Ultra High Temperature Thermionic Sensor

parc
A Xerox Company

NETL Crosscutting Research Review Meeting

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Program Manager: Barbara Carney

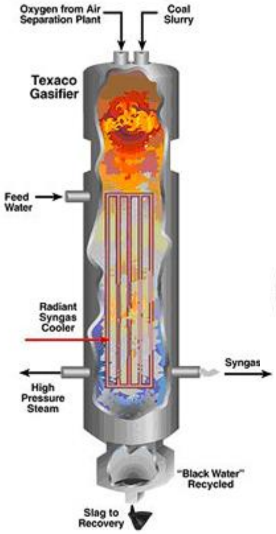
HEAT Sensor Project Goal

Harsh **E**nvironment **A**daptable **T**hermionics

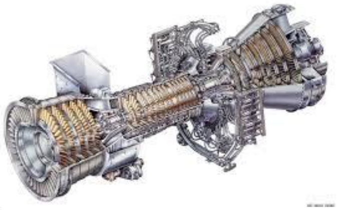
- **Develop sensors that measure process parameters**
  - Gasifiers -- harsh fuel, oxidizer and combustion product environment
  - High Temperature (750-1600 C)
  - High Pressure (up to 1000 psi)

- **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

Source: GE Energy



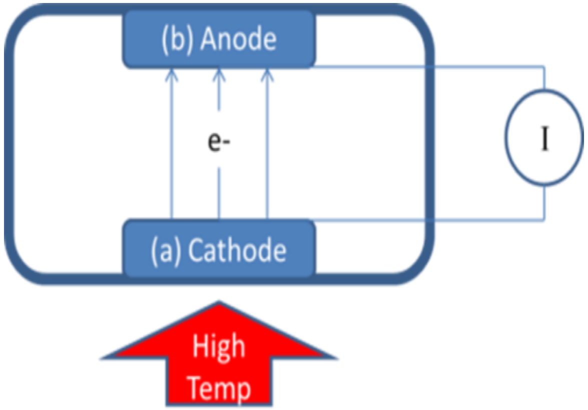
Source: GE Energy

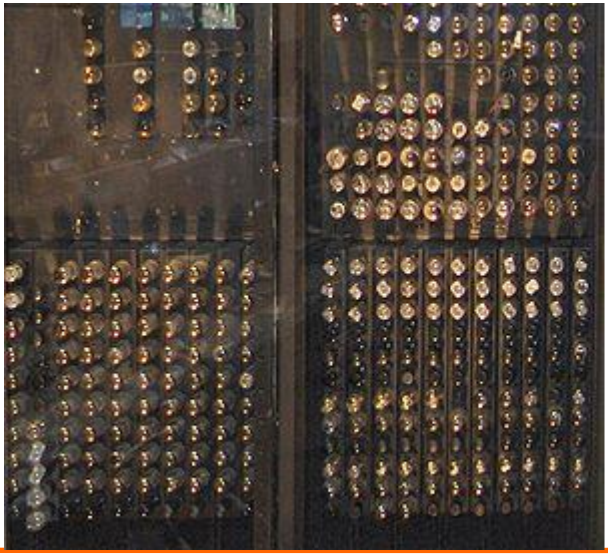


Thermocouple protection system for gasifiers (NETL website)

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





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]

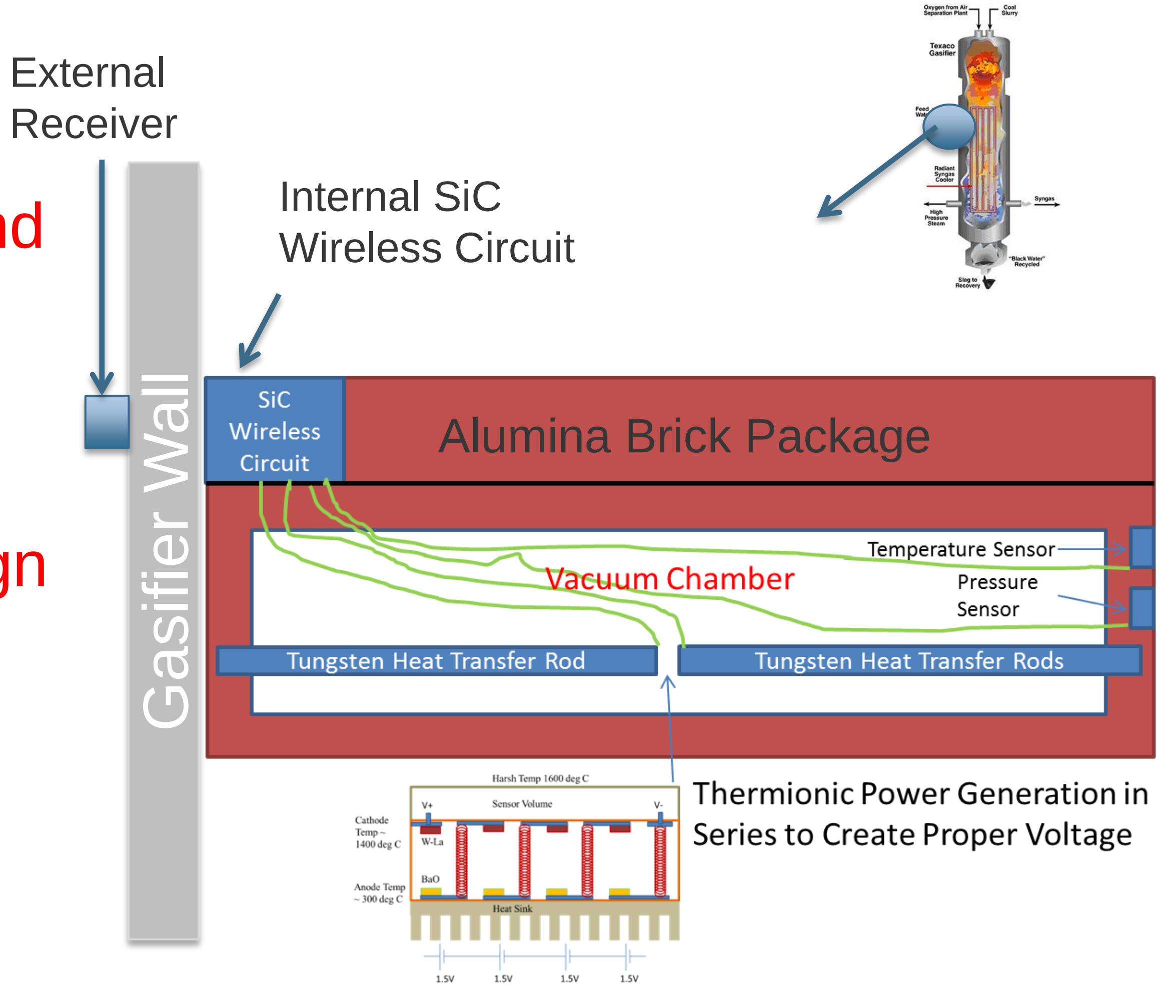
HEATS Platform Project Development

- 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**

Characteristics	Vacuum Tubes	HEATS Platform
Vacuum level	Similar	Similar
Package -- hermetic sealing temperature	<300 C	> 1300 C
Package -- operating temperature	<300 C	> 1300 C
Package dimensions	~ cm	~ mm to cm

