INTEGRATED VEHICLE
HEALTH MANAGEMENT

High Temperature Wireless Sensor Systems

Gary W. Hunter

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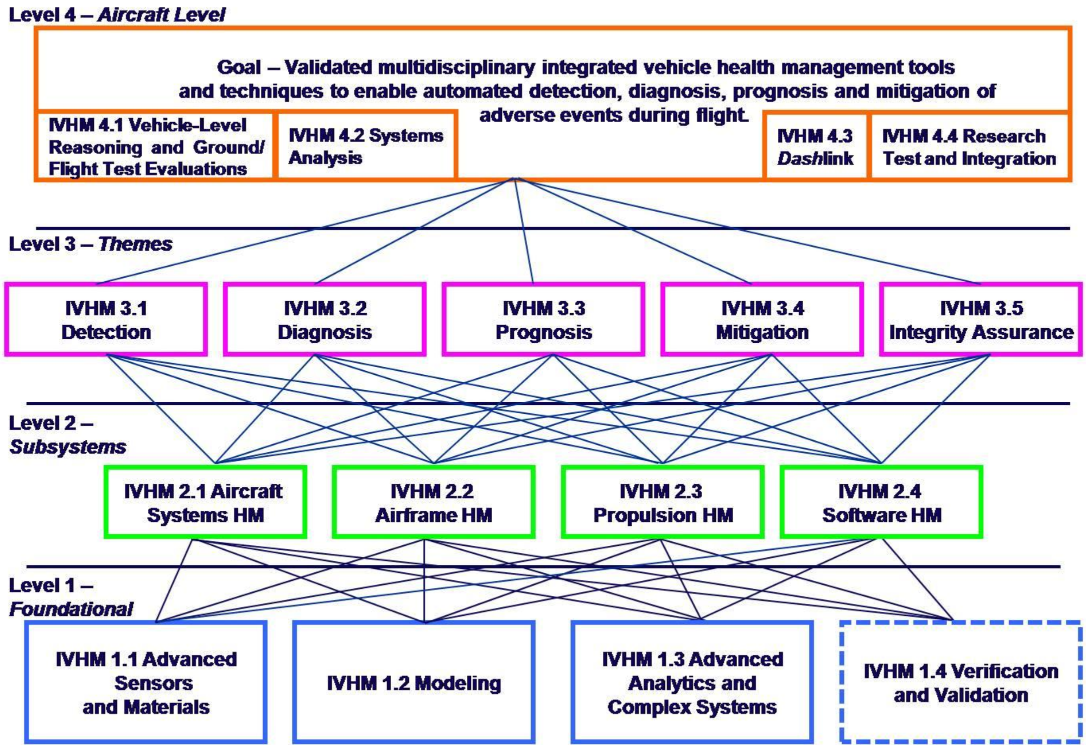
Washington D.C.

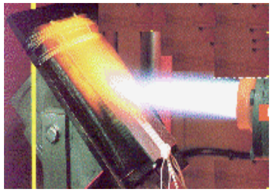
Outline

- Problem Statement
- Background
- IVHM milestones being addressed
- Approach
- Results
- Conclusions
- Future Plans

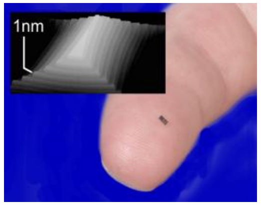


HARSH ENVIRONMENT ELECTRONICS AND SENSORS APPLICATIONS

- **NEEDS:**
  - ➢ OPERATION IN HARSH ENVIRONMENTS
  - ➢ RANGE OF PHYSICAL AND CHEMICAL MEASUREMENTS
  - ➢ INCREASE DURABILITY, DECREASE THERMAL SHIELDING, IMPROVE IN-SITU OPERATION

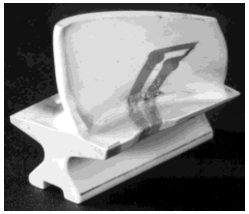


1998 R&D 100 Award



2004 R&D 100 Award

- **RESPONSE: UNIQUE RANGE OF HARSH ENVIRONMENT TECHNOLOGY AND CAPABILITIES**
  - ➢ STANDARD 500C OPERATION BY MULTIPLE SYSTEMS
  - ➢ TEMPERATURE, PRESSURE, CHEMICAL SPECIES, WIND AVAILABLE
  - ➢ HIGH TEMPERATURE ELECTRONICS TO MAKE SMART SYSTEMS

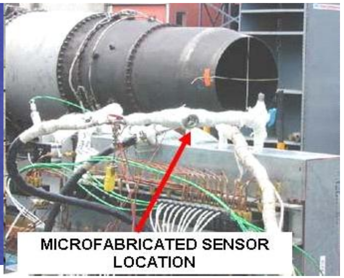


1995 R&D 100 Award

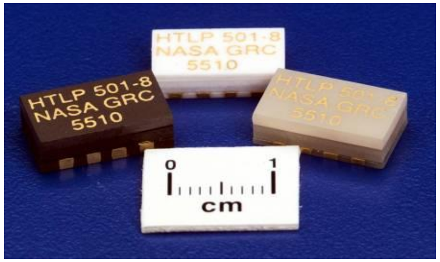
1991 R&D 100 Award

- **ENABLE EXPANDED MISSION PARAMETERS/IN-SITU MEASUREMENTS**

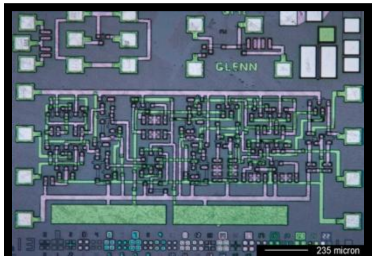
Range of Physical and Chemical Sensors for Harsh Environments



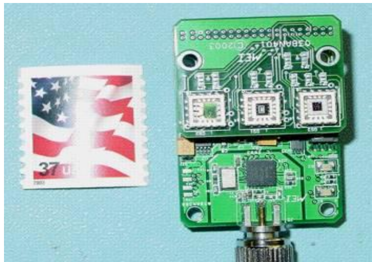
Harsh Environment Packaging



High Temperature Signal Processing and Wireless



Long Term: High Temperature "Lick and Stick" Systems



High Temperature Sensors, Electronics, And Communications

Objective:

- ➢ High Temperature Wireless Telemetry, Distributed Electronics Over A Broad Operating Range

Technical Approach:

- Integration of sensor technology with high temperature wireless communications and energy harvesting to enable a smart systems operable at high temperatures.
  - ➢ High-temperature wireless communications based on SiC electronics and rugged RF passive components
  - ➢ Energy harvesting systems focusing on thermo-electric materials for generation of power for remote sensors.

Technical Challenges:

- ➢Development Of Reliable High Temperature
- ➢ Telemetry Electronics, Power Sources
- ➢ Remote Communication Electronics, And Packaging

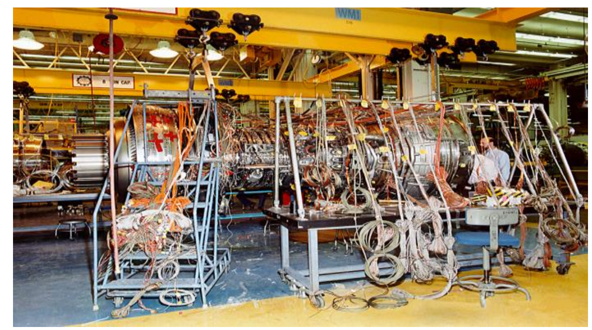
Goals Supported:

- ➢Enhance Performance
- ➢Significantly Reduce Cost

Provide Data Transfer In Harsh Environments Improving Reliability And Enabling New Capabilities

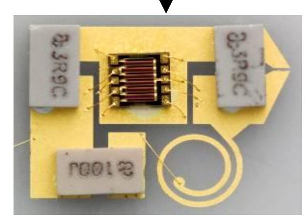
Provide a New Generation of Sensor Technology

Significant wiring exists with present sensor systems

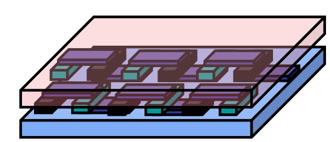


Allow Sensor Implementation by Eliminating Wires

World Record High Temperature Electronics Device Operation



High Temperature RF Components



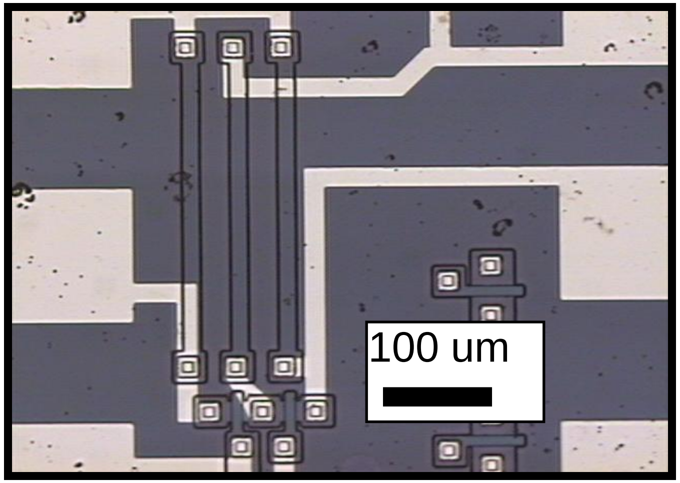
Energy Harvesting Thin Film Thermoelectrics

NASA Glenn Silicon Carbide Differential Amplifier

World's First Semiconductor IC to Surpass
5000 Hours of Electrical Operation at 500 °C

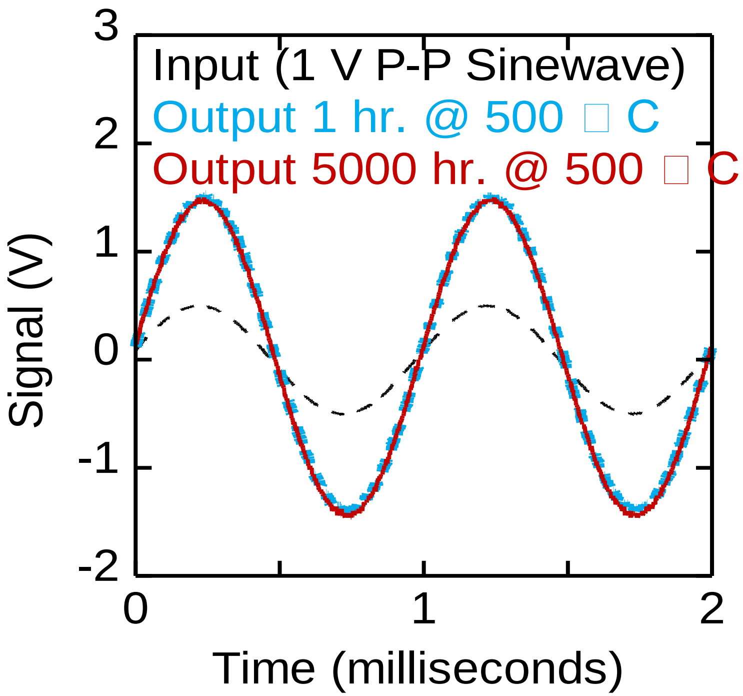
Demonstrates CRITICAL ability to interconnect transistors and other components (resistors) in a small area on a single SiC chip to form useful integrated circuits that are durable at 500 °C.

