Thin Film Ceramic Strain Sensor Development for Harsh Environments

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Presented at 53rd International Instrumentation Symposium (IIS), Tulsa, Oklahoma
May 3, 2007

Abstract

The need to consider ceramic sensing elements is brought about by the temperature limits of metal thin film sensors in propulsion system applications. In order to have a more passive method of negating changes of resistance due to temperature, an effort is underway at NASA GRC to develop high temperature thin film ceramic static strain gauges for application in turbine engines, specifically in the fan and compressor modules on blades. Other applications include on aircraft hot section structures and on thermal protection systems.

The near-term interim goal of this research effort was to identify candidate thin film ceramic sensor materials to test for viability and provide a list of possible thin film ceramic sensor materials and corresponding properties to test for viability. This goal was achieved by conducting a thorough literature search for ceramics that have the potential for application as high temperature thin film strain gauges chemically and physically compatible and selecting potential candidate materials for with NASA GRC's microfabrication procedures and substrates.

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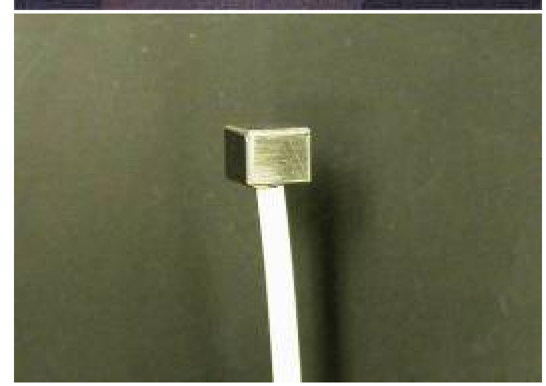
The Researchers

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 dabble in Radiation Detectors, and Research in Sonoluminescence & other Revolutionary Concepts



Outline

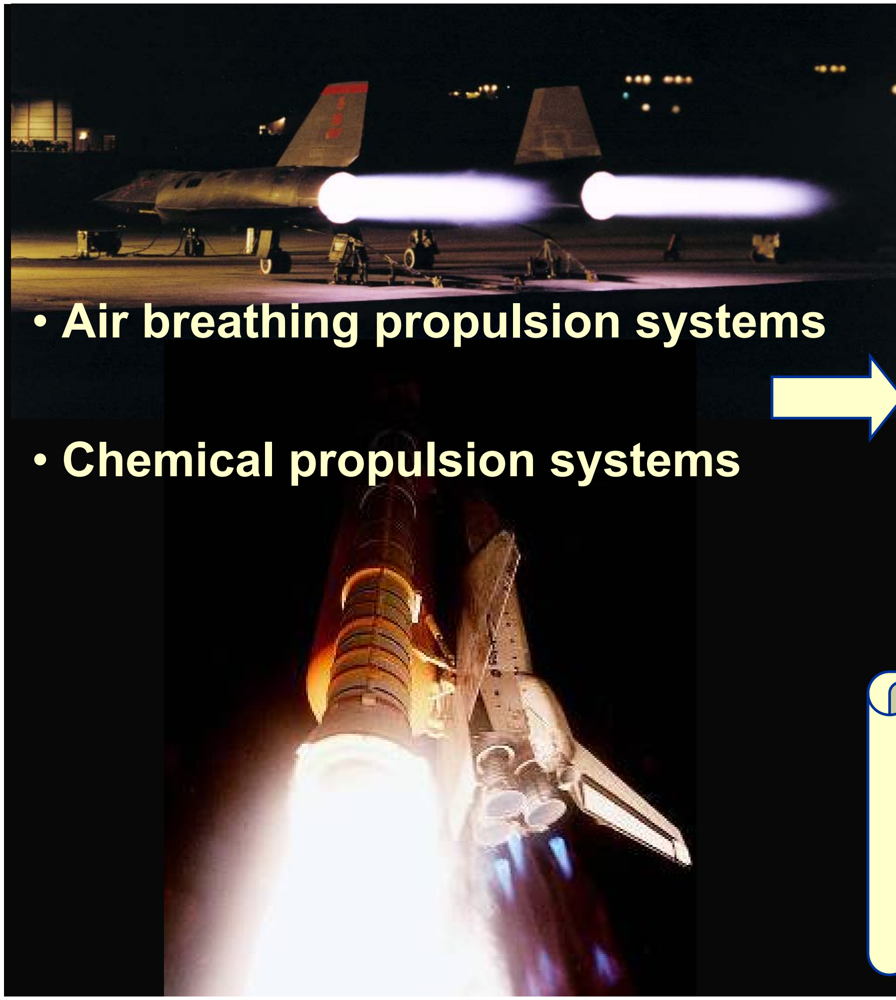
- Thin Film Physical Sensors at GRC
- Ceramics as Thin Film Sensors
- Static Strain Gauges
- AFRL/NASA Space Act Agreement (SAA)
- Preliminary Results