HEAT Novel Sensor Brick Package

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



External Receiver

Gasifier Wall

Internal SiC Wireless Circuit

SiC Wireless Circuit

Alumina Brick Package

Vacuum Chamber

Temperature Sensor

Pressure Sensor

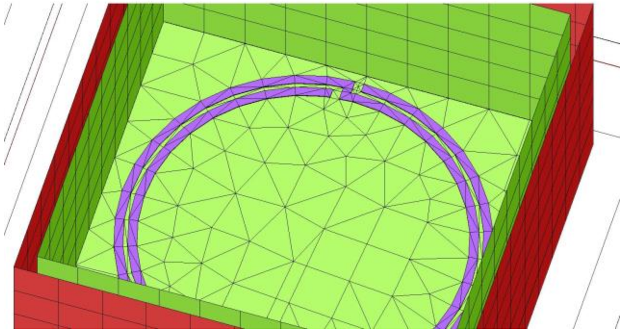
Tungsten Heat Transfer Rod

Tungsten Heat Transfer Rods

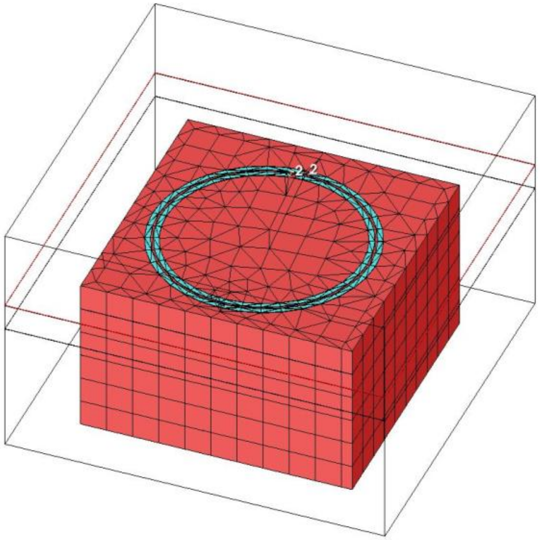
Thermionic Power Generation in Series to Create Proper Voltage

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

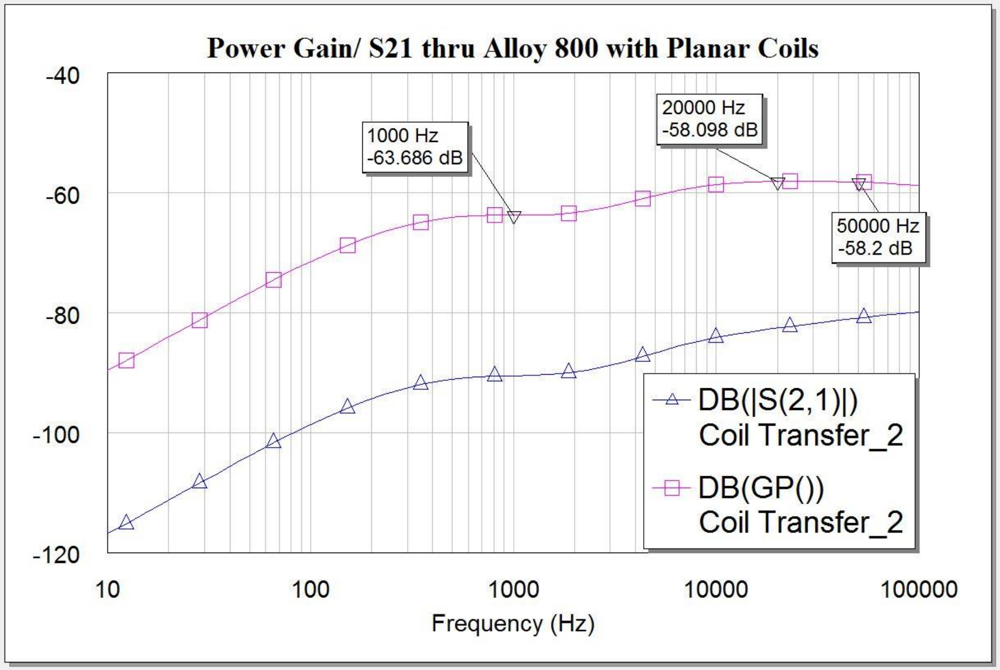


External view of 1” thick alloy 800 enclosure with 8 inch copper planar spiral coil, 10 mil thick, 200 mil wide trace



SiC Wireless Circuit – Electromagnetic Model

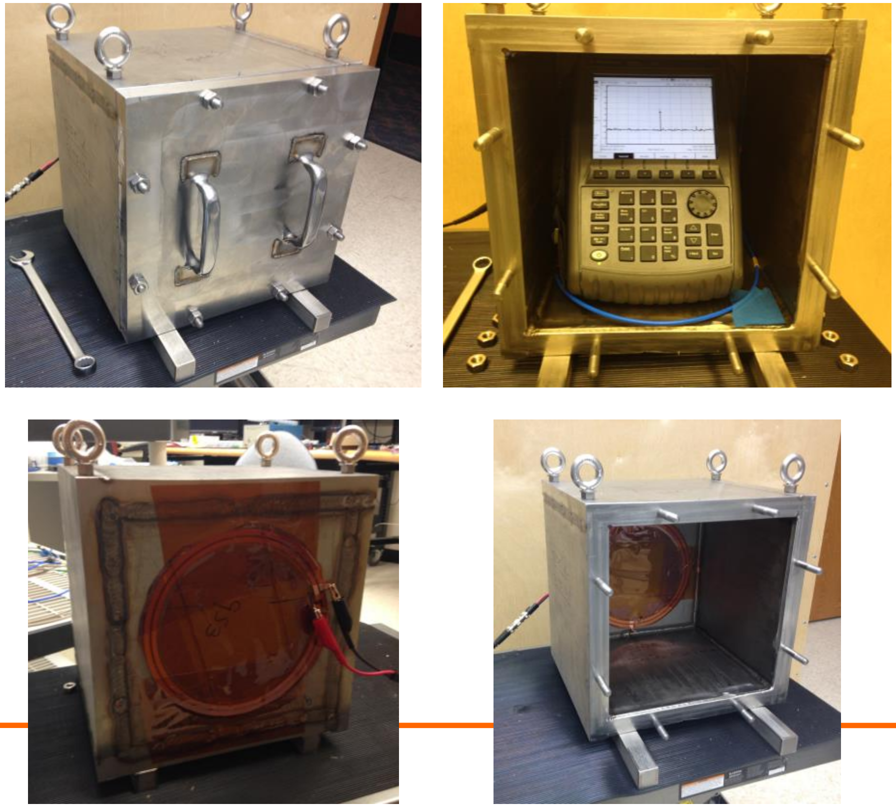
Microwave Office with Axiem Solver Results

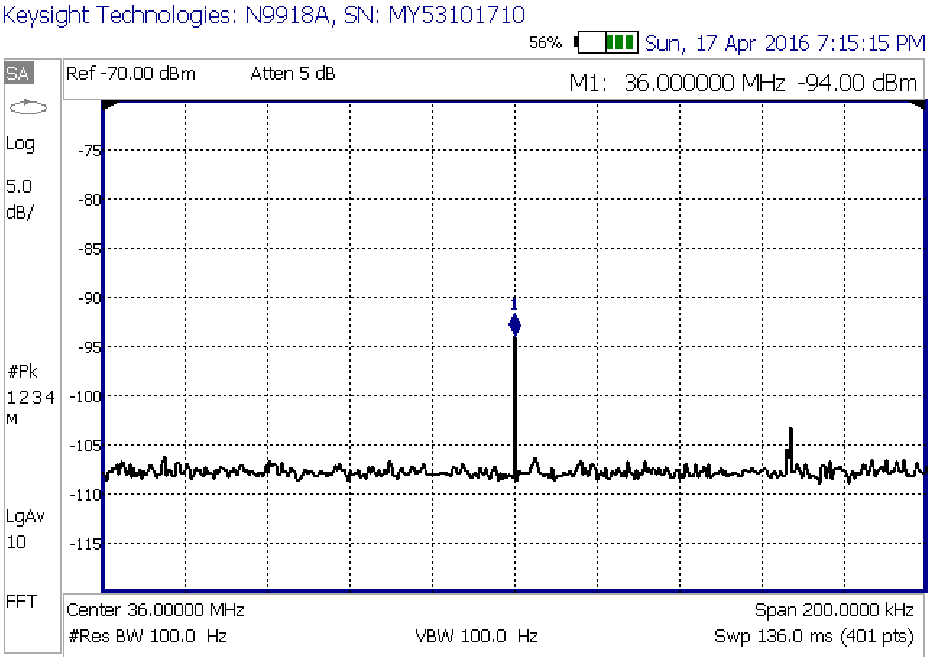


- The results indicate that the 8” diameter planar coils are capable of providing a link with 58 dB of attenuation at 20 kHz
- This indicates that a 30 dBm signal would be received at -28 dBm which is a reasonable level to be detected and processed

SiC High Temperature Wireless Test

- 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.