Optical micrograph of demonstration amplifier circuit before packaging



2 transistors and 3 resistors integrated into less than half a square millimeter.
Single-metal level interconnect.

Test waveforms at 500 °C



Less than 5% change in operating characteristics during 5000 hours of 500 °C operation.

RELEVANT IVHM MILESTONES

Milestone 2.3.1.1

Demonstrate high-temperature wireless sensing system for the detection of propulsion system anomalies.

- **i) Breadboard demonstration of power scavenging at 300°C with 3V voltage, pressure sensor at 300°C, and a wireless circuit with RF communication at 300°C over 1m distance. (FY09Q4)**

  Due Date: 9/30/2009

- **ii) Demonstrate an integrated self-powered wireless sensor system at 500°C with data transmission over 1 m distance minimum and operational life of at least 1 hr. (FY11Q2)**

  Due Date: 3/30/2011

Glenn Beheim, Liangyu Chen, Fred Dynys, Jennifer Jordan, Roger Meredith, Elizabeth McQuaid, Philip Neudeck, George Ponchak, Maximilian Scardelletti, Nick Varaljay

RELEVANT IVHM MILESTONES

Milestone 1.1.1.3

Demonstrate power harvesting at high temperatures to enable remote sensing technologies.

Fred Dynys

Milestone 1.1.1.6

Demonstrate health monitoring nanostructured sensors for the monitoring of propulsion emissions

Gary W. Hunter, Jennifer C. Xu, Laura J. Evans, Azlin Biaggi-Labiosa
NASA Glenn Research Center
Cleveland, OH 44135

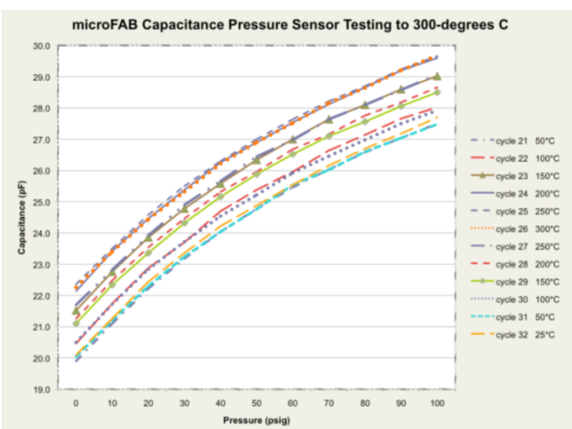
Randy L. Vander Wal, Gordon M. Berger, and Michael J. Kulis
USRA at NASA Glenn Research Center
Cleveland, OH 44135

MILESTONE APPROACH

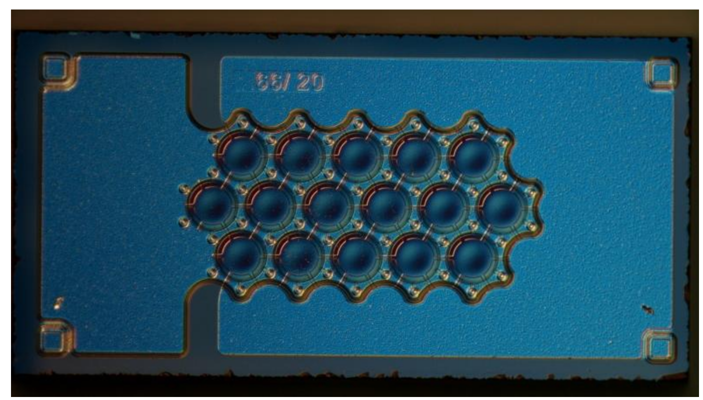
- PREPARE FOR 500˚C BY MAKING A SYSTEM WORK AT 300˚C. THIS MILESTONE IS A TRIAL AND PROVING GROUND FOR:
  - SYSTEM APPROACHES AND INTEGRATION NEEDED FOR 500° C OPERATION
  - CHARACTERIZATION AND BENCHMARKING OF OPERATIONAL SENSOR SYSTEMS OPERABLE AT 300°C
  - IDENTIFY TECHNOLOGY CONCENTRATION AREAS WHICH WILL BE NEEDED FOR 500°C OPERATION
- OVERALL APPROACH IS TO USE EXISTING TECHNOLOGIES AT 300˚C IF VIABLE
  - DEVELOP WHAT IS NEEDED FOR THE MILESTONE/LEVERAGE THE REST
- MILESTONE BRINGS TOGETHER MULTIPLE FIELDS OF EXPERTISE IN HIGH TEMPERATURE TECHNOLOGY
- NECESSARY COMPONENTS FOR MILESTONE DEMONSTRATION
  - PRESSURE SENSOR
  - POWER SUPPLY
  - SiC CIRCUITY
  - WIRELESS CIRCUIT
  - SYSTEM INTEGRATION
  - TESTING SYSTEM

CAPACITIVE PRESSURE SENSOR

- CAPACITIVE SENSOR SYSTEMS HAVE SIGNIFICANT ADVANTAGES FOR WIRELESS CIRCUITS
  - IN AN OSCILLATING CIRCUIT, CAPACITIVE CHANGES MORE READILY AFFECT RESONANT FREQUENCY
- WHILE NASA GRC HAS A LONG STANDING EFFORT IN PRESSURE SENSORS BASED ON RESISTANCE CHANGES, CAPACITIVE SENSOR DEVELOPMENT IS STILL AT AN EARLY STAGE
- COMMERCIAL CAPACITIVE PRESSURE SENSOR CHOSEN FOR THIS DEMONSTRATION
  - MAXIMUM OPERATING TEMPERATURE: 300°C
  - IN-HOUSE CHARACTERIZATION PERFORMED TO VERIFY SENSOR OPERATION
  - IN-HOUSE PACKAGING TECHNIQUES USED TO PREPARE SENSOR FOR SYSTEM DEMONSTRATION



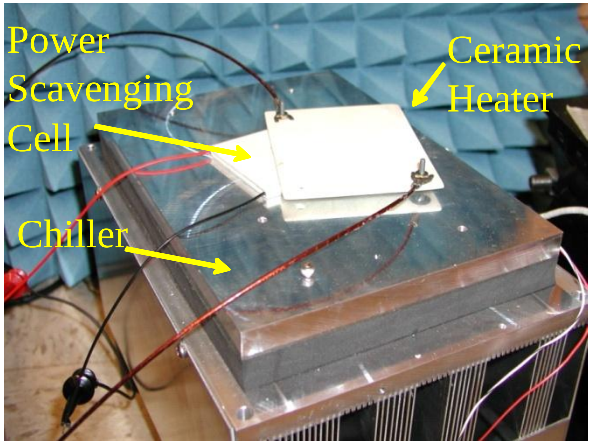
Capacitance versus Pressure plot of the microFAB Pressure sensor in Characterization Testing



Close up view of the Capacitive Pressure Sensor. Shown are sixteen 60-micron diaphragms.

POWER SCAVENGING

- COMMERCIAL THERMAL ELECTRIC POWER SUPPLIES EXIST WHICH OPERATE FOR LIMITED TIMES AT 300°C
  - ➢ CHOOSE CUSTOM THERMOELECTRICS (TE) SYSTEM TO DEMONSTRATE POWER SCAVENGING APPROACH
  - ➢ A THERMOELECTRIC APPROACH, BUT USING MATERIALS OPERATIONAL AT LOWER TEMPERATURES
  - ➢ UNIT ENCAPSULATED TO DECREASE DEGRADATION
- EACH UNIT PROVIDES LIMITED VOLTAGE; SERIES CONNECTION OF UNITS NECESSARY TO ACHIEVE 3 V AND ABOVE
- IN ORDER TO MAXIMIZE VOLTAGE OUTPUT, THE HOT SIDE IS EXPOSED TO 300°C WHILE THE OTHER SIDE OF THE UNIT IS COOLED WITH THE HEATSINK



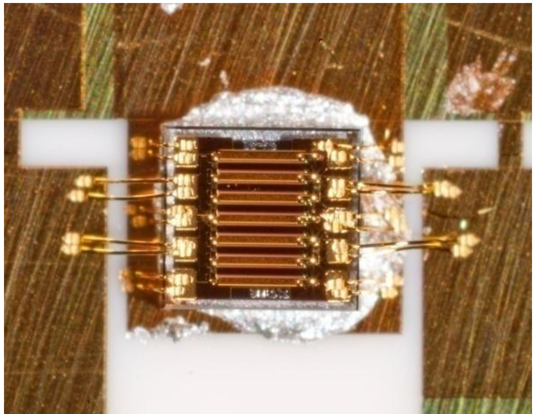
Commercial thermoelectric power unit on hotplate


