Thin Film Ceramic Strain Sensor Development for Harsh Environments: Identification of Candidate Thin Film Ceramics to Test for Viability for Static Strain Sensor Development

John D. Wrbanek, Gustave C. Fralick and Gary W. Hunter
NASA Glenn Research Center, Cleveland, Ohio
Presented at Air Force Research Laboratory, Wright-Patterson AFB, OH
October 25, 2006

Summary

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 a thorough literature search for ceramics that have the potential for application as high temperature thin film strain gauges, reviewing potential candidate materials for chemical & physical compatibility with NASA GRC’s microfabrication procedures and substrates.
Thin Film Ceramic Strain Sensor Development for Harsh Environments

Identification of Candidate Thin Film Ceramics to Test for Viability for Static Strain Sensor Development

John D. Wrbanek, Gustave C. Fralick and Gary W. Hunter

NASA Glenn Research Center, Cleveland, Ohio

October 25, 2006
Outline

• Thin Film Physical Sensors at GRC
• Ceramics as Thin Film Sensors
• Static Strain Gauges
• AFRL/NASA Space Act Agreement (SAA)
• Preliminary Results
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
SENSORS AND ELECTRONICS BRANCH

SCOPE OF WORK

PHYSICAL SENSORS (Temp, Strain, Heat Flux)  CHEMICAL SENSORS

SILICON CARBIDE HIGH TEMP ELECTRONICS  MICRO-ELECTRO-MECHANICAL SYSTEMS  NANOTECHNOLOGY
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

• Air breathing propulsion systems
• Chemical propulsion systems
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)

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

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

Evaluation of thin films with in-house Materials Characterization Facilities

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

Sputtering PVD Systems

Microfabrication Clean Room

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 using 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
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
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 reducing or eliminating apparent strain

• Temperature Sensitivity Goal: <±20 µε/°C
Apparent Strain

- **Gauge factor** ($\gamma$) of the strain gauge relates the sensitivity of the gauge to **Strain** ($\varepsilon$):

  \[
  \frac{\delta R}{R} = \gamma \frac{\delta l}{l} = \gamma \varepsilon
  \]

- **Apparent Strain** ($\varepsilon_a$) can be falsely interpreted as actual strain due to the gauge’s **Temperature Coefficient of Resistance** (TCR) and **Coefficient of Thermal Expansion** (CTE):

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

- **Goal**: To minimize apparent strain by minimizing TCR and maximizing gauge factor
## Past Ceramic-Based Sensor Development

<table>
<thead>
<tr>
<th>Gauge Material</th>
<th>TCR (ppm/°C)</th>
<th>Gauge Factor (γ) (δR/R/ε)</th>
<th>Apparent Strain Sensitivity (ε&lt;sub&gt;a&lt;/sub&gt;/ΔT)(µε/°C)</th>
<th>Maximum Use Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni-20%Cr (ONERA,1993)</td>
<td>+290</td>
<td>2.5</td>
<td>+116</td>
<td>700°C</td>
</tr>
<tr>
<td>Pd-13%Cr (GRC, 1998)</td>
<td>+135</td>
<td>2 –1.4</td>
<td>+85</td>
<td>1100°C</td>
</tr>
<tr>
<td>ITO (URI, 1996)</td>
<td>-469 – +230</td>
<td>-6.5– -11.4</td>
<td>-35 - +72</td>
<td>&gt;1100°C</td>
</tr>
<tr>
<td>Al:ITO (URI, 2005)</td>
<td>-1200</td>
<td>8</td>
<td>-150</td>
<td>1280°C</td>
</tr>
<tr>
<td>TaN (CEIT, 1994)</td>
<td>-80</td>
<td>3.5</td>
<td>-23</td>
<td>&lt;3000°C</td>
</tr>
<tr>
<td>TaON (CEIT, 1995)</td>
<td>-290</td>
<td>3.5</td>
<td>-83</td>
<td>&lt;3000°C</td>
</tr>
<tr>
<td>Cu:TaN (NTU, 2004)</td>
<td>-800 – +200</td>
<td>2.3–5.1</td>
<td>-348 - +87</td>
<td>&lt;3000°C</td>
</tr>
<tr>
<td>TiB&lt;sub&gt;2&lt;/sub&gt; (HTW, 2006)</td>
<td>-50</td>
<td>1.4</td>
<td>-36</td>
<td>&lt;3225°C</td>
</tr>
</tbody>
</table>
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
  – 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)
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