Keysight Technologies: N9918A, SN: MY53101710

56% Sun, 17 Apr 2016 7:15:15 PM

Ref -70.00 dBm Atten 5 dB

M1: 36.000000 MHz -94.00 dBm

Log 5.0 dB/

#Pk 1234 M

LgAv 10

FFT

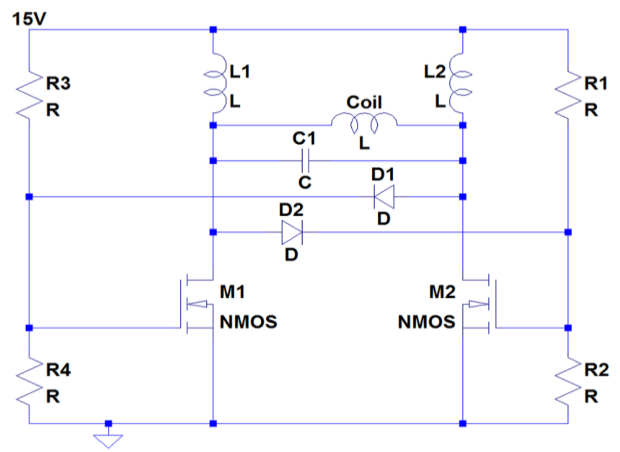
Center 36.00000 MHz Span 200.0000 kHz

#Res BW 100.0 Hz VBW 100.0 Hz Swp 136.0 ms (401 pts)

