremely high temperature applications
- Advantages of the stability and robustness of ceramics and the non-intrusiveness of thin films
- Advances have been made in ceramic thin film sensors through collaborations with Case Western Reserve University (CWRU) and University of Rhode Island (URI)



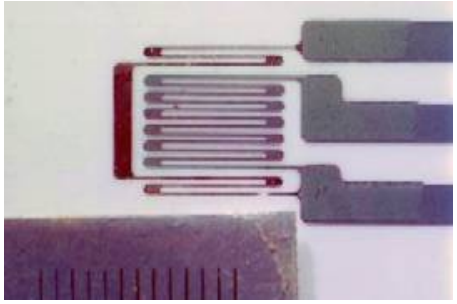
Ceramic TC Sputtering Targets fabricated by the CWRU & NASA GRC Ceramics Branch



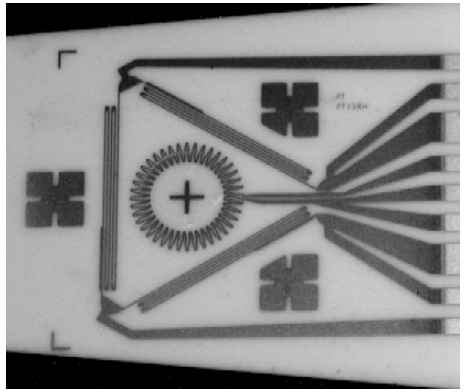
Ceramic TC fabricated at URI

Considerations for Static Strain Gauges

- Required accuracy: ±200 με (±10% full scale)
  - Currently accomplished with a temperature compensating bridge circuit with PdCr in a limited temperature range
- Multifunctional Sensor design does not lend itself to compensating bridges
  - Multiple strain gauges in a rosette pattern does not allow compensation to be included in design
  - Design eliminates temperature effects if apparent strain is low enough
- High Temperature Static Strain measurements with Multifunctional Sensor requires a more passive method of <u>reducing or eliminating apparent strain</u>
- Temperature Sensitivity Goal: <±20 με/°C



PdCr Strain Gauge in Compensation Bridge



Multifunctional Sensor Design

Apparent Strain

- Gauge factor (γ) of the strain gauge relates the sensitivity of the gauge to Strain (ε):

$$\frac{\delta R}{R} = \gamma \frac{\delta l}{l} = \gamma \varepsilon$$

- Apparent Strain (ε_a) can be falsely interpreted as actual strain due to the gauge's Temperature Coefficient of Resistance (TCR) and Coefficient of Thermal Expansion (CTE):

$$\varepsilon_a = \left(\frac{TCR}{\gamma} + \Delta CTE \right) \Delta T$$

- Goal: To minimize apparent strain by minimizing TCR and maximizing gauge factor

Past Ceramic-Based Sensor Development

Gauge Material	TCR (ppm/°C)	Gauge Factor (γ) ($\delta R/R/\varepsilon$)	Apparent Strain Sensitivity ($\varepsilon_a/\Delta T$)($\mu\varepsilon$/°C)	Maximum Use Temperature
Ni-20%Cr (ONERA,1993)	+290	2.5	+116	700°C
Pd-13%Cr (GRC, 1998)	+135	2 –1.4	+85	1100°C
AlN (URI, 1996)	-1281 – +109	3.72–15	-344 - +29	>1100°C
ITO (URI, 1996)	-469 – +230	-6.5– -11.4	-35 - +72	>1100°C
Al:ITO (URI, 2005)	-1200	8	-150	1280°C
TaN (CEIT, 1994)	-80	3.5	-23	<3000°C
TaON (CEIT, 1995)	-290	3.5	-83	<3000°C
Cu:TaN (NTU, 2004)	-800 – +200	2.3–5.1	-348 - +87	<3000°C
TiB_2 (HTW, 2006)	-50	1.4	-36	<3000°C