Complete thermoelectric power system

SiC HIGH TEMPERATURE CIRCUITY

- MESFET IS ONE APPROACH TO PROVIDE HIGHER FREQUENCY OPERATION
- A CREE MESFET WAS CHOSEN AS THE PRIME SIC CIRCUIT APPROACH
  - ALLOWED WIDEST FREQUENCY RANGE IN WIRELESS CIRCUIT DESIGN AND OPERATION
  - LIMITED IN DURABILITY/APPLICABILITY AT HIGHER TEMPERATURES
- CHARACTERIZED CREE SIC MESFET TRANSISTOR TO 400°C.
- EXISTING NASA GRC CIRCUITS HAVE SHOWN THE WORLD RECORD DURABILITY BUT WOULD OPERATE IN A LOWER AND LIMITED FREQUENCY RANGE (ORDER OF MHz OR LESS)
  - WIDER FREQUENCY RANGED CIRCUITS BEING DESIGNED AND FABRICATED FOR 2011 MILESTONE
  - LOWER FREQUENCY CIRCUIT ASSEMBLED WITH NASA GRC LONG-LIVED PARTS ASSEMBLED AND DEMONSTRATED AT 500°C (COMMERCIAL CAPACITIVE PRESSURE SENSOR LOCATED OUTSIDE OF OVEN)

Cree MESFET CRF24010D



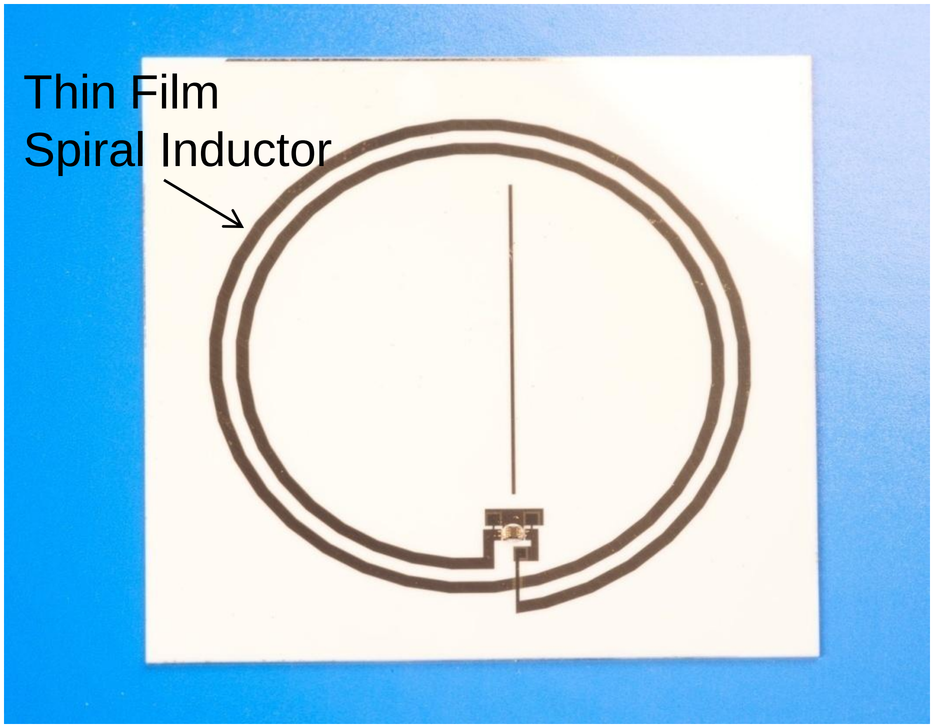
WIRELESS CIRCUIT

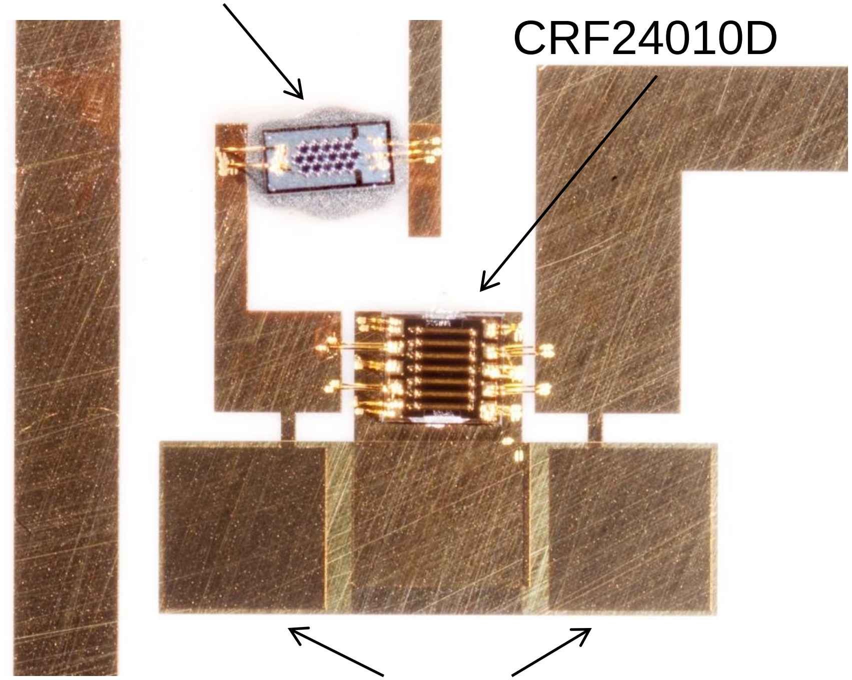
- **PREVIOUS WORK AND CIRCUIT DESIGNS ARE INSUFFICIENT TO MEET THIS MILESTONE/TARGETED SYSTEM DEVELOPMENT NECESSARY**
- **SIGNIFICANT ADVANCEMENTS MADE**
  - **DEVELOPED AND CHARACTERIZED THIN FILM COMPONENTS (MIM CAPACITORS AND THIN FILM SPIRAL INDUCTORS) TO 400°C**
  - **DEVELOPED AND CHARACTERIZED PLANAR ANTENNAS TO 400°C**
  - **DEVELOPED AND CHARACTERIZED OSCILLATORS OPERATING AT 30, 100, 800, AND 1000 MHZ**
    - **OPERATED 800 AND 1000 MHZ OSCILLATORS TO 270°C**
    - **OPERATED 30 AND 100 MHZ OSCILLATORS TO 470°C**
  - **DEVELOPED AND CHARACTERIZED TRANSMISSION LINES ON BOTH SAPPHIRE AND ALUMINA SUBSTRATES TO 400°C**
  - **DESIGNED MINIATURE ANTENNAS UTILIZING CAPACITIVE LOADING TECHNIQUES ON FOLDED SLOT ANTENNAS TO REDUCE OVERALL SIZE OF THE WIRELESS PRESSURE SENSOR.**
  - **DEVELOPED THIN FILM PECVD SIC PACKAGING TECHNOLOGY FOR HIGH TEMPERATURE ELECTRONICS AND HARSH ENVIRONMENTS**

IT SHOULD BE NOTED THAT EACH OF THESE ARE CONSIDERED WORLD FIRSTS. NOTABLE SYSTEM INTEGRATION USING THIN FILM APPROACHES

ACTIVITIES IN RED CONSIDERED PARTICULARLY SIGNIFICANT AND FOUNDATIONAL FOR 500° C OPERATION

WIRELESS CIRCUIT



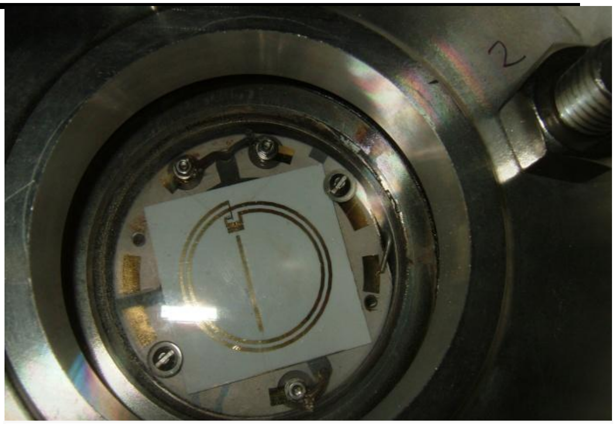


- **100 MHz Wireless Pressure Sensor System**

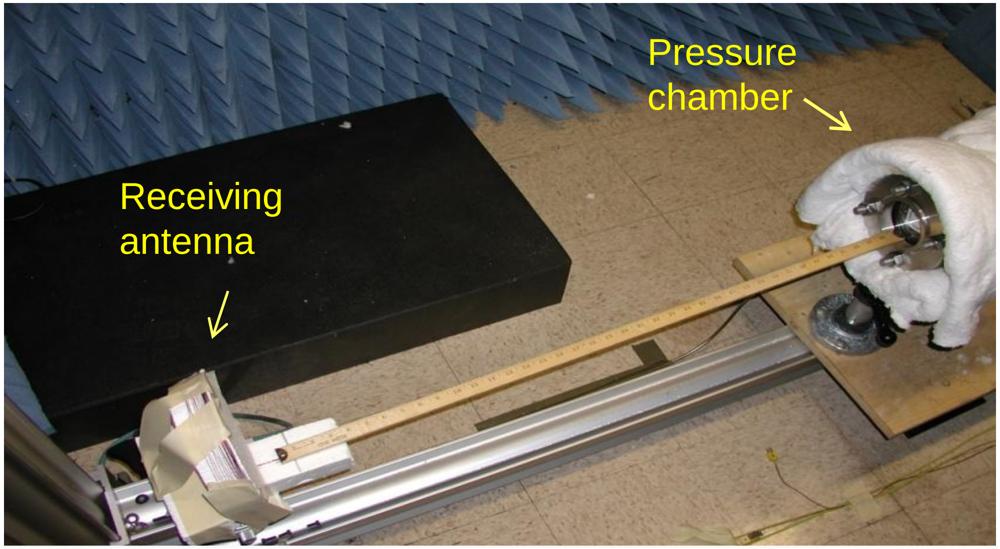
- **Close up of MESFET, capacitive pressure sensor, and MIM capacitors from adjacent photo.**

SYSTEM INTEGRATION AND TESTING

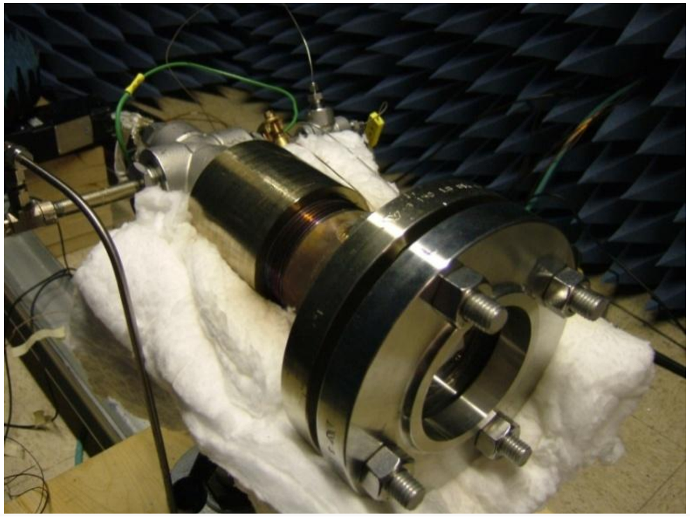
- DESIGNED HIGH TEMPERATURE PRESSURE VESSEL WHICH ALLOWED WIRELESS SENSOR TO TRANSMIT OVER A 1 METER DISTANCE TO RECEIVING ANTENNA WHILE UNDER VARIOUS PRESSURES AND TEMPERATURE RANGES FROM 25°C TO 300°C.