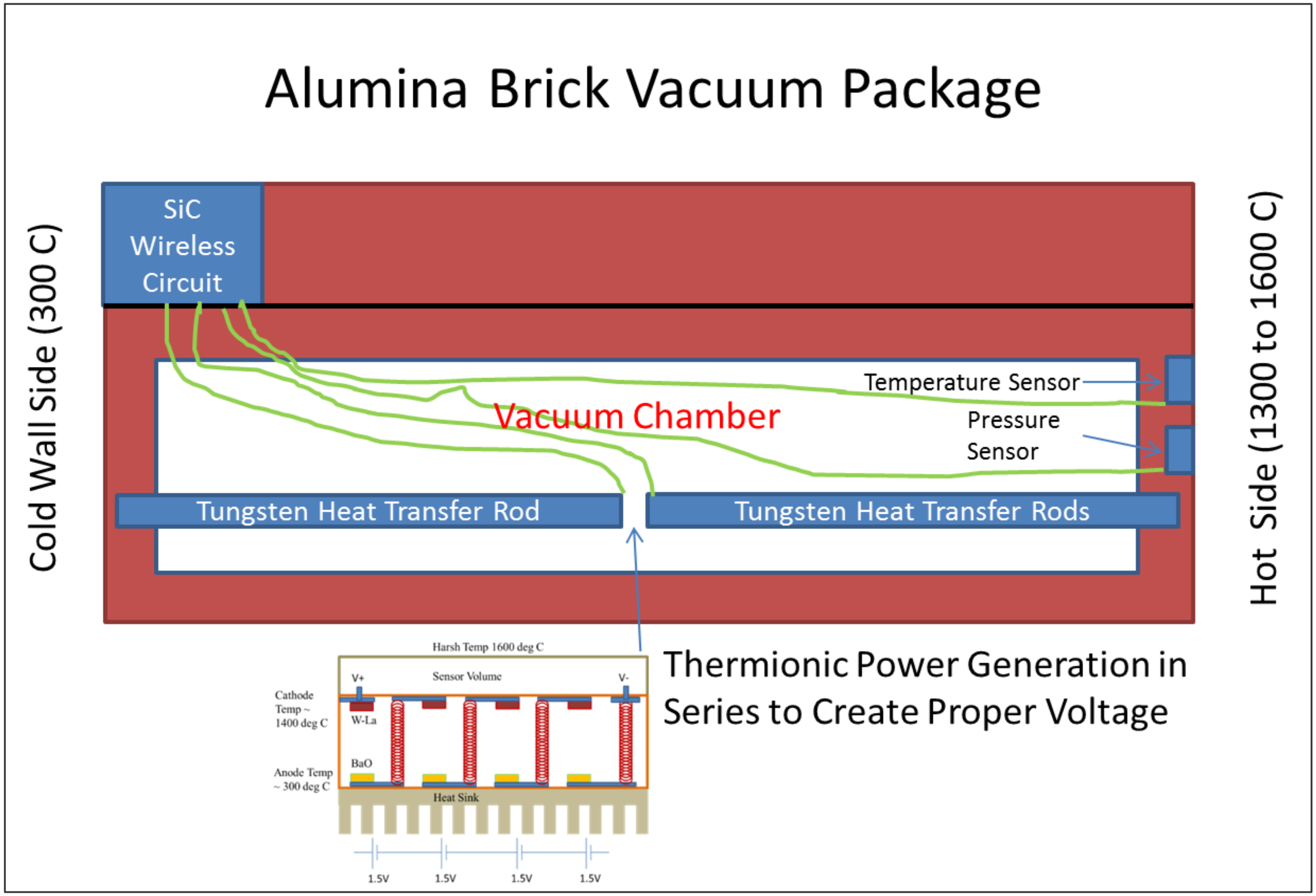
SiC Wireless Circuit

- 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

SiC Mosfet Oscillator

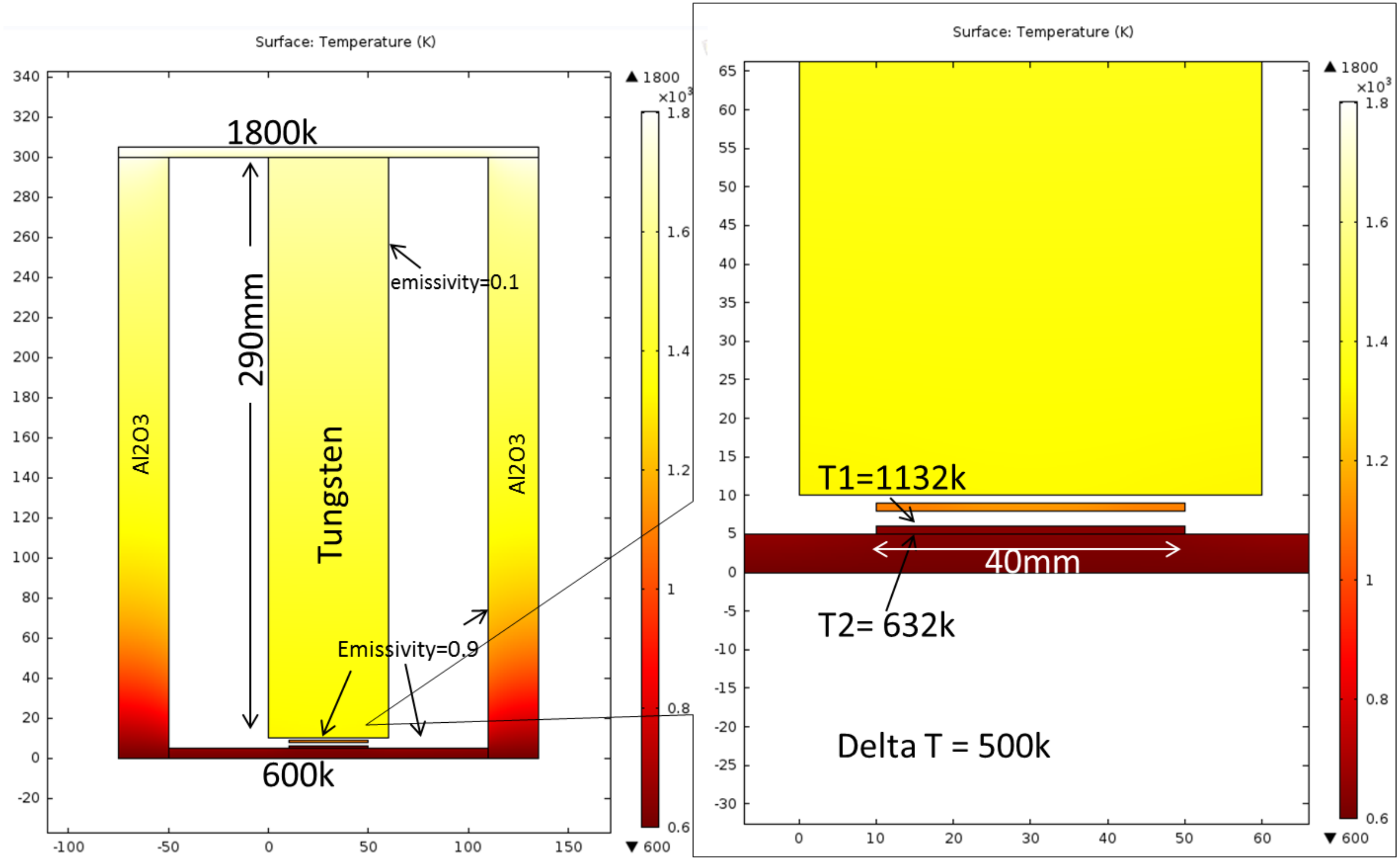


Thermionic Power Generation Concept

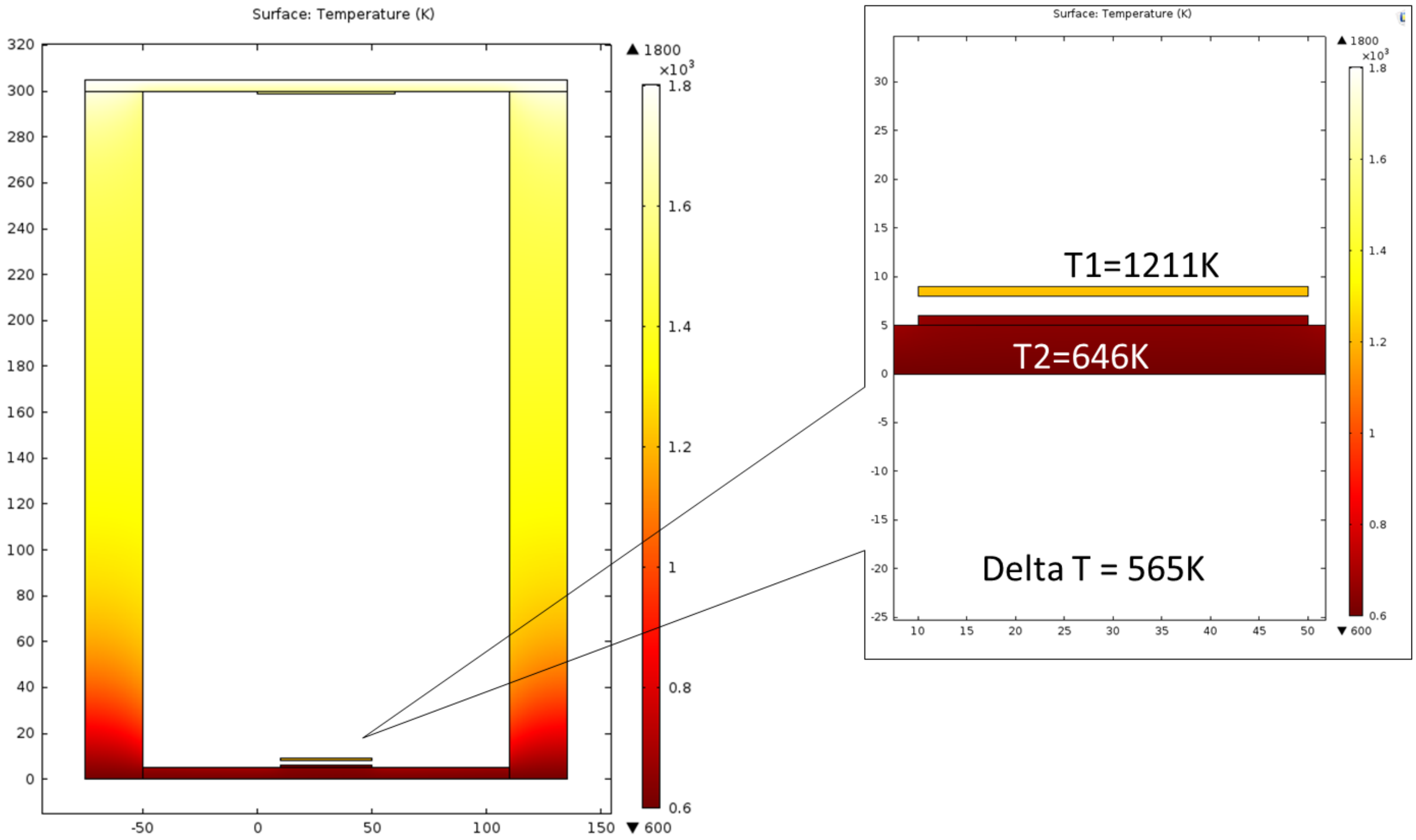


Thermionic Power Generation in Series to Create Proper Voltage

Thermal Modeling – 2D