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

Issues for Life Prediction of Engine Hot Section

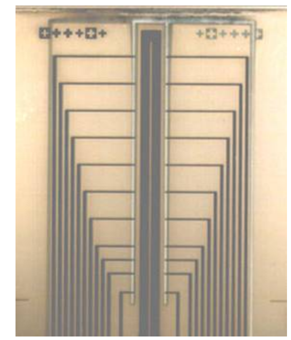
- Centrifugal Stress
- Thermal Stress
- Vibrational Stress from gas flow
- Contact Stresses from different materials (Thermal Expansions, Deformations)
- Blade Clearance (Creep)

Catastrophic Turbine Engine Failures

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)

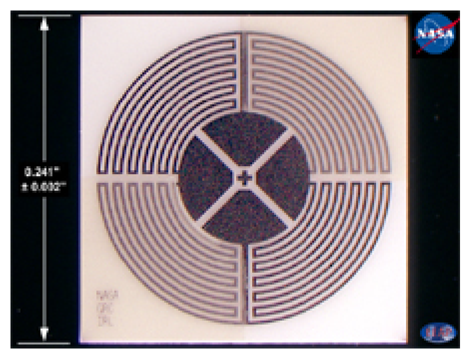


Flow sensor made of high temperature materials

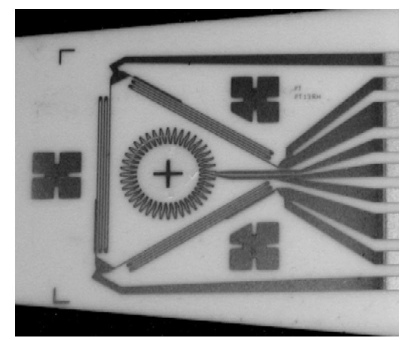
Multifunctional smart sensors being developed