Circuit installed inside chamber



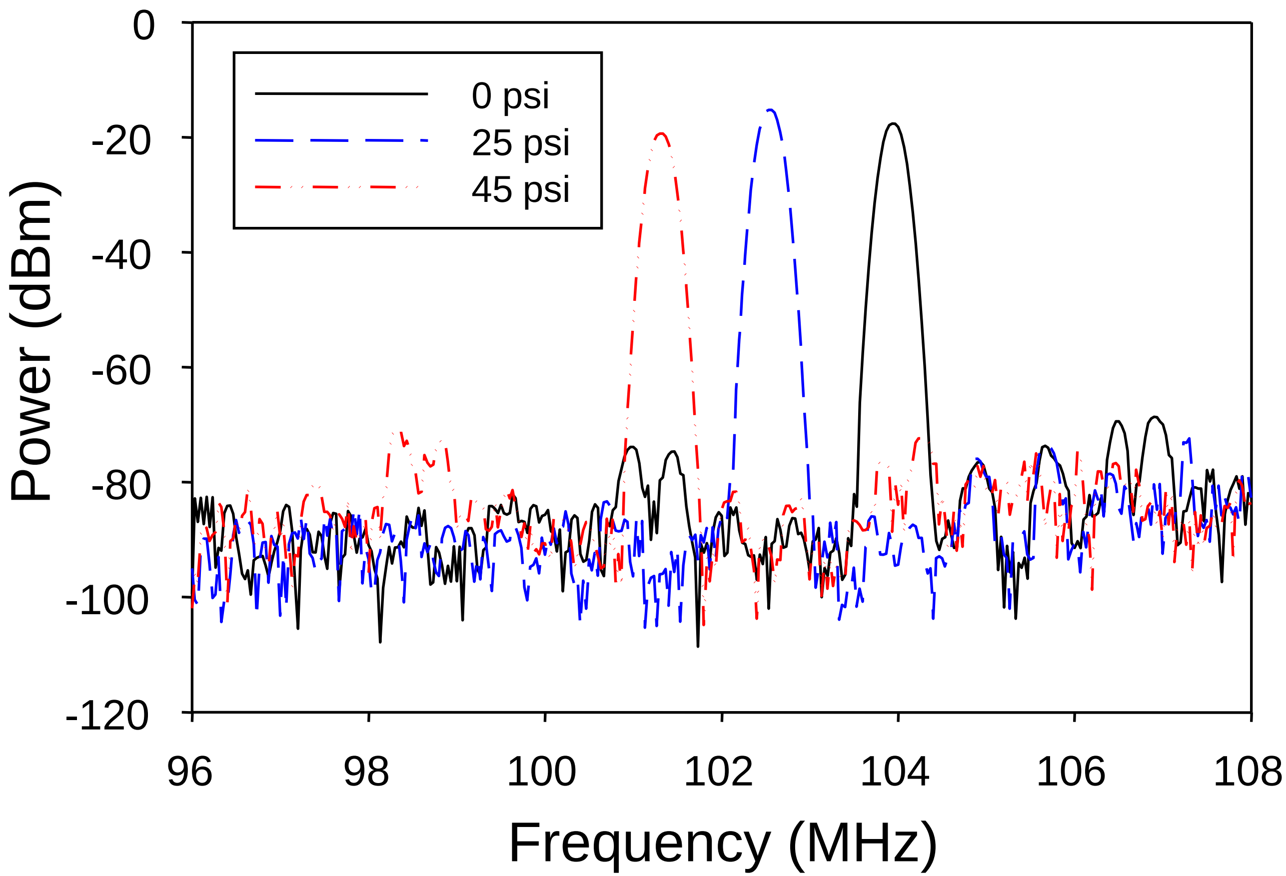
High temperature/pressure measurement system.