Thermal Modeling – 2D

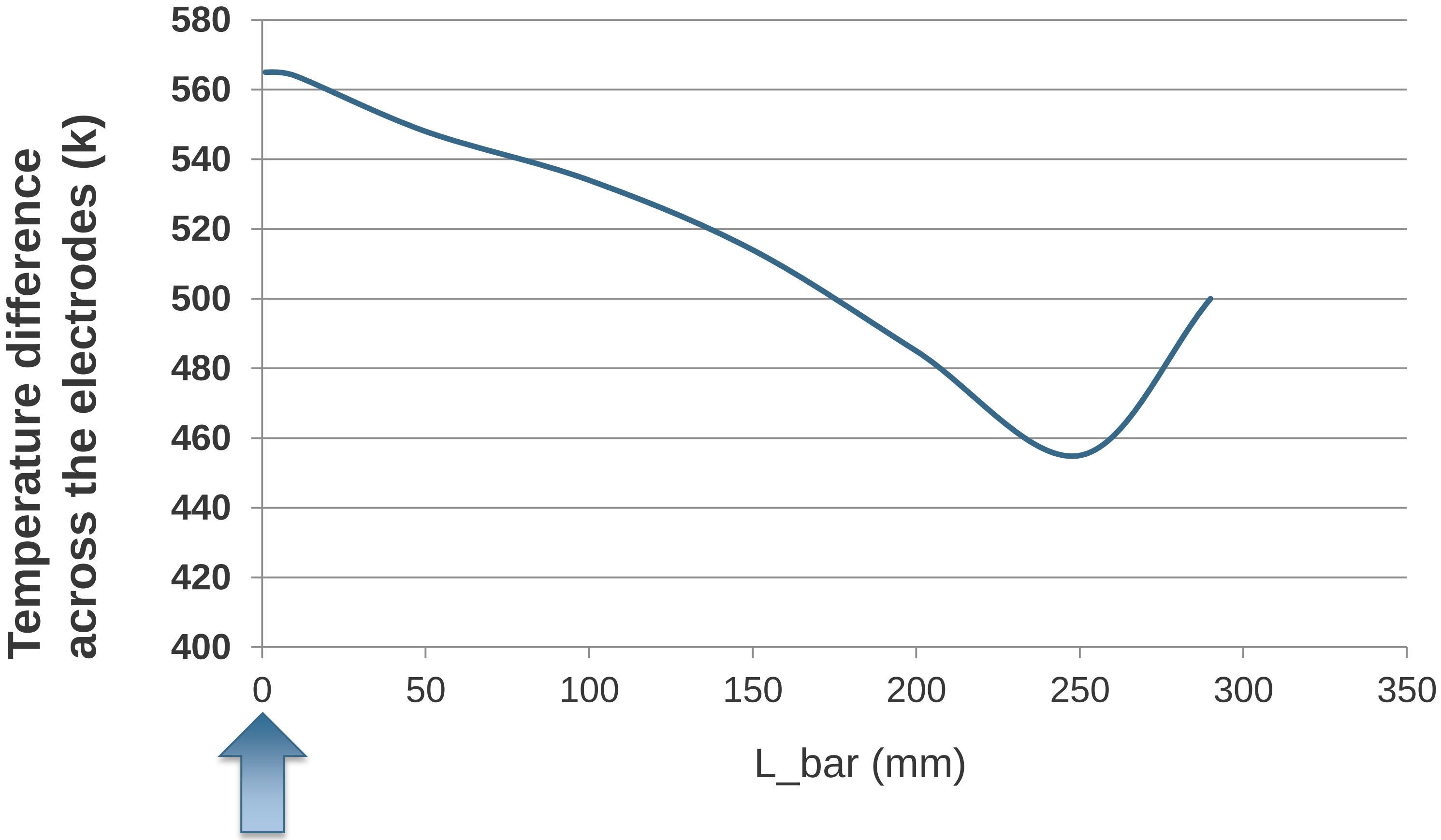


T1=1211K

T2=646K

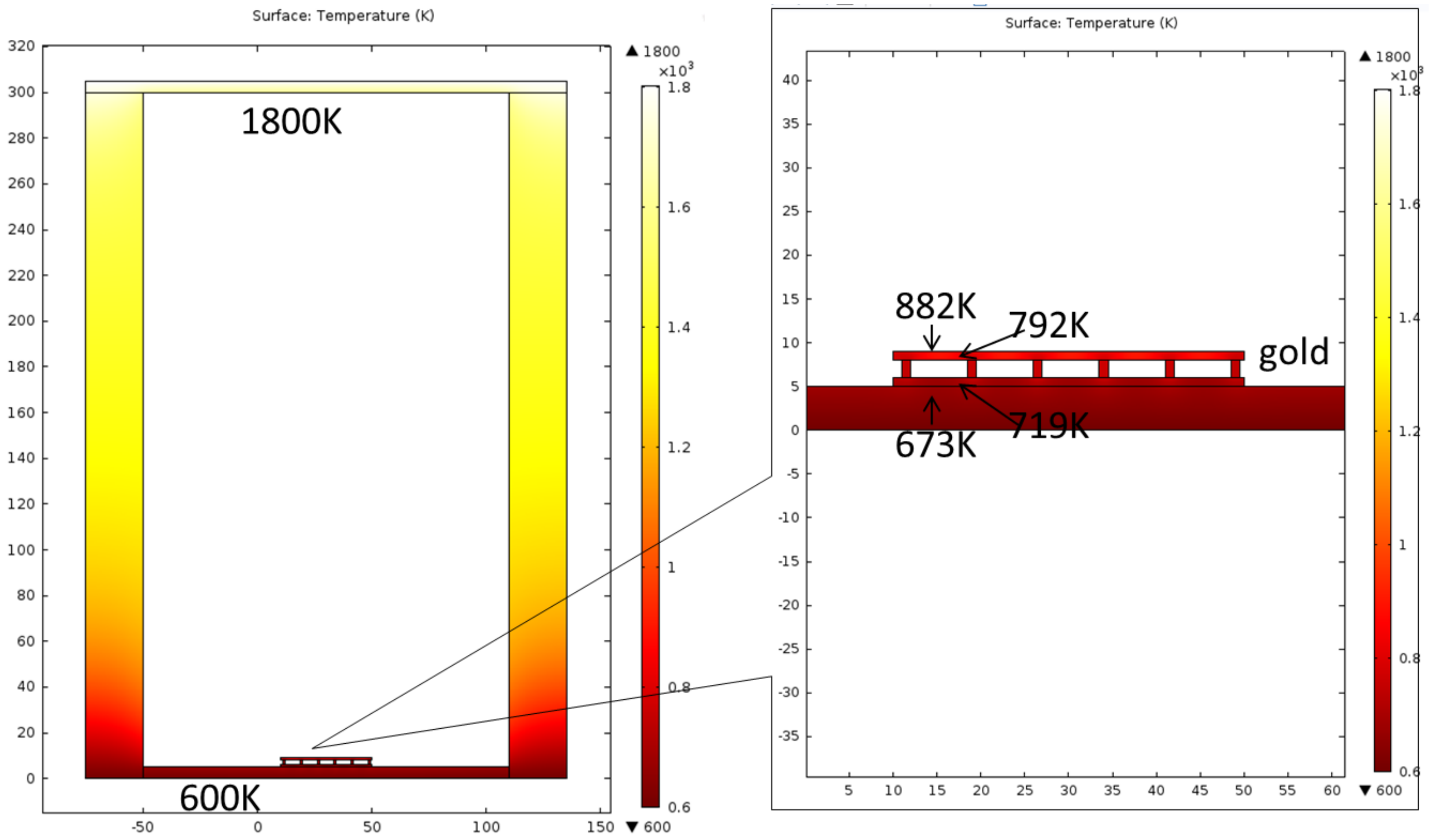
Delta T = 565K

Parameter Study – Bar Length

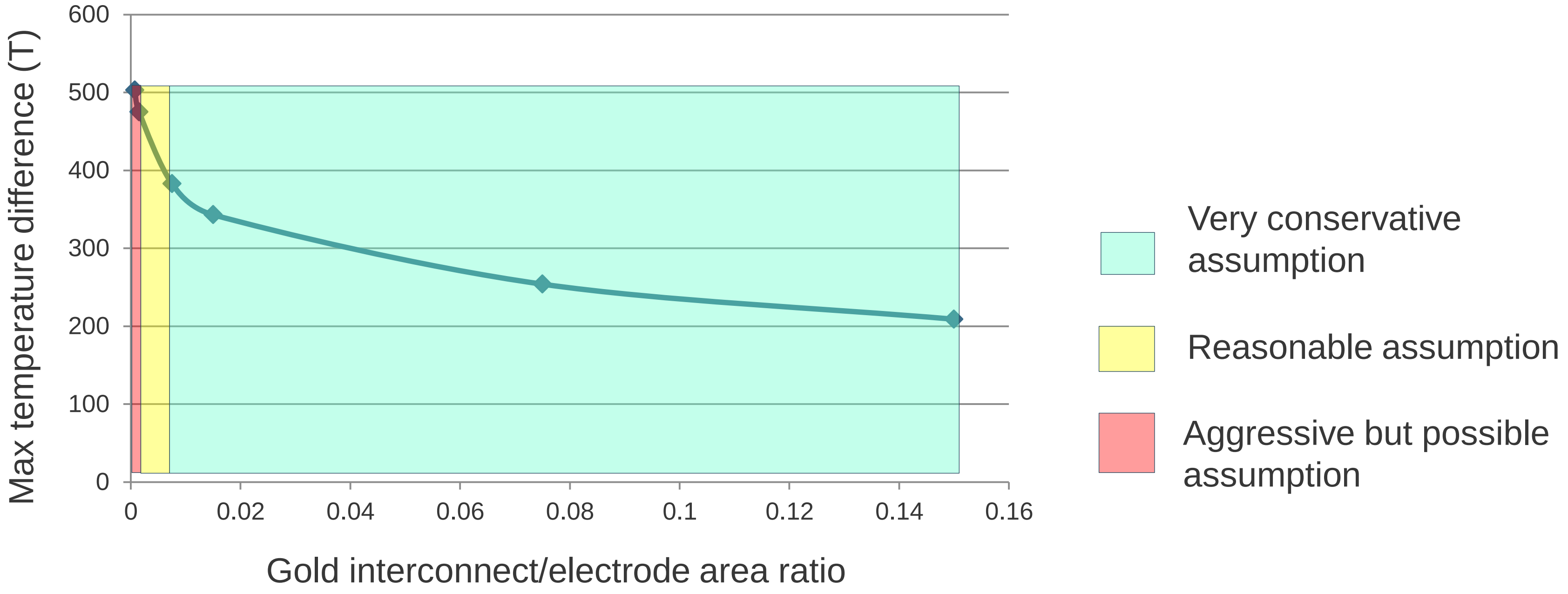


Optimal Point

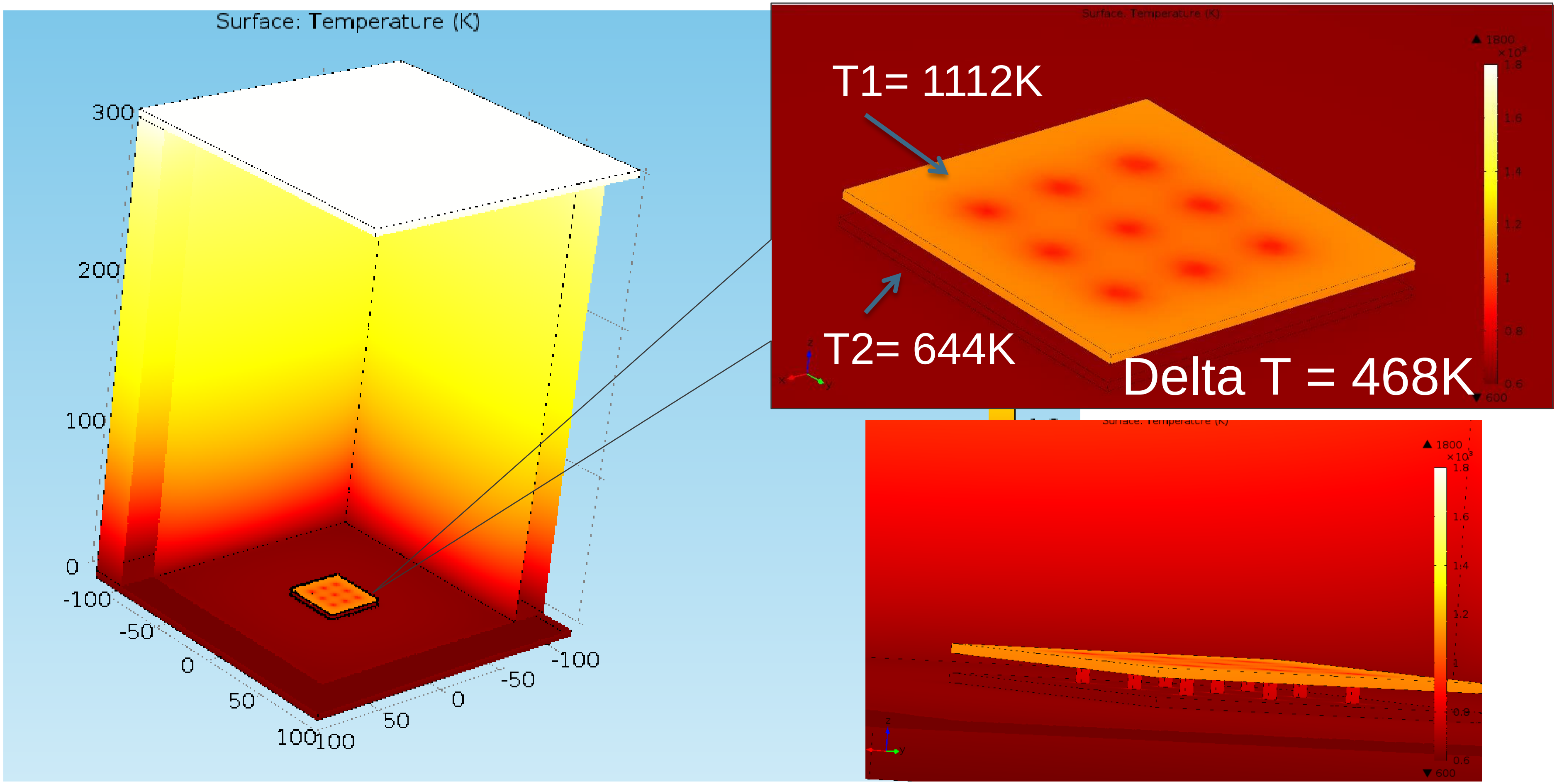
Cathode/Anode Series Interconnect



Parameter study on the gold interconnect/electrode area ratio



