Ultra High Temperature Thermionic Sensor

NETL Crosscutting Research Review Meeting
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HEAT Sensor Project Goal

Harsh Environment Adaptable Thermionics

• Develop sensors that measure process parameters
  – Gasifiers -- harsh fuel, oxidizer and combustion product environment
  – High Temperature (750-1600 C)
  – High Pressure (up to 1000 psi)

• Develop sensors that are wireless and self-powered
  – Generate their own energy to operate and wirelessly transmit data
  – Avoids wires that may be a reliability or inconvenience concern
HEAT Sensor Project Concept

- Use Thermionic Materials as Sensors
  - Heat induced flow of electrons from a metal surface
  - Thermionic emissions occur at high temperature without need for external heater source

- Thermionic Technology
  - Diodes, Triodes, Tetrodes, etc…
  - Amplifier, Oscillators, Power Generation

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The 1946 ENIAC computer used 17,468 vacuum tubes and consumed 150 kW of power.

70-watt tube audio amplifier selling for US$2,680[31] in 2011, about 10 times the price of a comparable model using transistors.[32]
HEATS Platform Project Development

- Model and Pattern Thin Film Thermionic Layers
- Develop Experimental System
- Characterize Temperature Thermionic Response
- Develop High Temperature Hermetic Package
- Develop Subsystems for Thermionic Sensor Al2O3 Brick Package

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Vacuum Tubes</th>
<th>HEATS Platform</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum level</td>
<td>Similar</td>
<td>Similar</td>
</tr>
<tr>
<td>Package -- hermetic sealing temp</td>
<td>&lt;300 C</td>
<td>&gt; 1300 C</td>
</tr>
<tr>
<td>Package -- operating temp</td>
<td>&lt;300 C</td>
<td>&gt; 1300 C</td>
</tr>
<tr>
<td>Package dimensions</td>
<td>~ cm</td>
<td>~ mm to cm</td>
</tr>
</tbody>
</table>
HEAT Novel Sensor Brick Package

- High Temperature Wireless SiC Circuit and Tests
- Power Generation Designs
- Pressure Sensor Design
- Temperature Sensor in Hermetic Package

Thermionic Power Generation in Series to Create Proper Voltage
SiC Wireless Circuit

• Normal wireless is not practical due to extremely high electrical attenuation of metal chamber to normal RF signals
• Utilize a magnetic coupling that is capable of overcoming the eddy currents and counter fields generated within the metal plate
• Generate an Electro-Magnetic simulation of the conditions in the chamber

External view of 1” thick alloy 800 enclosure with 8 inch copper planar spiral coil, 10 mil thick, 200 mil wide trace
The results indicate that the 8” diameter planar coils are capable of providing a link with 58 dB of attenuation at 20 kHz.

This indicates that a 30 dBm signal would be received at -28 dBm which is a reasonable level to be detected and processed.
• Enclosed alloy 800 steel box with 1” thick walls. Chamber isolation was >120 dB.
• A small signal 15 mW(12dBm) at 36 MHz is injected into the outside coil and is picked up by the matching internal coil.
• The signal of -94 dBm is readily detected by the spectrum analyzer.
• 300 C continuous use
• Silicon Carbide MOSFET based oscillator circuit
• Ceramic capacitors
• Ceramawire connections and air core wound inductors
• The external circuit would use conventional electronics
• Power provided by thermionic generator
• Sensor transducer controls frequency modulation
Thermionic Power Generation Concept

Alumina Brick Vacuum Package

Cold Wall Side (300°C)

SiC Wireless Circuit

Vacuum Chamber

Tungsten Heat Transfer Rod

Temperature Sensor

Pressure Sensor

Hot Side (1300 to 1600°C)

Thermionic Power Generation in Series to Create Proper Voltage
Thermal Modeling – 2D

- Surface Temperature (K)
  - 1800k
  - 290mm
  - Emissivity = 0.1
  - Tungsten
  - Emissivity = 0.9
  - 600k

- Surface Temperature (K)
  - T1 = 1132k
  - 40mm
  - T2 = 632k
  - Delta T = 500k
Thermal Modeling – 2D

T1 = 1211K

T2 = 646K

ΔT = 565K
Parameter Study – Bar Length

Optimal Point

Temperature difference across the electrodes (K) vs. L_bar (mm)
Cathode/Anode Series Interconnect
Parameter study on the gold interconnect/electrode area ratio

![Graph showing the relationship between gold interconnect/electrode area ratio and max temperature difference (T). The graph includes three assumptions: very conservative, reasonable, and aggressive but possible.](image)
Thermal Model – 3D Verification

Surface Temperature (K)

T1 = 1112K

T2 = 644K

ΔT = 468K
# Thermionic Generation Design

<table>
<thead>
<tr>
<th></th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tungsten bar</td>
<td>No</td>
<td>100mm</td>
<td>No</td>
</tr>
<tr>
<td>Interconnect-to-electrode area ratio</td>
<td>0.0014</td>
<td>0.0014</td>
<td>0.0056</td>
</tr>
<tr>
<td>Delta T</td>
<td>480 K</td>
<td>458 K</td>
<td>468 K</td>
</tr>
<tr>
<td>Counter part in 2D</td>
<td>~475K</td>
<td>NA</td>
<td>~ 415K</td>
</tr>
</tbody>
</table>