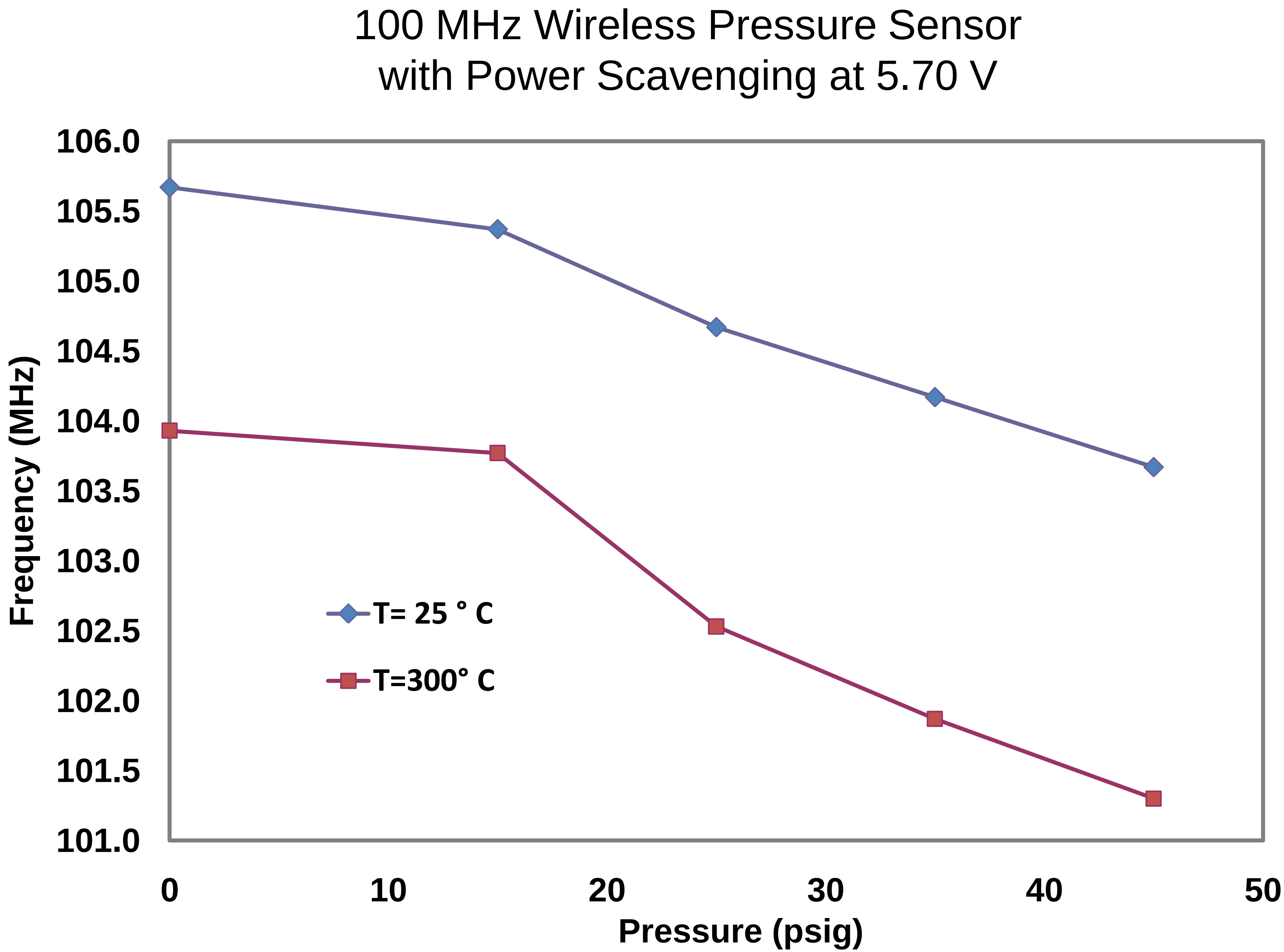
High temperature/pressure test vessel

TESTING RESULTS

100 MHz Wireless Pressure Sensor at 300°C
with Power Scavenging of 5.70 V

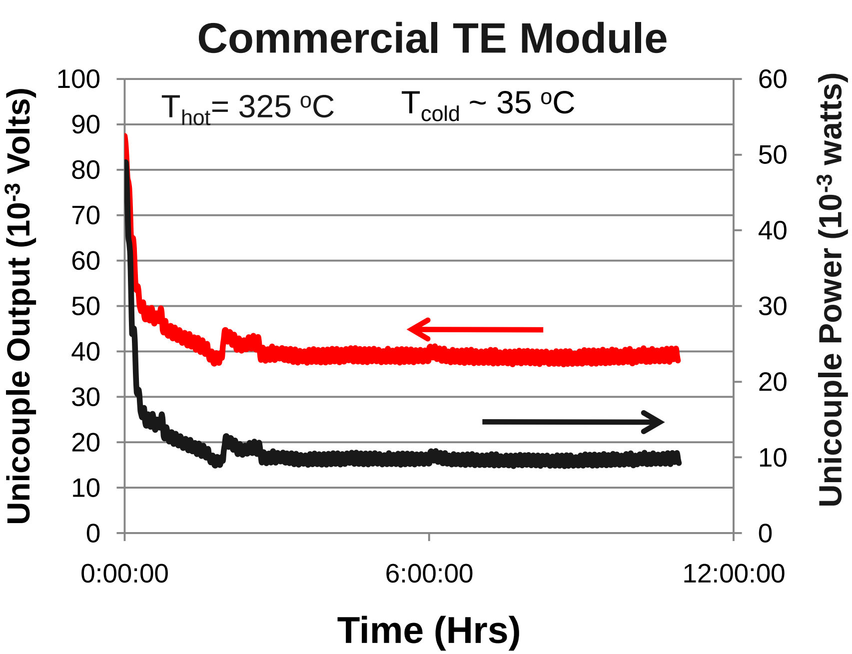


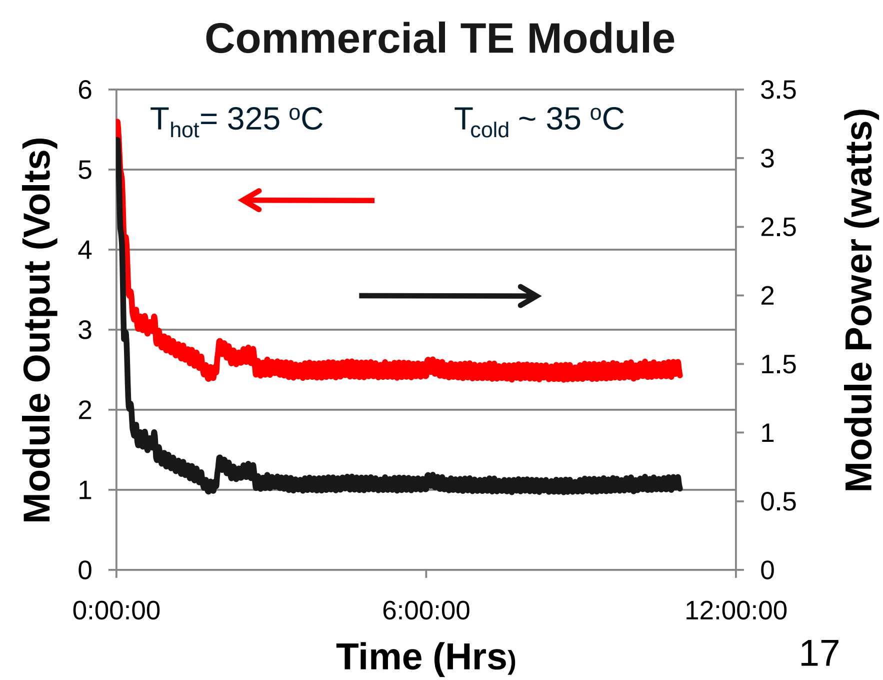
TESTING RESULTS



COMMERCIAL TE MODULE

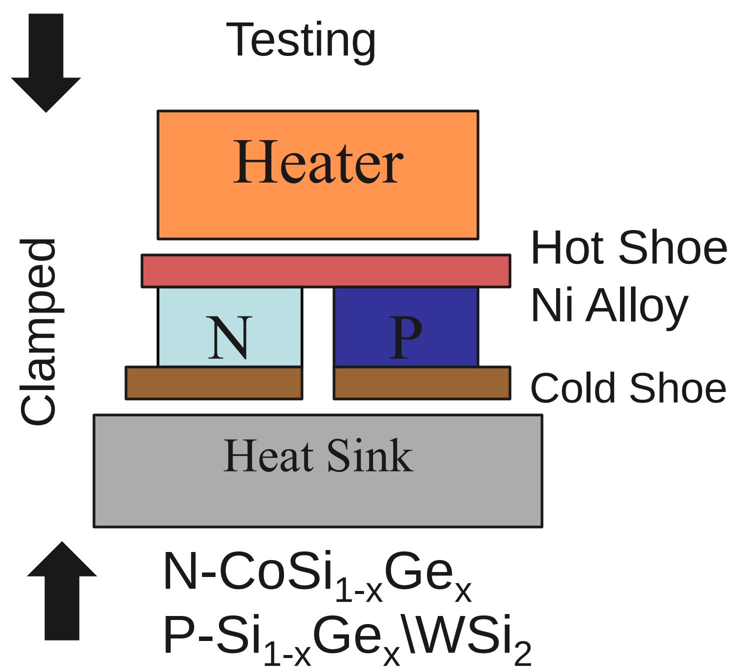
- THERE ARE NO COMMERCIAL TE MODULES THAT CAN SUSTAIN OPERATION ABOVE 250 ^{0}C IN AIR.
  - ➢ OXIDATION OF TE MATERIAL MAJOR FACTOR IN HIGH TEMPERATURE DEGRADATION
  - ➢ SEALING OF MATERIAL SIMPLY NOT ENOUGH FOR HIGH TEMPERATURE OPERATION/THERMAL CYCLING
- TESTING OF COMMERCIAL TE MODULE AT 325^{O}C SHOWS RAPID DETERIORATION IN 1 HR.
  - ➢ COMPLETE UNIT HAS NEAR 2.5V/0.6W AFTER DEGRADATION
  - ➢ EACH UNICOUPLE 40mV/10mW AFTER DEGRADATION
- ANOTHER APPROACH IS NEEDED FOR 500°C OPERATION





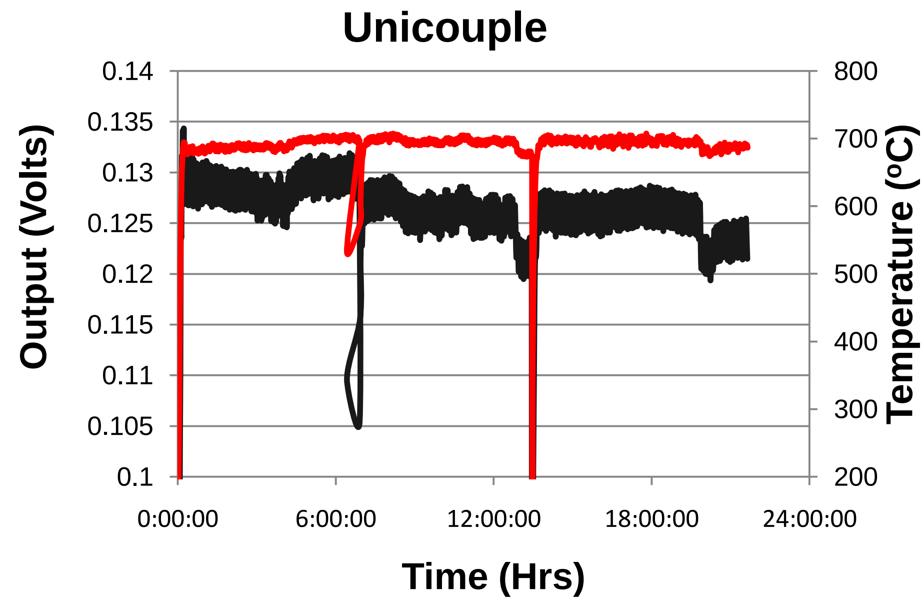
BULK THERMOELECTRICS FOR 500˚C OPERATION

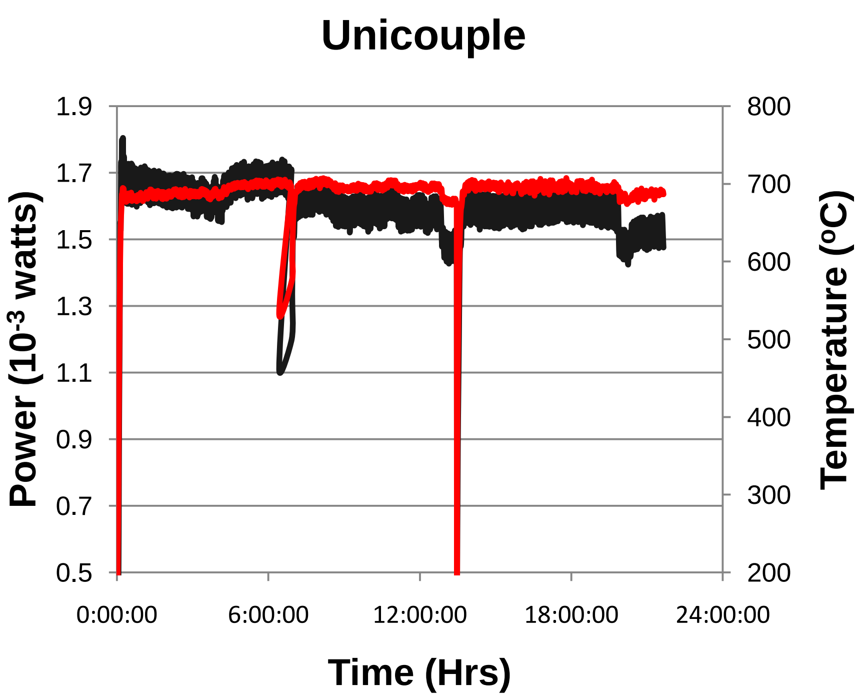
- A PN BULK TE MATERIAL COMBINATION WAS CHOSEN:
  - $P\text{-}Si_{1\text{-}x}Ge_x \backslash WSi_2$
  - $N\text{-}CoSi_{1\text{-}x}Ge_x$
- ALTHOUGH BULK MATERIAL, THIS REFERS TO MATERIAL THICKNESS
  - NOT A THIN FILM
  - UNICOUPLE SIZE CAN BE SMALL E.G. COMMERICAL UNIT
- TESTED IN A CLAMPED SYSTEM BETWEEN A HEATER AND HEAT SINK
- TEST CONFIGURATION HAS LOSSES (ELECTRICAL, HEAT) AROUND 30%.