Thermal Model – 3D Verification



T1= 1112K

T2= 644K

Delta T = 468K

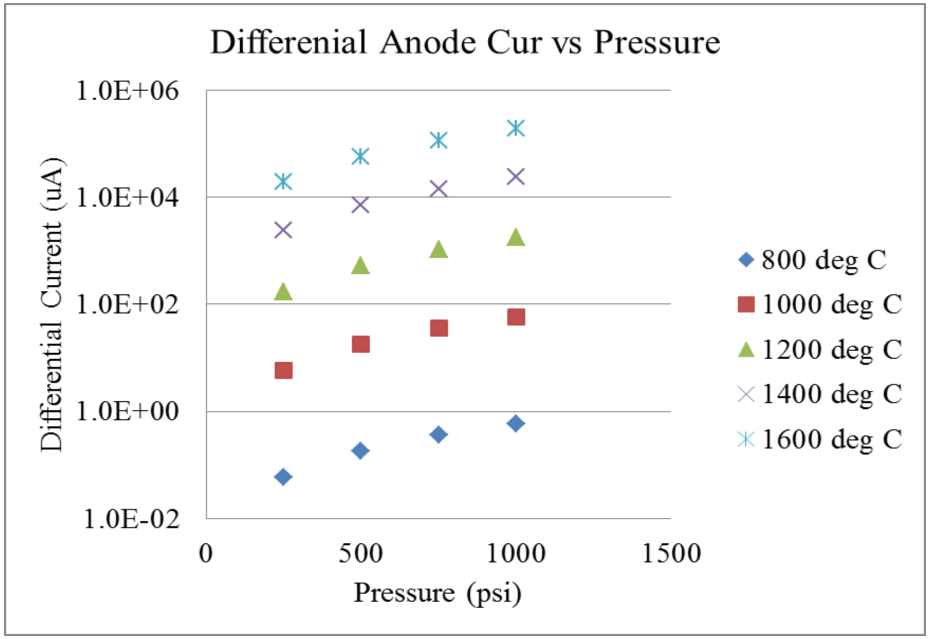
Thermionic Generation Design

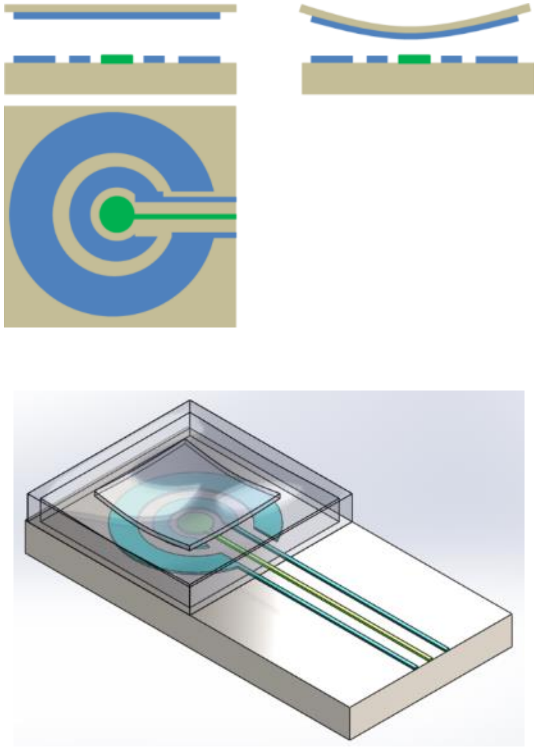
	Case 1	Case 2	Case 3
Tungsten bar	No	100mm	No
Interconnect-to-electrode area ratio	0.0014	0.0014	0.0056
Delta T	480 K	458 K	468 K
Counter part in 2D	~475K	NA	~ 415K