PdCr strain sensor to T=1000°C

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



Heat Flux Sensor Array to T=1000°C



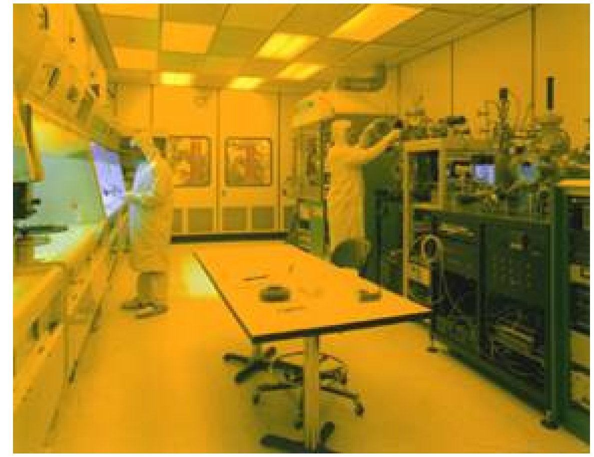
Multifunctional Sensor Array

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



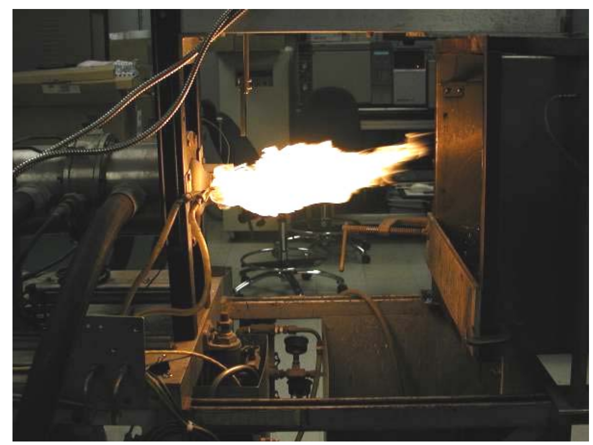
Microfabrication Clean Room

Evaluation of thin films with in-house Materials Characterization Facilities

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

SEM/EDAX

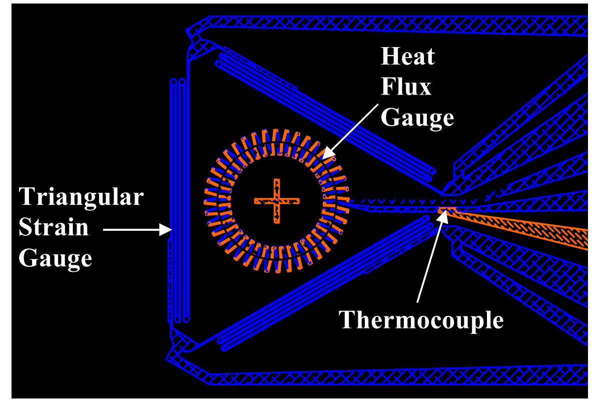
IRL Thin Film Lab



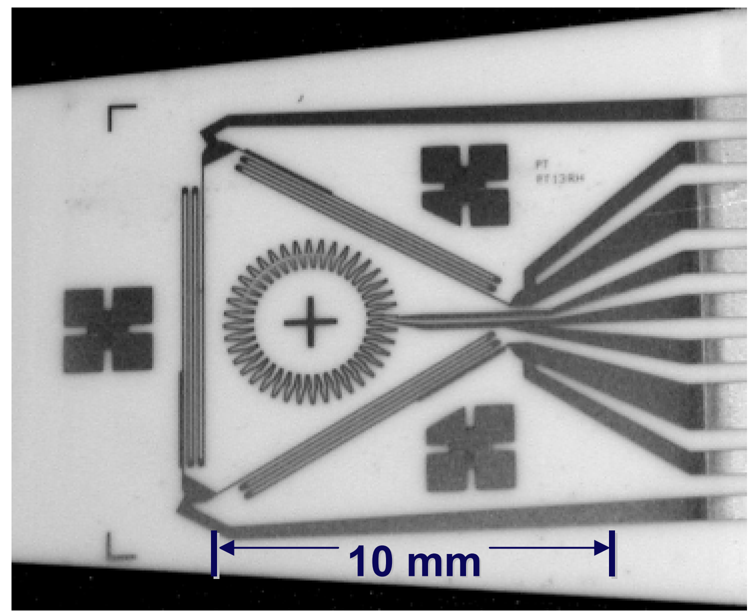
ERB Burn Rig

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 one the same microsensor
- 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