BULK THERMOELECTRIC RESULTS
P type -$Si_{1-x}Ge_x$\WSi_2 and N type -$CoSi_{1-x}Ge_x$

- SINGLE UNICOUPLE TESTED UP TO 700^{O}C IN AIR.
- MATERIALS SHOW GOOD DURABILITY AFTER 22 HRS OF TESTING IN AIR
- THIS EXCEEDS THE MILESTONE OF 500^{O}C FOR 10 HOURS
- HAVE IDENTIFIED A VIABLE MATERIAL FOR HIGH TEMPERATURE AIR ENVIRONEMENTS





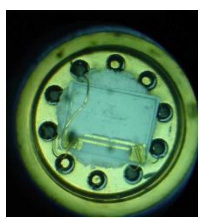
- POWER DEMONSTRATED BY UNICOUPLE THERMOELCTRICS IS NEAR 1.6 mW AT 700^{O}C.
- COMPARABLE TO COMMERICAL UNIT AT 10mW BUT AT MORE THAN TWICE THE TEMPERATURE
- IF PACKAGED IN THE COMMERCIAL MODULE OF 64 UNICOUPLES, ~104 mW
- ACHIEIVING INCREASED POWER IS A MATTER OF PUTTING APPROPRIATE NUMBER OF UNICOUPLES IN SERIES

MEMS Based Emission Sensors

NAVY FUNDED PROGRAM

- **MULTISPECIES MICROSENSOR DETECTION IN SINGLE PACKAGETO ALLOW MINIATURIZATION OF THE DETECTION APPARATUS**
- **QUANTIFY COMPOSITION OF CRITICAL CONSTITUENTS IN TURBINE ENGINE EXHAUST PRODUCTS, E.G., CO, CO_2, NOX, O_2, HC (UNBURNED HYDROCARBONS) AND H_2**
- **IMPROVE ACCURACY IN MEASURING EXHAUST PRODUCTS**
- **USE TO TEST NEW ENGINES, NEW FUEL FORMULATIONS, AND EXPERIMENTAL ENGINE MATERIALS**

Standard Multi-gas Analyzer

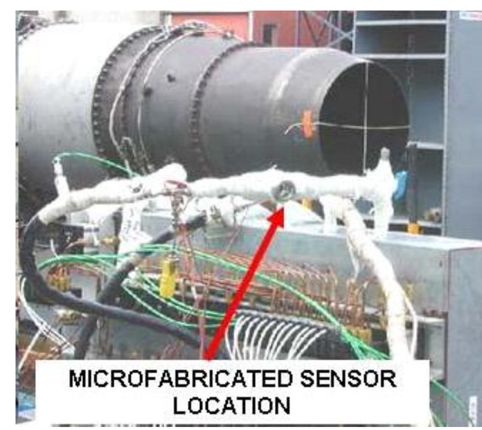


CO Sensor

SiC Hydrocarbon Sensor

CO2 Sensor

MEMS Emissions Sensors



Engine Teststand Testing

Metal Oxide Nanostructures for Chemical Sensor Development

Move From Nanocrystalline Materials To Nanostructure e.g. Tubes, Rods, Ribbons

- **Develop Basic Tools To Enable Fabrication Of Repeatable Sensors Using Nanostructures**
- **Approach 3 Basic Problems In Applying Nanostructures As Chemical Sensors**
- **Demonstrate Nanostructure Sensor System at 600°C for low concentrations of hydrocarbons**

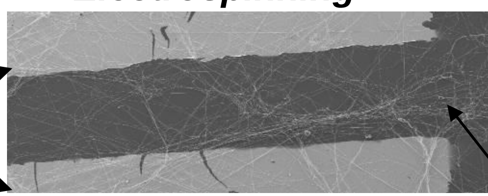
▶ ***Micro-Nano Contact Formation*** ▶ ***Nanomaterial Structure Control***

▶ ***Range Of Nano Structured Oxides Available***

IMPROVE NANOSTRUCTURE TO MICROELECTRODE CONTACTS

Electrospinning

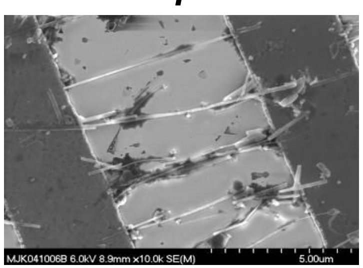
Pt Electrodes



SnO_2 Nanofibers

Bridging of electrospun SnO_2 nanofibers across electrodes.

Dielectrophoresis



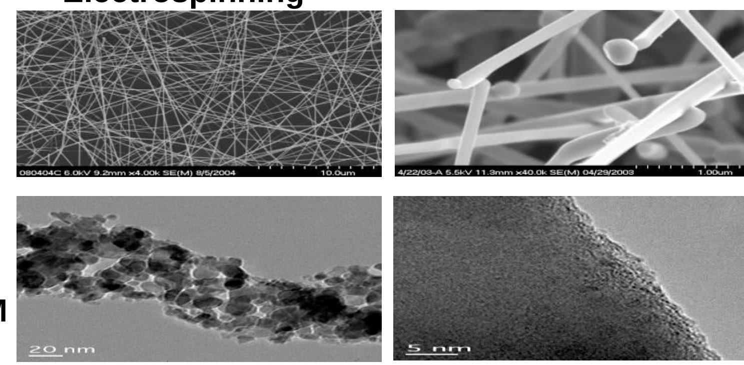
TiO2 Nanorods aligned by dielectrophoresis across interdigitated electrode patterns.

NANOMATERIAL STRUCTURE CONTROL

Electrospinning **TEC**

SEM

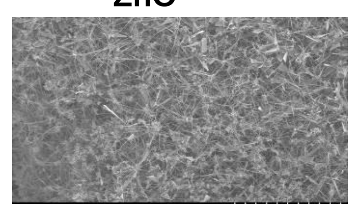
HRTEM

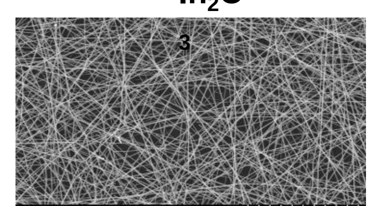


Different Processing of nanostructures produces different crystal structures

EXPAND RANGE OF NANOSTRUCTURES AVAILABLE

ZnO **In_2O_3**

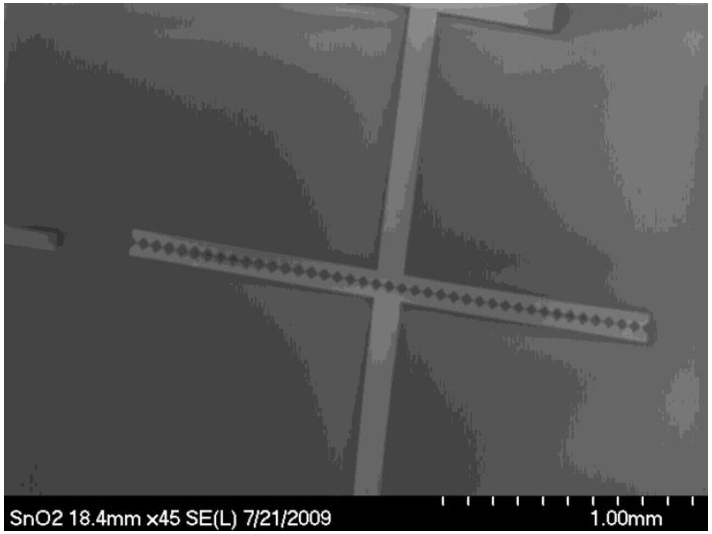


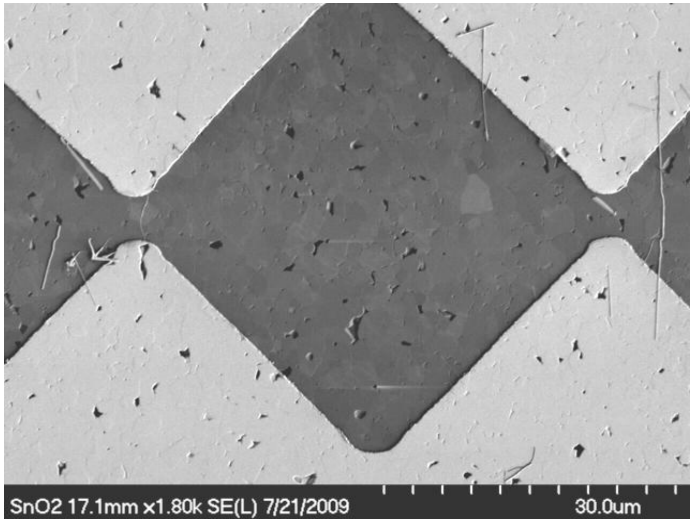


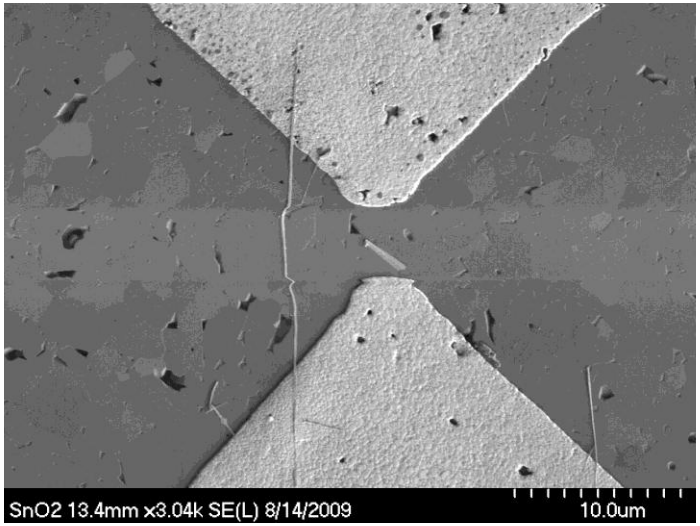
Multiple oxide nanostructured materials fabricated

Sensor Structure

- SnO_2 nano rods fabricated by Thermal Evaporation Condensation
- Pt Saw tooth pattern on alumina
- 5 micron spacing between electrodes
- 7 nanowires bridging the electrodes
- Open Contacts (i.e. did not bury electrode contacts)