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

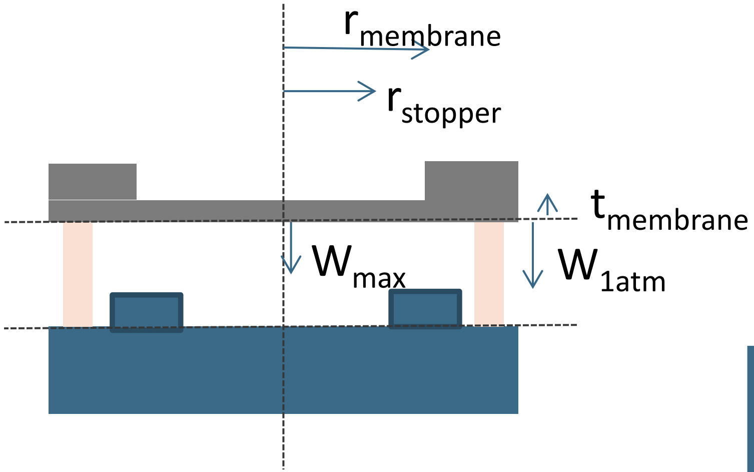
Pressure Sensor

Simulation





Recommended Design for Pressure Sensing

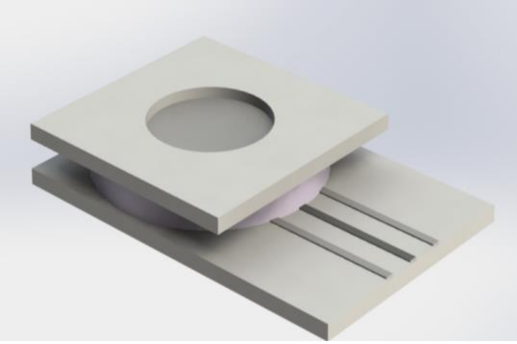


Max Deflection @ r=0 and 1 atm → W_{1atm}

Membrane Radius →$r_{membrane}$

Max Deflection @ r = 0 → W_{max}

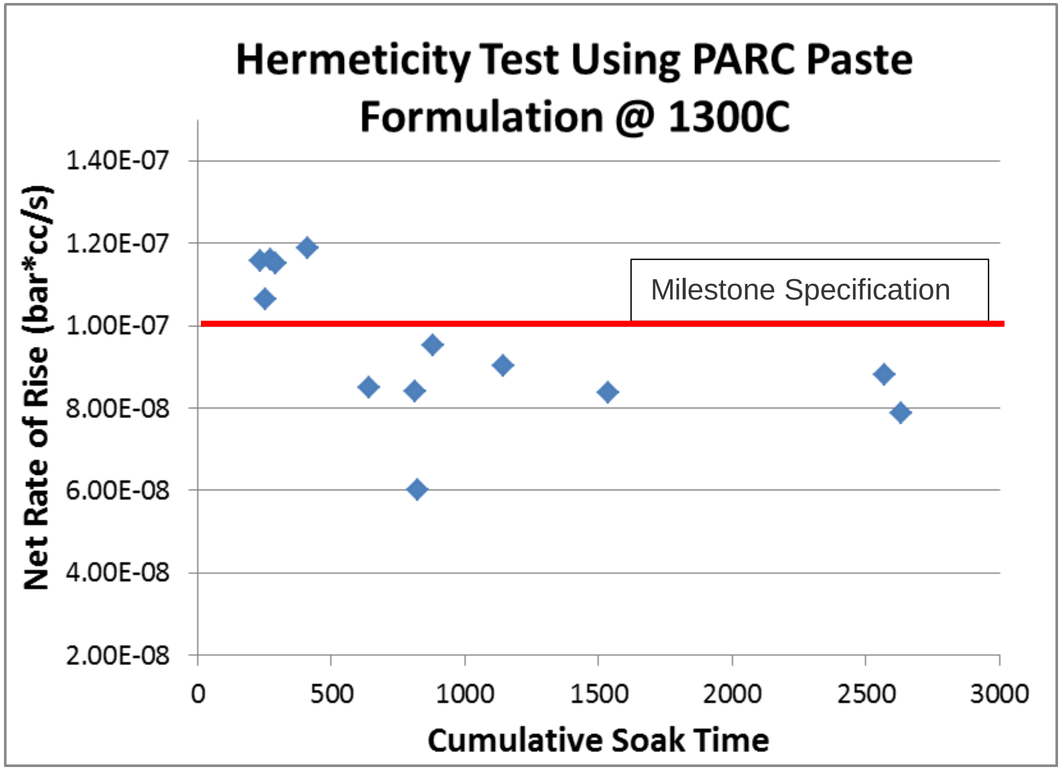
Stopper Radius → $r_{stopper}$



Thickness (um)	Radius (cm)	Stopper Radius (cm)	Calculated Max Deflection @ r=0 and 1 atm (um)	Calculated Max Deflection @ r=0 and 100 atm (um)
300	2.5	1.0	35	561
400	3.0	1.5	21	532
500	4.5	2.0	25	485
1000	15.0	6.0	34	545

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.