10 X 500um X 500um gold bump over 4 CMX4CM = 0.0016
Pressure Sensor

Simulation

Differential Anode Current vs Pressure

- 800 deg C
- 1000 deg C
- 1200 deg C
- 1400 deg C
- 1600 deg C

Pressure (psi)
**Recommended Design for Pressure Sensing**

Max Deflection @ \( r=0 \) and 1 atm \( \rightarrow W_{1\text{atm}} \)

Membrane Radius \( \rightarrow r_{\text{membrane}} \)

Max Deflection @ \( r = 0 \) \( \rightarrow W_{\text{max}} \)

Stopper Radius \( \rightarrow r_{\text{stopper}} \)

<table>
<thead>
<tr>
<th>Thickness (um)</th>
<th>Radius (cm)</th>
<th>Stopper Radius (cm)</th>
<th>Calculated Max Deflection @ ( r=0 ) and 1 atm (um)</th>
<th>Calculated Max Deflection @ ( r=0 ) and 100 atm (um)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>2.5</td>
<td>1.0</td>
<td>35</td>
<td>561</td>
</tr>
<tr>
<td>400</td>
<td>3.0</td>
<td>1.5</td>
<td>21</td>
<td>532</td>
</tr>
<tr>
<td>500</td>
<td>4.5</td>
<td>2.0</td>
<td>25</td>
<td>485</td>
</tr>
<tr>
<td>1000</td>
<td>15.0</td>
<td>6.0</td>
<td>34</td>
<td>545</td>
</tr>
</tbody>
</table>
Hermeticity Testing

- Used single layer alumina plate to minimize plate curvature during curing
- Soaked for over 2500 hrs at 1300C.
- Cycled to room temperature 3x and repeatedly cycled between 1000C to 1300C.
- Outgassing was further reduced by an high temperature cycle of 1400C.

![Graph showing hermeticity test results using PARC paste formulation at 1300C](image)
Test Apparatus

- Converted bell jar evaporator for thermionic testing
- Background pressure – 1e-7 mbar vs 1e-4 mbar for MTI furnace
- Temperature control up to 1500C
$J = A_G T^2 e^{\frac{W}{kT}}$

**Measured vs. Computed Device Current**

Cathode area = 1.77 cm$^2$, gap = 0.15 cm

Current limited by emission (Richardson-Dushman).

Fitted values: $W_f = 2.866$ eV, const = 39 A/cm$^2$/K$^2$
Hermetic Thermionic Package

• Process develop hermetic package independently
• Process develop thermionic cathode and anode
• Integrate both processes
• What can go wrong?
## Process Development

<table>
<thead>
<tr>
<th>Issue</th>
<th>Observation</th>
<th>Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Background Oxygen</strong></td>
<td>LaB6 Oxidation (EDX)</td>
<td>Zr Wire Getters</td>
</tr>
<tr>
<td>Al203 Volatility &gt;1400 °C</td>
<td>Al203 deposition on LaB6 (EDX analysis)</td>
<td>1. &lt;1400 °C Lower Seal Temp</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. &gt;1400 °C Zr sputtered interior surface</td>
</tr>
<tr>
<td>Thermal variation in vacuum oven</td>
<td>Stress cracks in glueline preventing hermetic seal</td>
<td>1. Thicker substrates</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Stability rings</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3. Smaller footprints</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4. Slower thermal rise and descent (3 full days for a single run)</td>
</tr>
<tr>
<td>Interconnect opens</td>
<td>Pt wire / LaB6 interface degradation</td>
<td>Sputtered Tungsten Bridge</td>
</tr>
</tbody>
</table>
Hermetic Thermionic Package Process

Interconnect Processing Steps:
1. Deposit/pattern Pt thin film under spacer ring
2. Deposit/pattern Tungsten thin film to connect Pt with LaB6 in the inside of the package (since Boron degrades Pt under high temperature)
3. Connect Zr wire to the Pt thin film outside the spacer ring

Cathode (bottom plate)  Anode (top plate)
Hermetically Packaged Thermionic Sensor

Measured vs. computed device current

Current limited either by space charge (Child-Langmuir) or emission (Richardson-Dushman).
Fitted values: $W_f = 3.7$ eV, $\text{const} = 120 \text{ A/cm}^2/\text{K}^2$

Measured on 20160415
Cathode area = 1.13 cm$^2$, gap = 0.1 cm
## Key Milestone Status

<table>
<thead>
<tr>
<th>Product</th>
<th>Current Status</th>
<th>Future Opportunities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hermetic Seal Package</td>
<td>1400 °C stable process</td>
<td>Increase to 1500 °C</td>
</tr>
<tr>
<td>Temperature Sensor</td>
<td>1400 °C process +/- 2% repeatability</td>
<td>Improve repeatability</td>
</tr>
<tr>
<td>(active pumping)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature Sensor</td>
<td>1300 °C process</td>
<td>Increase repeatability and temp to 1500 °C</td>
</tr>
<tr>
<td>(hermetic package)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure Sensor</td>
<td>Dimensional Design Modeled</td>
<td>Build structure using new vacuum oven apparatus</td>
</tr>
<tr>
<td>Wireles Circuit</td>
<td>Modeled, Fabricated, and Tested Wireless Design</td>
<td>Test at 300 °C and integrate with system</td>
</tr>
<tr>
<td>Thermionic Generator</td>
<td>Designed, modeled, and testing 1st prototype</td>
<td>Extensive process development needed</td>
</tr>
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