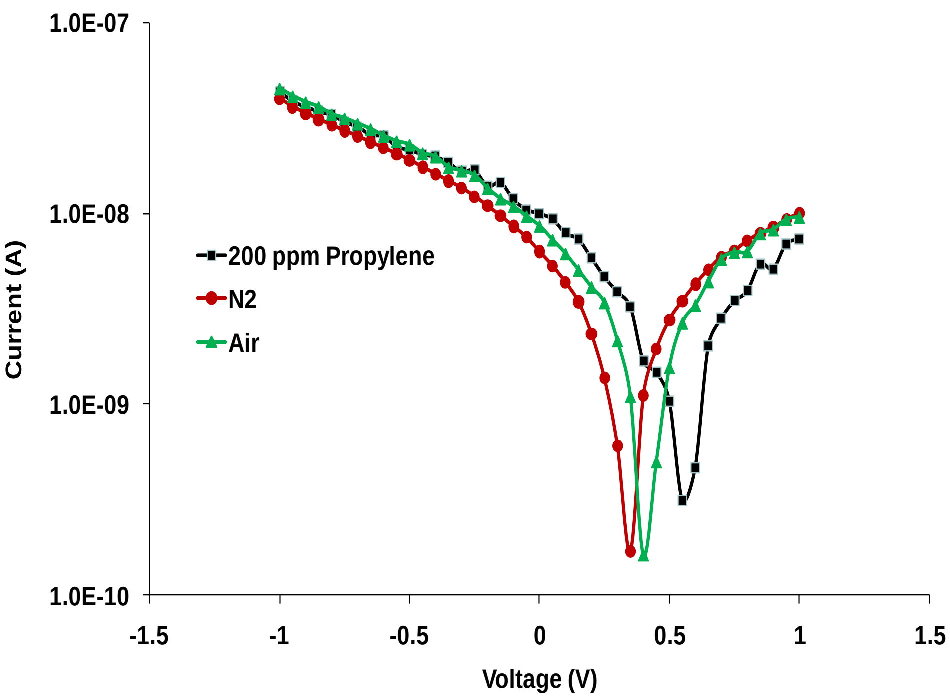




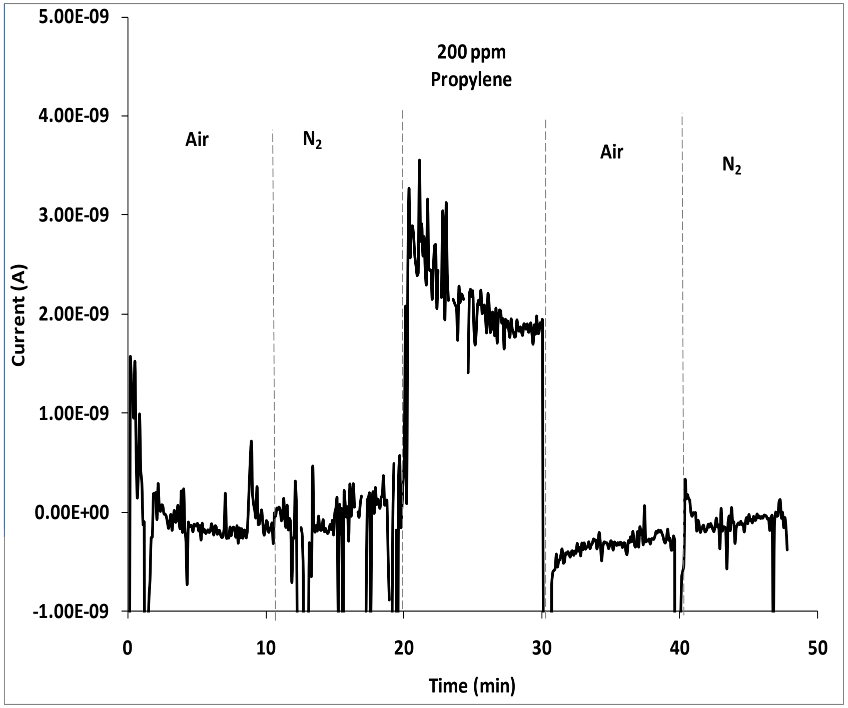


SnO_2 Nanowires
T= 600^0C, 75 hours

- CONTINUED SENSOR OPERATION AFTER 75 HOURS AT 600 °C WITH HIGH SENSITIVITY
- DETERMINED BY BOTH I-V CHARACTERISTICS AND RESPONSE OVER TIIME
- BASIC SENSING MECHANISMS STILL NEED TO BE INVESTIGATED



CURRENT VS VOLTAGE MEASUREMENTS AT 600 °C IN AIR, NITROGEN, AND 200 ppm PROPLYENE



CURRENT VS TIME MEASUREMENTS AT 600°C IN AIR, NITROGEN, AND 200 ppm PROPLYENE

SUMMARY

- BREADBOARD DEMONSTRATION OF POWER SCAVENGING AT 300^{O}C WITH 3V VOLTAGE, PRESSURE SENSOR AT 300^{O}C, AND A WIRELESS CIRCUIT WITH RF COMMUNICATION AT 300^{O}C OVER 1M DISTANCE
  - ➢ WIRELESS PRESSURE SENSOR CONSISTS OF AN OSCILLATOR WITH MIM CAPACITORS, THIN FILM SPIRAL INDUCTORS, CREE SIC MESFET AND MICROFAB CAPACITIVE PRESSURE SENSOR AT 105 MHZ AND 300°C.
  - ➢ ESTABLISHED POWER SCAVENGING AT ROOM TEMPERATURE AND 300°C TO DEMONSTRATE SELF-POWERING CAPABILITY
- POWER SCAVENING 500°C MATERIALS INVESTIGATED/A VIABLE SILICON BASED BULK MATERIAL IDENTIFIED
  - ➢ TESTING SHOWED OPERATION AT 700°C IN OXIDIZING ENVIRONMENT FOR >22 HOURS WITH1.6 mW FOR SINGLE UNICOUPLE
- FABRICATED A HIGH TEMPERATURE SENSOR BY ALIGNING TIN OXIDE NANOSTRUCTURES ON A MICROSENSOR PLATFORM
  - ➢ TESTING SHOWED 75 HOURS/600˚C/200 PPM PROPYLENE DETECTION

SUMMARY

- THIS WORK HAS DEMONSTRATED 300˚C CAPABILITIES AND BUILDS TOWARD 500˚C OPEARATION
- THESE ACTIVITES ARE INTENDED TO LAY THE FOUNDATION FOR A REVOLUTION IN HIGH TEMPERATURE ENGINE MONITORING
  - HIGH TEMPERATURE “LICK AND STICK” SYSTEM COMPOSED OF SENSORS, SIGNAL CONDITIONING, WIRELESS COMMUNICATION, AND POWER
  - MAKE IT SMART AND SMALL, AND ABLE TO OPERATE IN HARSH ENVIRONMENTS
  - PLACE SENSORS WHERE THEY ARE NEEDED/ MINIMIZE BURDEN TO THE VEHICLE
- BASED ON WORLD-LEADING ADVANCEMENTS IN HIGH TEMPERATURE ELECTRONICS, COMMUNICATION, AND POWER
  - UNIQUE SET OF CAPABILITIES INTEGRATED INTO A SINGLE PROJECT
  - HIGH TEMPERATURE ELECTRONICS WORK PREVIOUSLY ONE OF NASA TOP TEN DISCOVERY STORIES (2007)
  - NANO 50 IN 2008 FOR CHEMICAL SENSOR DEVELOPMENT INVOLVING NANOMATERIALS
  - A NOTABLE NUMBER PUBLICATIONS AND INVITED TALKS

SUMMARY

- A RANGE OF TECHNOLOGY TRANSFER/DEMONSTRATION ACTIVITIES
  - PROPULSION INSTRUMENTATION WORKING GROUP TEAM EVALUATING WIRELESS FOR AERONAUTIC ENGINES
    - AERONAUTIC ENGINE COMPANY CONSORTIUM COMPOSED OF COMPANIES SUCH AS ROLLS ROYCE, HONEYWELL, WILLIAMS INTERNATIONAL, GE, P&W AND OTHERS
  - CASE WESTERN RESERVE UNIVERSITY DEVELOPMENT OF SiC ELECTRONIC CIRCUITS
    - RECENT APPLICATION OF NASA TECHNIQUES TO NEW HIGH TEMPERATURE CIRCUIT DESIGN
  - MISSE 7 (MATERIALS INTERNATIONAL SPACE STATION EXPERIMENT) SCHEDULED FOR 11-09
    - SIC DEMONSTRATION CIRCUIT TO BE DEPLOYED OUTSIDE OF THE INTERNATIONAL SPACE STATION
  - VENUS SEISMOMETER UNDER DEVELOPMENT BASED ON HIGH TEMPERATURE ELECTRONICS
    - POTENTIALLY REVOLUTIONIZE VENUS SCIENCE WITH PROOF-OF-CONCEPT SEISMIC MEASUREMENT INSTRUMENT INCLUDING WIRELESS
  - FUTURE TESTING PLANNED FOR HIGH TEMPERATURE MULTI-SPECIES GAS SENSOR ARRAY (NAVY FUNDED DEVELOPMENT)
    - MEMS BASED SYSTEM/NANO TECHNOLOGY VERSION BEING DEVELOPED

FUTURE PLANS
HIGH TEMPERATURE ELECTRONICS, COMMUNICATION AND POWER

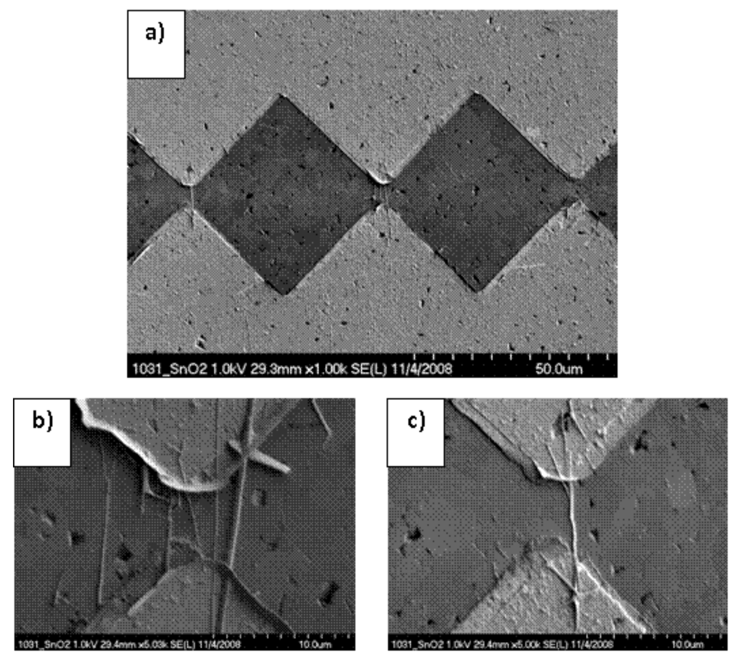
- **FUTURE WORK:**
  - **DEMONSTRATE AN INTEGRATED *SELF-POWERED* WIRELESS SENSOR SYSTEM AT 500^{O}C WITH DATA TRANSMISSION OVER 1 M DISTANCE MINIMUM AND OPERATIONAL LIFE OF AT LEAST 1 HR. (FY11Q2)**
  - **DUE DATE: 3/30/2011**