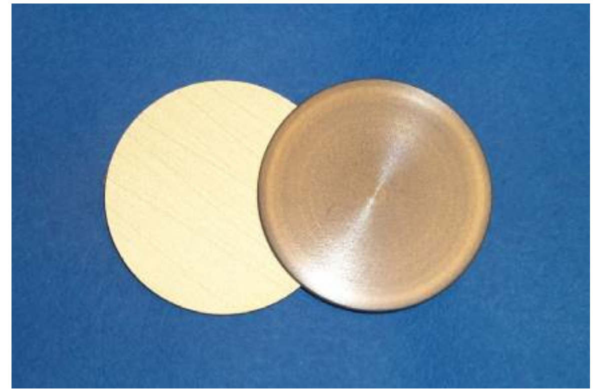
Schematic of Multifunctional Sensor



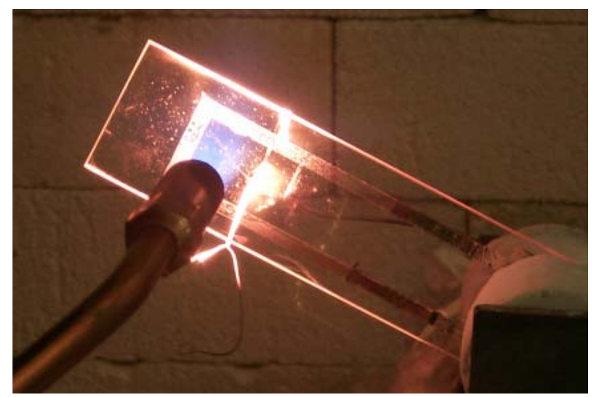
Multifunctional Sensor Prototype

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 CWRU & URI



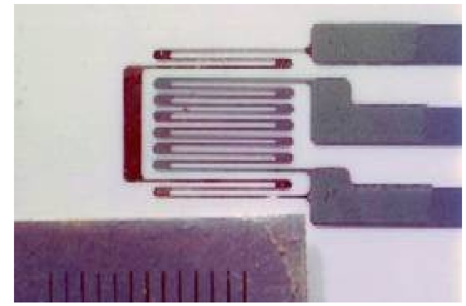
Ceramic TC Sputtering Targets fabricated by the CWRU & NASA GRC Ceramics Branch



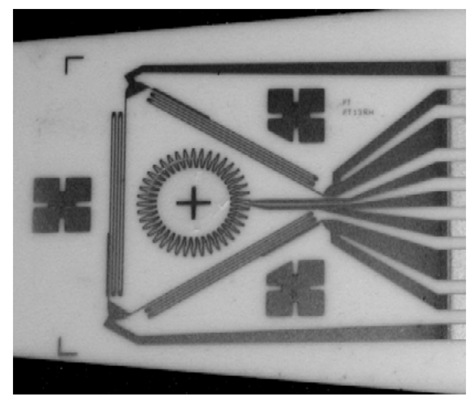
Ceramic TC fabricated at URI

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

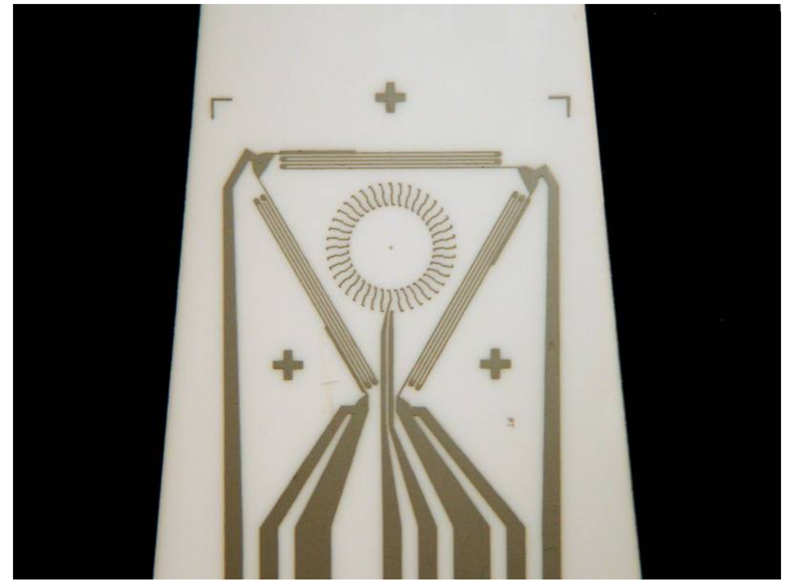
Tantalum Nitride Sensor Fabrication

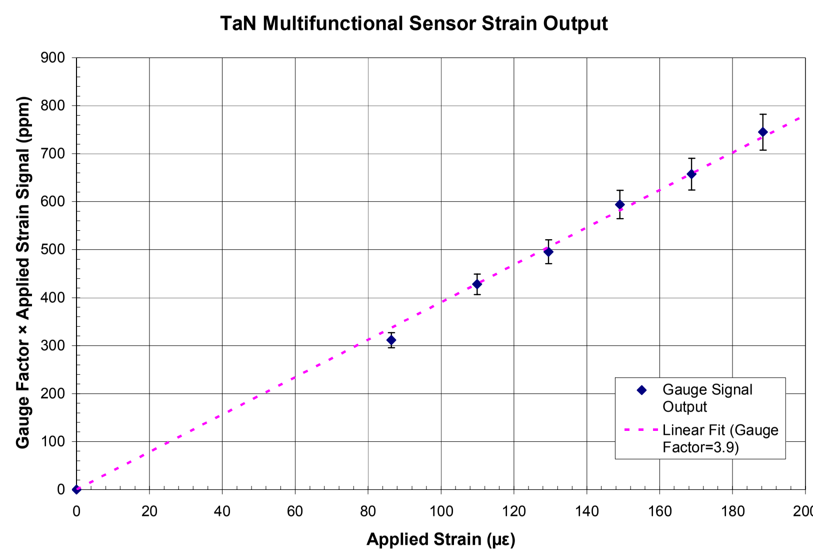
TaN Test Films (2004)