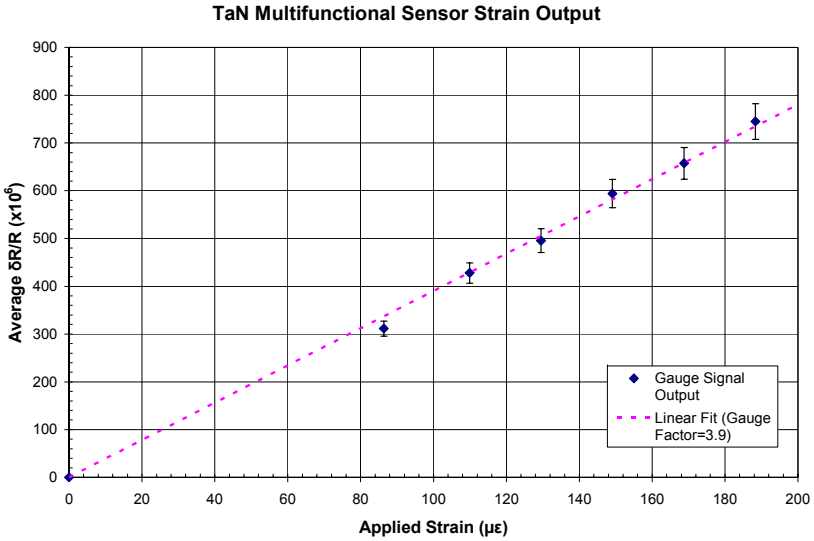
Tantalum Nitride Sensor Fabrication

Tantalum Nitride (TaN) Test Films

- Reactively-sputtered
- Patterned using shadow masks

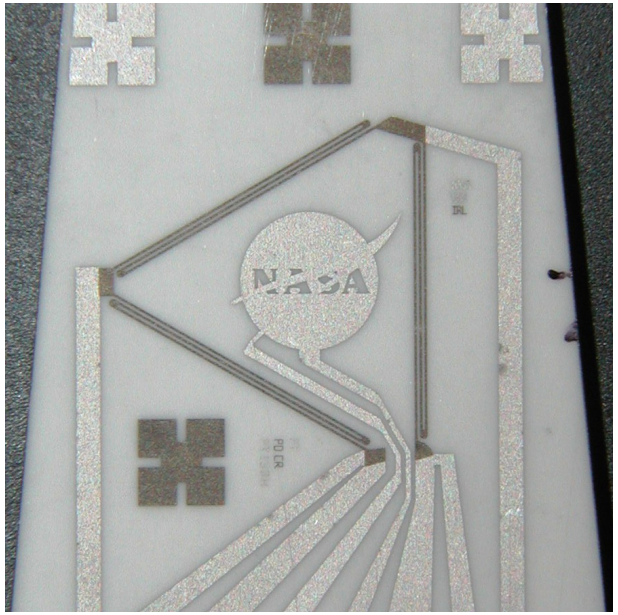
TaN Multifunctional Rosette

- Patterned using lift-off
- Gauge Factor: 3.9
- Resistivity: 259 μΩ-cm @20°C
- TCR: -93 ppm/°C
- $\varepsilon_a/\Delta T$: -24 με/°C (>20με/°C)



Multilayered Multifunctional Sensor

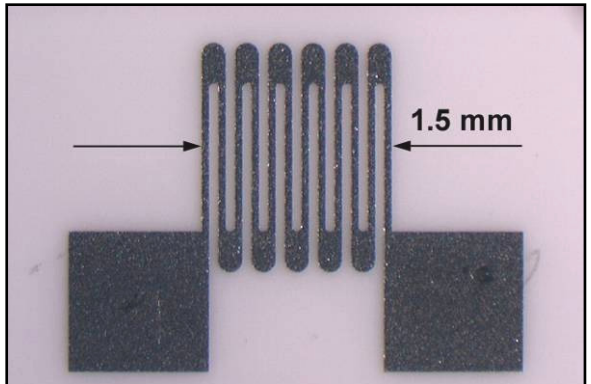
- TaN layered to PdCr strain gauge for the passive elimination of apparent strain sensitivity
- Initial test to 150°C
  - Gauge Factor: 1.2
  - Resistivity: 146 μΩ-cm
  - TCR: +15 ppm/°C
  - $\varepsilon_a/\Delta T$: +12 με/°C (<20με/°C)
- Follow-up test to 600°C
  - Unstable: $\varepsilon_a/\Delta T$: +156 με/°C (>20με/°C)
- Potential Issues
  - Multilayer Delamination / Diffusion
  - Compatible with sacrificial lift-off patterning process (Reactivity)
  - High Temperature Expansion Issues (CTE)
- Other Materials? (AFRL NDE Branch)