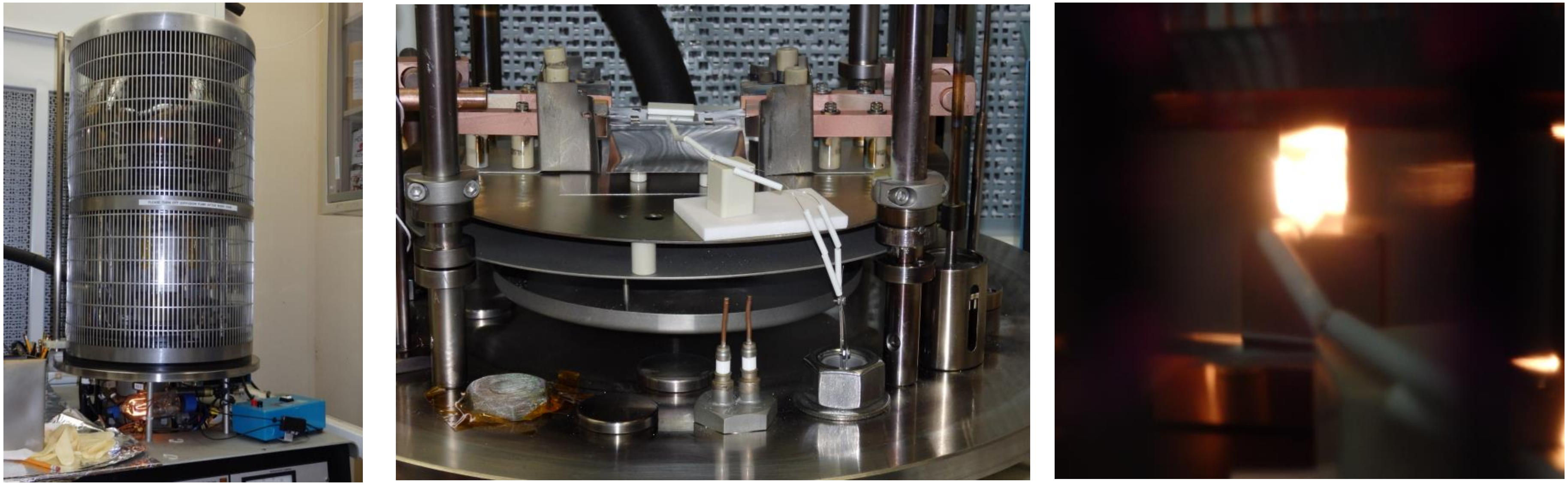
Firing in furnace #2

After firing, can see that some of sealant material flowed

Sample 20140910-A

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

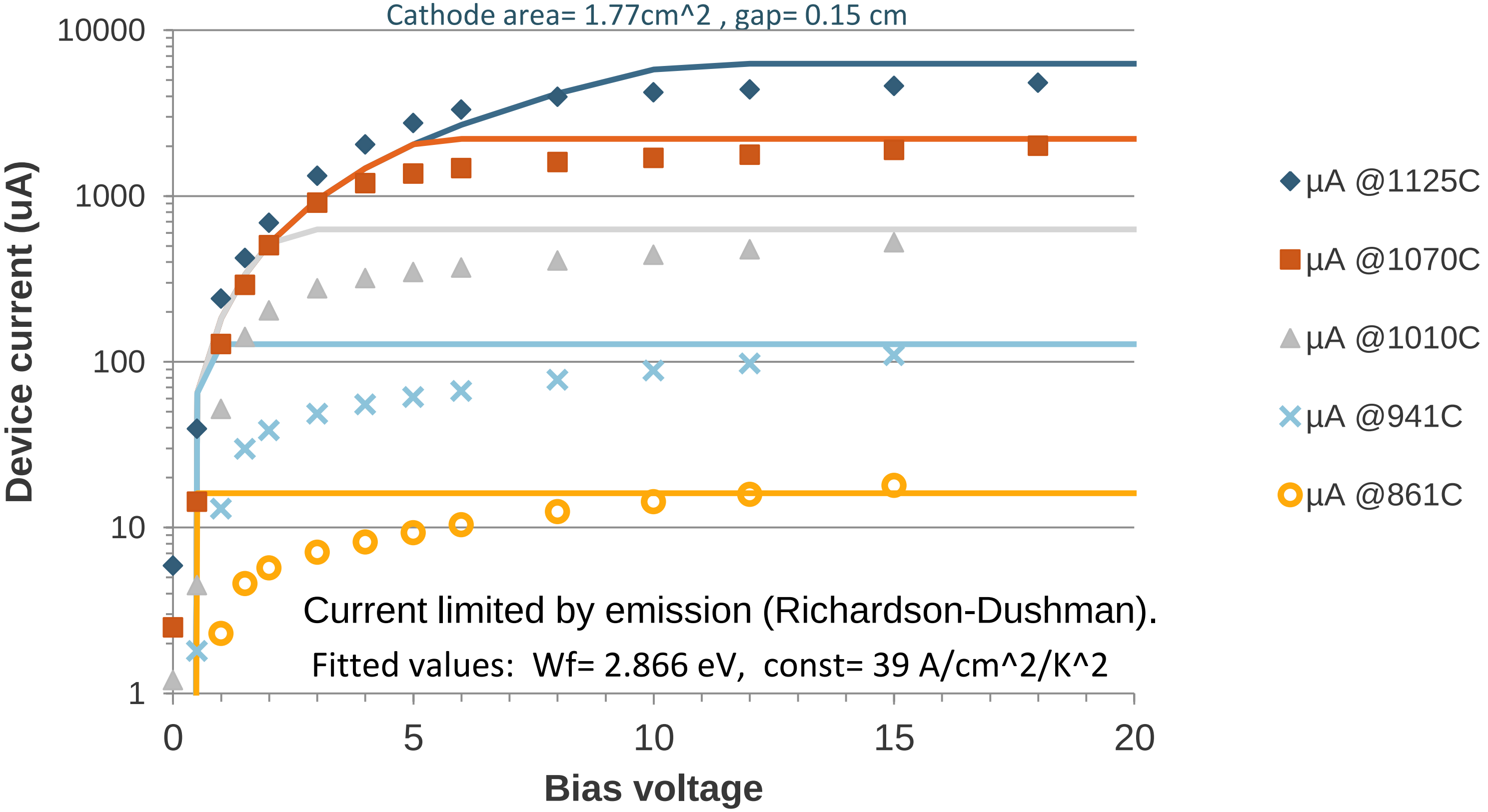


Data – Theory vs Actual (no package)

$$J = A_G T^2 e^{\frac{-W}{kT}}$$

Measured vs. Computed Device Current

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



Current limited by emission (Richardson-Dushman).

Fitted values: Wf= 2.866 eV, const= 39 A/cm^2/K^2

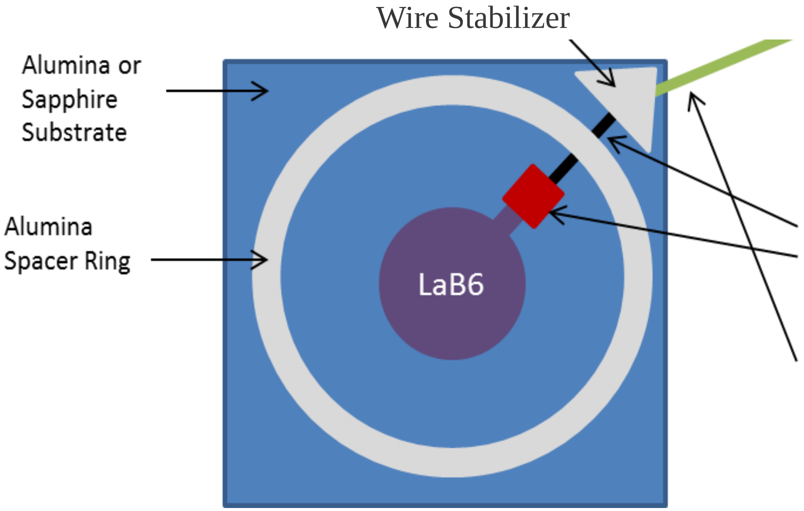
Hermetic Thermionic Package

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

Process Development

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

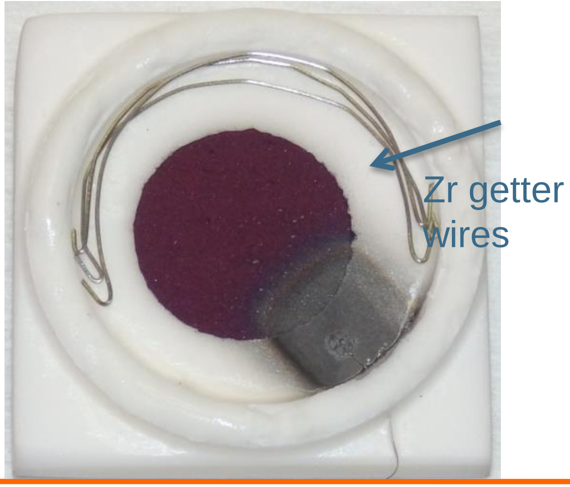
Hermetic Thermionic Package Process



Interconnect Processing Steps

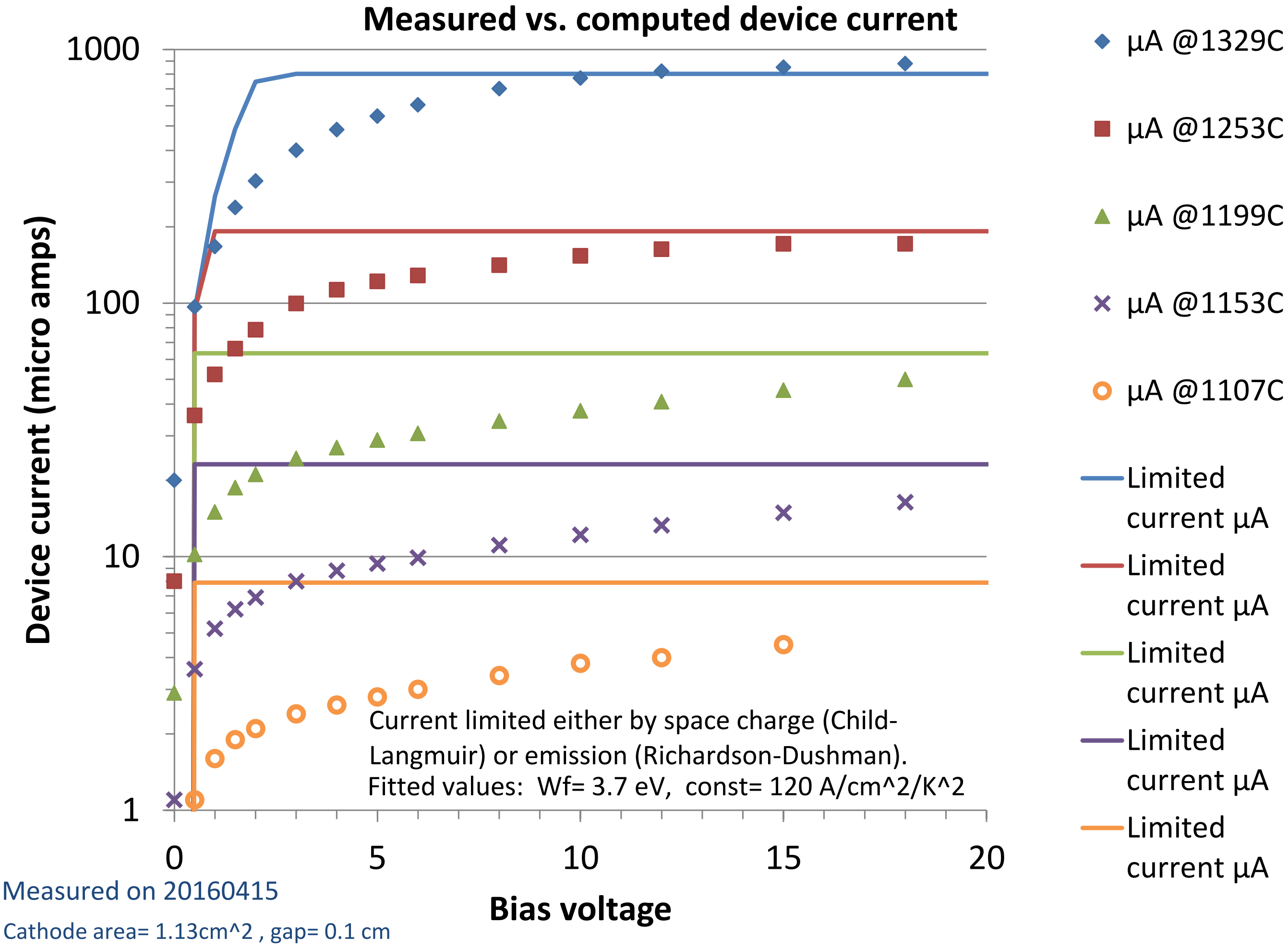
1. Deposit/pattern Pt thin film under spacer ring
2. Deposit/pattern Tungsten thin film to connect Pt with LaB6 in the inside of the package (since Boron degrades Pt under high temperature)
3. Connect Zr wire to the Pt thin film outside the spacer ring


Cathode (bottom plate)



Anode (top plate)

Hermetically Packaged Thermionic Sensor



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

Measured on 20160415

Cathode area= 1.13cm^2 , gap= 0.1 cm

Key Milestone Status

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