- Reactively-sputtered
- Patterned using shadow masks

TaN Multifunctional Rosette (2005)

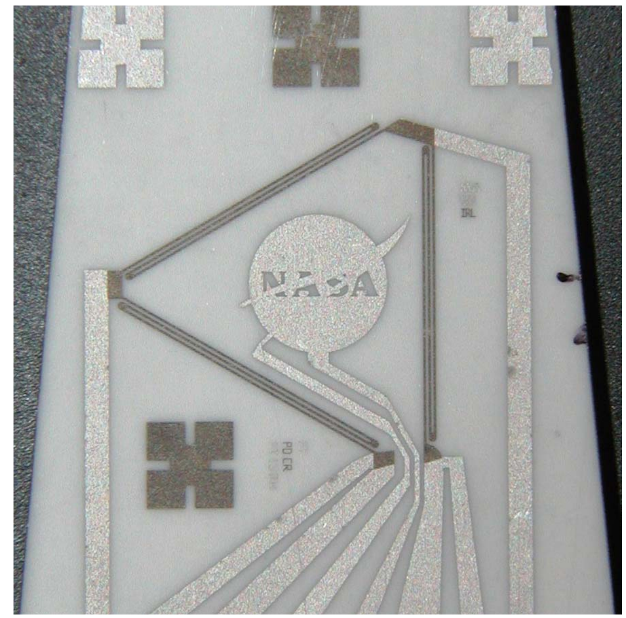
- Patterned using lift-off
- Gauge Factor: 3.9
- Resistivity: 259 μΩ-cm @20°C
- TCR: -93 ppm/°C
- $\varepsilon_a/\Delta T$: -24 με/°C (>20με/°C)





Multilayered Multifunctional Sensor

- TaN to PdCr strain gauge for the passive elimination of apparent strain sensitivity:
  - Gauge Factor: 1.2
  - Resistivity: 146 μΩ-cm
  - TCR: +15 ppm/°C
  - $\varepsilon_a/\Delta T$: +12 με/°C (<20με/°C)
- Initial test to 150°C (2006)
  - Next round of tests to 700°C
- Potential Issues
  - Multilayer Delamination?
  - Compatibly with sacrificial lift-off patterning process (Reactivity)?
  - High Temperature Issues (CTE)?
- Other Materials? (AFRL)



AFRL/NASA SAA3-307-A30

Objectives:

- Develop high temperature thin film ceramic sensors to allow the non-intrusive in-situ measurement of static strain characteristics of engine components at high temperatures.

Milestones / Deliverables:

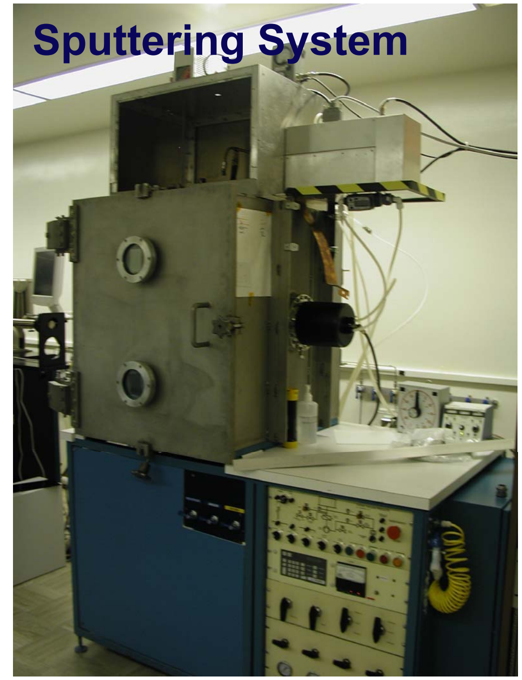
- June 2006
  - Identify candidate thin film ceramic sensor materials to test for viability / List of possible thin film ceramic sensor materials and corresponding properties to test for viability
- September 2006
  - Preliminary testing of candidate thin film materials for high temperature strain measurement applications / Preliminary data on temperature & strain characteristics
- May 2007
  - Identify viable thin film ceramic sensors / Demonstrate viable thin film ceramic sensors in low temperature tests
- September 2007
  - Preliminary high temperature cycling tests of viable thin film ceramic sensors / Preliminary data on temperature & strain characteristics
- September 2008
  - Identify thin film ceramic sensor viability for component qualifications / Demonstrate thin film ceramic sensors under high temperature cycling test