AFRL/NASA SAA3-307-A30

Film	Ar/N/O flow mix	Deposition Time	Thickness	Resistivity	TCR	ΔR_o for 200°C Cycle
Ti	40/0/0	369 min.	2.0 µm	133 µΩ-cm	1360 ppm/°C	4.45%
TiN	38/2/0	1200 min.	2.8 µm	1490 µΩ-cm	624 ppm/°C	114%
TiON	18/1/0.5	360 min.	0.6 µm	62 µΩ-cm	1400 ppm/°C	0.83%
Zr	40/0/0	198 min.	2.0 µm	140 µΩ-cm	1090 ppm/°C	2.73%
ZrN	38/2/0	750 min.	2.4 µm	1090 µΩ-cm	146 ppm/°C	4.26%
ZrON	18/1/0.5	360 min.	1.7 µm	82 µΩ-cm	695 ppm/°C	-1.3%

- All films fabricated using a 3” unbalanced magnetron source at 125W RF
- All films patterned & vacuum annealed at 600°C
- Initial TCR tests to 200°C in air using a 4-wire method
- ON films more stable in air
- Examining Al incorporation, multilayered films



Sample Pattern (detail)

Aircraft Aging & Durability: Novel Thin Film Sensor Technology

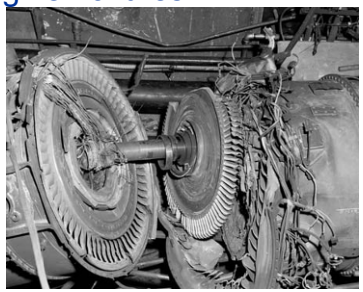
Problem:
- Degradation and damage that develops over time in hot section components can lead to catastrophic failure.
- Poor characterization of degradation processes in harsh environment conditions hinders development of durable hot section components

Demonstrated Need:
- Very difficult to model turbine blade temperatures, strains, heat fluxes; measurements are needed
- The turbine section has been consistently responsible for >$40M/yr in losses to the Air Force

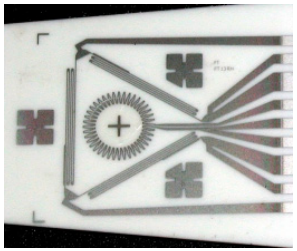
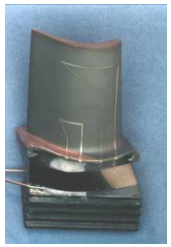
Project Content:
- Develop new sensor and insulation materials capable of withstanding the hot section environment
- Develop techniques for applying sensors onto complex high temperature structures
- Develop thin film sensors to measure temperature, strain, and heat flux during aging studies for hot propulsion materials.

Current SOA:
- Wire thermocouples, strain gauges-disrupt flow, change thermal & mechanical behavior of substrate
- Metal thin films, NiCoCrALY insulation


Catastrophic Turbine Engine Failures

Value Added, Contribution of Research:
- New bulk and nano-structured sensor materials with tailored properties
- Novel thin film harsh environment sensors for high temperature characterizations


On-Component Thin Film Sensors for Harsh Environments

Summary of Ceramics of Interest and Application

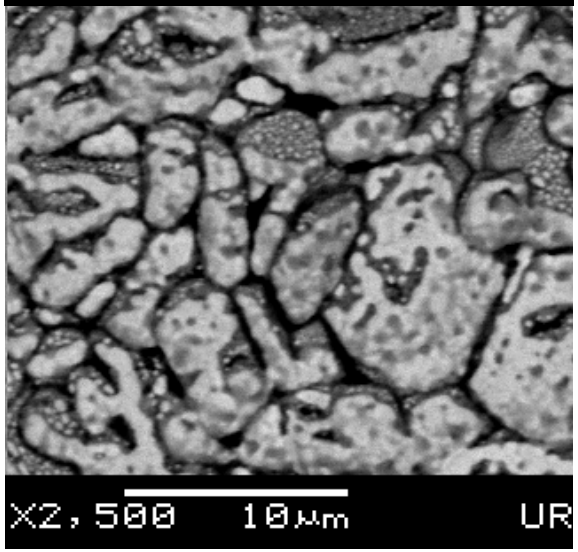
Ceramic	Thermocouple	RTD	Strain Gauge	Flow Sensor
TiC	X			
ZrC	X		X	
TaC	X			
$CrSi_2$	X			
$MoSi_2$		X		X
$TaSi_2$	X			
CrN	X			
ZrN		X	X	X
TaN			X	
CrB_2		X		X
ZrB_2			X	
TiB_2			X	