<table>
<thead>
<tr>
<th>Ceramic</th>
<th>Base</th>
<th>Dopant(s)</th>
<th>Common Name</th>
<th>Melting Point</th>
</tr>
</thead>
<tbody>
<tr>
<td>TiO</td>
<td>Ti</td>
<td>O</td>
<td>Titanium Oxide</td>
<td>1750°C</td>
</tr>
<tr>
<td>ZAO</td>
<td>ZnO</td>
<td>AlOx</td>
<td>Zinc Aluminum Oxide</td>
<td>1800°C?</td>
</tr>
<tr>
<td>ZAON</td>
<td>ZnO</td>
<td>Al, N</td>
<td>Zinc Aluminum Oxynitride</td>
<td>1800°C?</td>
</tr>
<tr>
<td>CrSiO</td>
<td>Cr</td>
<td>Si,O</td>
<td>Chromium Silicon Oxide</td>
<td>1800°C?</td>
</tr>
<tr>
<td>ATO</td>
<td>SnO</td>
<td>SbO</td>
<td>Antimony Tin Oxide</td>
<td>1900°C?</td>
</tr>
<tr>
<td>N:ATO</td>
<td>ATO</td>
<td>N</td>
<td>Nitrogen doped ATO</td>
<td>1900°C?</td>
</tr>
<tr>
<td>GITO</td>
<td>ITO</td>
<td>GaOx</td>
<td>Gallium-ITO</td>
<td>1900°C</td>
</tr>
<tr>
<td>CrTiN</td>
<td>Ti</td>
<td>Cr, N</td>
<td>Chromium Titanium Nitride</td>
<td>2900°C?</td>
</tr>
<tr>
<td>TiN</td>
<td>Ti</td>
<td>N</td>
<td>Titanium Nitride</td>
<td>&lt;2930°C</td>
</tr>
<tr>
<td>TiB₂</td>
<td>Ti</td>
<td>B</td>
<td>Titanium Diboride</td>
<td>&lt;2970°C</td>
</tr>
<tr>
<td>ZrN</td>
<td>Zr</td>
<td>N</td>
<td>Zirconium Nitride</td>
<td>&lt;2980°C</td>
</tr>
<tr>
<td>HfN</td>
<td>Hf</td>
<td>N</td>
<td>Hafnium Nitride</td>
<td>&lt;3310°C</td>
</tr>
<tr>
<td>HfC</td>
<td>Hf</td>
<td>C</td>
<td>Hafnium Carbide</td>
<td>&lt;3890°C</td>
</tr>
<tr>
<td>AuTaO</td>
<td>Ta</td>
<td>Au,O</td>
<td>Gold-Tantalum Oxide</td>
<td>3000°C?</td>
</tr>
</tbody>
</table>
Work Plan

• Reactivity restrictions allow:
  – Ta, Cr, Al, Au
  – TiO, ITO, CrSiO, TiB₂
  – TaN, TiN, ZrN, HfN

• CTE Issues?
  – TiO, ITO, CrSiO, TiB₂, TiN, ZrN

• Procurements
  – Targets & Substrates ($9k)
  – Equipment & Clean Room Support ($12k)

• Test to Increasing Temperatures
  – 200°C, 700°C, 1300°C +

• TCR, εₘ/ΔT, Drift Rate
# Low Temperature Testing

<table>
<thead>
<tr>
<th>Film</th>
<th>Ar/N/O flow mix</th>
<th>Deposition Time</th>
<th>Thickness</th>
<th>Resistivity</th>
<th>TCR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti</td>
<td>40/0/0</td>
<td>369 min.</td>
<td>2.0 µm</td>
<td>133 µΩ-cm</td>
<td>1360 ppm/°C</td>
</tr>
<tr>
<td>TiN</td>
<td>38/2/0</td>
<td>1200 min.</td>
<td>2.8 µm</td>
<td>1490 µΩ-cm</td>
<td>624 ppm/°C</td>
</tr>
<tr>
<td>TiON</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Film Testing in Progress</td>
</tr>
<tr>
<td>Zr</td>
<td>40/0/0</td>
<td>198 min.</td>
<td>2.0 µm</td>
<td>140 µΩ-cm</td>
<td>1090 ppm/°C</td>
</tr>
<tr>
<td>ZrN</td>
<td>38/2/0</td>
<td>750 min.</td>
<td>2.4 µm</td>
<td>1090 µΩ-cm</td>
<td>146 ppm/°C</td>
</tr>
<tr>
<td>ZrON</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Film Testing in Progress</td>
</tr>
</tbody>
</table>

- All films fabricated using a 3” unbalanced magnetron source at 125W RF
- All films fabricated with 2 mTorr pressure
- All films patterned & vacuum annealed at 600°C
- TCR tested using a 4-wire method to 200°C
- N-doping lowered TCR, but not low enough
- Examining O₂ incorporation
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
Future Directions

Continuing High Temperature Sensor and Electronics Branch Activities:

• Aging Aircraft
  – Hot Section Durability
  – Energy Harvesting

• IVHM
  – High Temperature Pressure
  – High Temperature Electronics Wireless

• Supersonics
  – Emission Measurement and Reduction

• Continued Interaction with AFRL
  – Continued Coordination of Activities
  – Continued Information Exchanged
Acknowledgements

• Craig Neslen of the Air Force Research Laboratory’s Nondestructive Evaluation (NDE) Branch (AFRL/MLLP) for support and discussions related to this work

• Kimala Laster of Sierra Lobo, Inc. supporting the Space Combustion and Microgravity Technical Branch (DRI) at NASA Glenn Research Center for the ceramic film depositions currently on-going
Researchers

Gustave C. Fralick
John D. Wrbanek

Physical Sensor Instrumentation Research
Sensors and Electronics Branch
NASA Glenn Research Center
Cleveland, Ohio

Gustave.C.Fralick@nasa.gov
John.D.Wrbanek@nasa.gov
http://www.grc.nasa.gov/WWW/sensors/PhySen/