Ceramic Mixes to Modify TCR in Bulk & Films

Ceramic	Base	Dopant(s)	Common Name	Melting Point
TiO	Ti	O	Titanium Oxide	1750°C
ZAO	ZnO	AlOx	Zinc Aluminum Oxide	1800°C?(s)
ZAON	ZnO	Al, N	Zinc Aluminum Oxynitride	1800°C?(s)
CrSiO	Cr	Si,O	Chromium Silicon Oxide	1800°C?
ATO	SnO	SbO	Antimony Tin Oxide	1900°C?
N:ATO	ATO	N	Nitrogen doped ATO	1900°C?
GITO	ITO	GaOx	Gallium-ITO	1900°C
CrTiN	Ti	Cr, N	Chromium Titanium Nitride	2900°C?
TiN	Ti	N	Titanium Nitride	<2930°C
TiB_2	Ti	B	Titanium Diboride	<3000°C
ZrN	Zr	N	Zirconium Nitride	<2980°C
HfN	Hf	N	Hafnium Nitride	<3310°C
HfC	Hf	C	Hafnium Carbide	<3890°C
AuTaO	Ta	Au,O	Gold-Tantalum Oxide	3000°C?

Work Plan

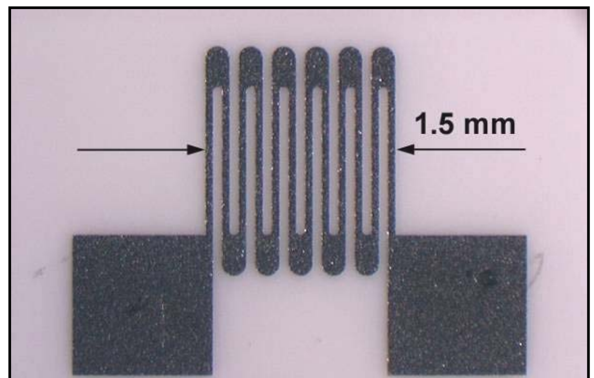
- Reactivity restrictions allow:
  - Ta, Cr, Al, Au
  - TiO, ITO, CrSiO, TiB_2
  - TaN, TiN, ZrN
- CTE Issues?
  - TiO, ITO, CrSiO, TiB_2, TiN, ZrN
- Procurements
  - Targets & Substrates
  - Equipment & Clean Room Support
- Test to Increasing Temperatures
  - 200°C, 700°C, 1300°C +
- TCR, $\varepsilon_a/\Delta T$, Drift Rate



Low Temperature Testing

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
- TCR tested using a 4-wire method to 200°C
- N- & O- doping lowered TCR (not enough)
- ON films more stable in air
- Examining Al incorporation, multilayered films



Sample Pattern (detail)

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, investigations for the applications of thin film ceramic sensors
- Initial attempts to improve thermal stability with Tantalum Nitride with an interlayered Palladium-Chromium strain gauge has met with positive results
- Under AFRL/NASA SSA, selected doped Zirconium Nitride, Titanium Nitride, and Titanium Diboride as possible candidates for ultra-high temperature strain gauges
- Currently optimizing sputtered films of candidate materials

Acknowledgements

- Craig Neslen of the AFRL Nondestructive Evaluation (NDE) Branch 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
- Kimala Laster of Sierra Lobo, Inc. for the ceramic film depositions currently on-going as part of the NASA GRC Test Facilities Operation, Maintenance, and Engineering (TFOME) organization

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http://www.grc.nasa.gov/WWW/sensors/PhySen/