- Film Fabrication and Testing a challenge; Purity large concern

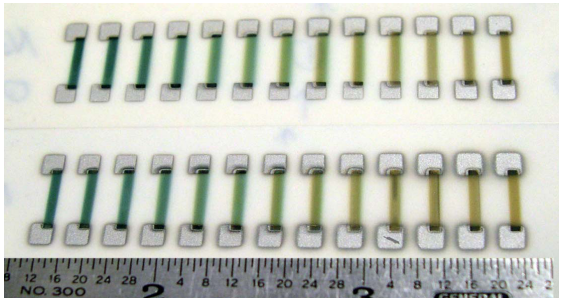
ITO-Nanocomposite Thin Film Strain Gages
(NASA Grant NNCO5GA67G w/ U. of Rhode Island)

- Low TCR nanocomposite strain gages fabricated by co-sputtering Indium-Tin Oxide (ITO) and refractory metals
- The TCR's measured for several ITO-Pt mixtures via Combinatorial Library
- Candidate Sample Result:
  - Gauge Factor: -26
  - TCR: -50 ppm/°C
  - $\varepsilon_a/\Delta T$: +2 με/°C (< 20 με/°C)
- Physics not understood at this time; more studies on-going

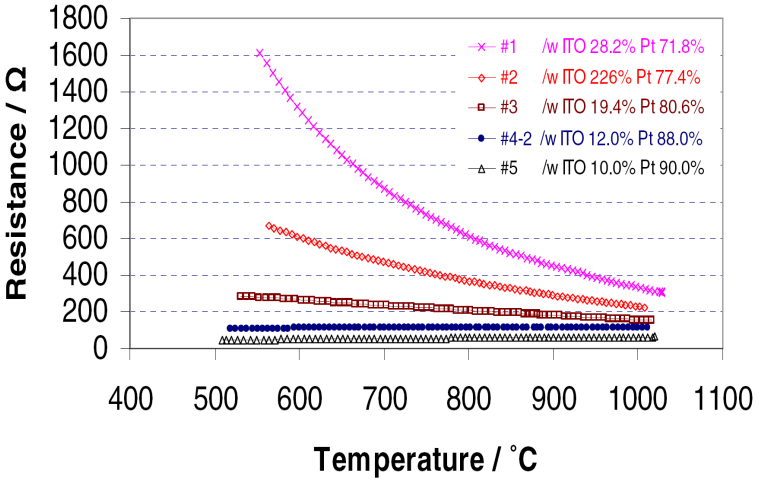
Backscattered SEM image



Equal Volumes of Pt and ITO → Min. TCR



Combinatorial Strain Gauge Library



Summary

- For the advanced engines in the future, knowledge of the physical parameters of the engine and components is necessary on the test stand and in flight
- NASA GRC is leveraging expertise in thin films and high temperature materials for applications of thin film ceramic sensors
- Attempts to improve thermal stability with Tantalum Nitride with an interlayered Palladium-Chromium strain gauge was met with positive results initially, but proved unstable
- Under AFRL/NASA SSA, began examination of other nitrides as possible candidates for ultra-high temperature strain gauges
- Currently examining sputtered films of candidate materials as sensors through NASA's Aircraft Aging & Durability (AAD) Project
- AAD is also sponsoring University of Rhode Island to examine nanostructured films as strain gauge materials

Acknowledgements

- Craig Neslen of the AFRL Nondestructive Evaluation (NDE) Branch at WPAFB for support and discussions related to this work
- Dr. Gary Hunter of the NASA GRC Sensors and Electronics Branch for his participation in discussions and advocacy of this work
- Dr. Otto Gregory of University of Rhode Island Dept. of Chemical Engineering for his studies in thin film ITO sensors
- Staff of the NASA GRC Test Facilities Operation, Maintenance, and Engineering (TFOME) organization in support of the fabrication and test capabilities of the NASA GRC Microsystems Fabrication Clean Room Facility.