- **LESSONS LEARNED/SPECIFIC ACTIVITIES**
  - ➢ **PRESSURE SENSOR HAS SIGNIFICANT IMPACT ON OVERALL CIRCUIT OPERATION. IN PARTICULAR, INTERNAL RESISTANCE CAN AFFECT OVERALL FREQUENCY OF OPERATION. NASA GRC IS WORKING ON A SIC CAPACITIVE PRESSURE SENSOR FOR 500^{O}C.**
  - ➢ **SIGNIFICANT CHANGES IN WIRELESS CIRCUIT DESIGN IMPLEMENTED DURING THE COURSE OF THIS WORK ENABLING GREATLY ENHANCE CIRCUIT OPERATION**
  - ➢ **INPUT TO BE USED FOR NEXT PROCESSING RUN OF SILICON CARBIDE ELECTRONICS PRODUCED AT NASA GRC**
  - ➢ **DEVELOP HIGH TEMPERATURE TE MODULE PROVIDING INCREASED POWER BY MATERIAL IMPROVEMENT AND OPTIMIZED DESIGN**
  - ➢ **POWER SCAVENGING AS THE SOLE SOURCE OF SYSTEM POWER IS PROBLEMATIC**

FUTURE PLANS
SENSOR DEVELOPMENT

- CHARACTERIZE, UNDERSTAND, AND CONTROL THE REACTION MECHANISMS ASSOCIATED WITH THESE OXIDE NANOSTRUCTURES
  - ➢ EARLY STAGES OF UNDERSTANDING SENSOR BEHAVIOR
  - ➢ LONGER-TERM AIM: DIODES, RESISTORS, ELECTROCHEMICAL CELLS
- USE MICROFABRICATION PROCESSING TECHNIQUES TO BETTER CONTROL SENSOR FORMATION
  - ➢ BURY ELECTRODE CONTACTS FOR IMPROVED REPEATABILITY/CONTROL OF STRUCTURE

- MILESTONE 2.3.1.3 DEMONSTRATE INCREASED ACCURACY OF FIBER OPTIC TEMPERATURE PROBE, MICROWAVE TIP CLEARANCE SENSOR AND EMISSIONS SENSOR SYSTEMS FOR OPERATION AT 600˚C AND ABOVE IN AN OPERATING ENGINE ENVIRONMENT.



Buried Oxide Nanostructures

Backup Slides

HIGH TEMPERATURE THERMOELECTRIC MATERIALS

- THERE ARE MULTIPLE APPROACHES TO POWER SCAVENING.
- ONE APPROACH IS THE USE OF THERMOELECTRIC MATERIALS (TE'S)
  - POWER GENERATED DUE TO THE DIFFERENTIAL OF TEMPERATURE ACROSS A MATERIAL
- THE AMOUNT OF POWER GENERATED IS A FUNCTION OF BOTH THE THERMAL GRADIENT AND THE MATERIAL
  - THE ZT OF THE MATERIAL AND THERMAL GRADIENT DETERMINES CONVERSION EFFICIENCY
- DESIRED PROPERTIES OF TE'S
  - HIGH SEEBECK COEFFICIENT (S)
  - HIGH ELECTRICAL CONDUCTIVITY (σ)
  - LOW THERMAL CONDUCTIVITY (Κ)

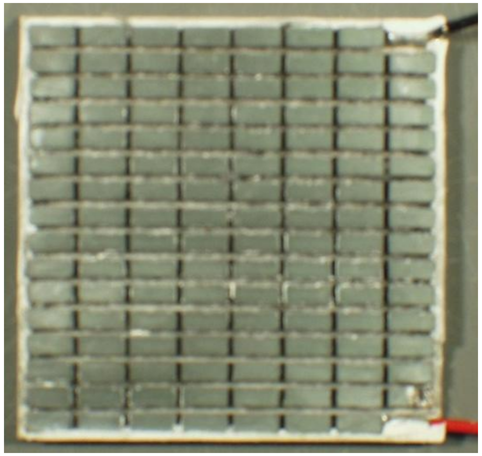
Efficiency

$$\eta_{\max} = \frac{\Delta T}{T_{hot}} \frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+T_{cold}/T_{hot}}$$

$$ZT = \frac{S^2\sigma}{\kappa} T$$

COMMERCIAL TE MODULE

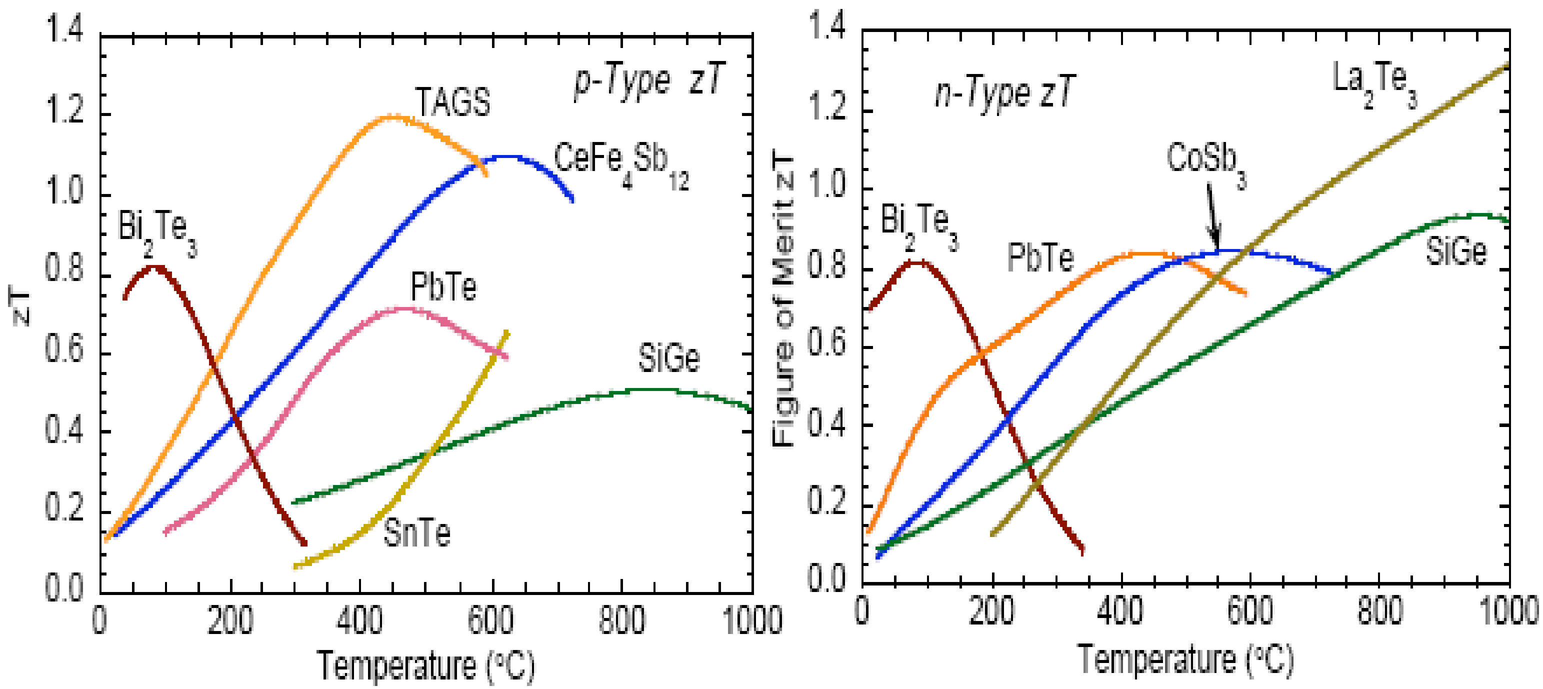
- COMMERCIAL MODULES ARE FABRICATED BY CONNECTING MULTIPLE THERMOELECTRIC UNICOUPLES TOGETHER TO ACHIEVE DESIRED VOLTAGE AND POWER.
- CORE COMMERCIAL TE MODULE USED IN MILESTONE 2.3.1.1 CONTAINS 64 UNICOUPLES (PN JUNCTIONS)
- COMPLETE MODULE INVOLVES NOT ONLY UNICOUPLE TECHNOLOGY BUT ALSO A RANGE OF PACKAGING AND INTERCONNECT TECHNOLOGY
- STANDARD PRACTICETO CONNECT MODULES IN SERIES FOR INCREASED POWER
    - SOME INEFFICIENCIES IN INTERCONNECTIONS (~10-30%)
    - TWO MODULES ARE REQUIRED TO ACHIEVE 3 VOLT MILESTONE.



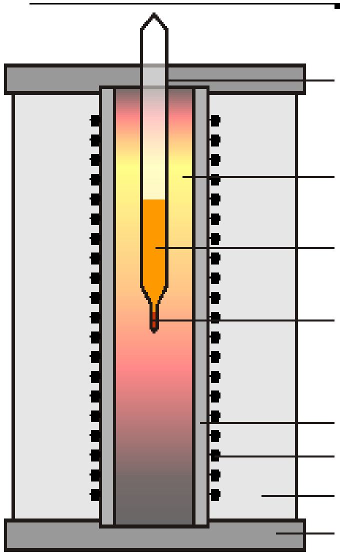
Commercial TE Module

CANDIDATE TE MATERIALS FOR HIGH TEMPERATURE OXYGEN BEARING ENVIRONMENTS

- EXCEPT FOR SiGe, THE BEST THERMOELECTRIC MATERIALS ARE NOT DURABLE TO OXYGEN AT HIGH TEMPERATURES. OXYGEN LIMITS MATERIAL SELECTION
- OXIDATON OCCURS BUT LIMITED IN VOLUME WITH A SURFACE SiO2 LAYER
- DOPING OF Si-BASED AND OTHER MATERIALS TO OBTAIN OPTIMUM PERFORMANCE
- PEAK PERFORMANCE IS ALSO A FUNCTION OF TEMPERATURE
- OVER 50 MATERIALS INVESTIGATED
- OXIDES ARE VIABLE BUT STILL MATURING



BULK THERMOELECTRICS: SIGNIFICANTLY IMPROVED MATERIAL PROPERTIES INCLUDING OXIDATION RESISTANCE



Melt ➡ Solidification