High Temperature Electronics for Intelligent Harsh Environment Sensors

PWIG Workshop

Laura J. Evans
NASA Glenn Research Center
Cleveland, OH 44135

The development of intelligent instrumentation systems is of high interest in both public and private sectors. In order to obtain this ideal in extreme environments (i.e., high temperature, extreme vibration, harsh chemical media, and high radiation), both sensors and electronics must be developed concurrently in order that the entire system will survive for extended periods of time.

The semiconductor silicon carbide (SiC) has been studied for electronic and sensing applications in extreme environment that is beyond the capability of conventional semiconductors such as silicon. The advantages of SiC over conventional materials include its near inert chemistry, superior thermomechanical properties in harsh environments, and electronic properties that include high breakdown voltage and wide bandgap. An overview of SiC sensors and electronics work ongoing at NASA Glenn Research Center (NASA GRC) will be presented. The main focus will be two technologies currently being investigated: 1) harsh environment SiC pressure transducers and 2) high temperature SiC electronics. Work highlighted will include the design, fabrication, and application of SiC sensors and electronics, with recent advancements in state-of-the-art discussed as well. These combined technologies are studied for the goal of developing advanced capabilities for measurement and control of aeropropulsion systems, as well as enhancing tools for exploration systems.

Setting the Standard for Automation™

High Temperature Electronics for Intelligent Harsh Environment Sensors

Laura J. Evans
NASA Glenn Research Center
May 8 2008

Standards
Certification
Education & Training
Publishing
Conferences & Exhibits

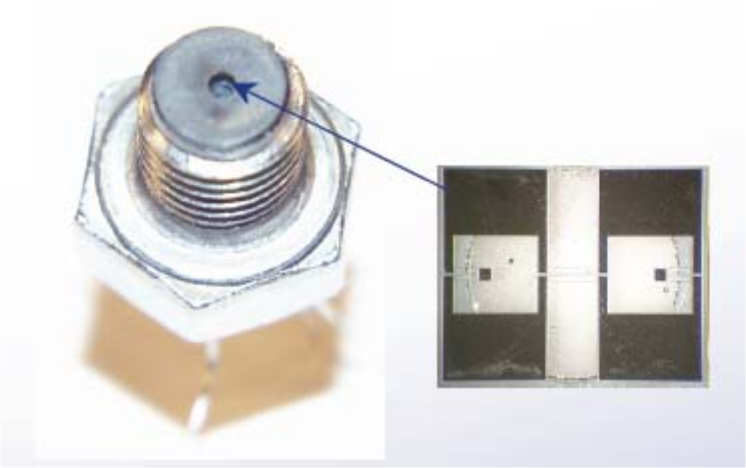
Presenter

- Laura J. Evans holds BS (2002) and MS (2003) degrees in Mechanical Engineering from Northwestern University. Since 2004, she has worked at NASA Glenn Research Center in the Microsystems Fabrication Clean Room on the advancement of Silicon Carbide technologies and Chemical Sensors for aerospace applications. Her main area of interest is MEMS processing techniques for silicon carbide and she has extensive experience in clean room microfabrication processing. This work includes development of processes that enable new advances in high temperature sensor structures. She has also co-authored publications in the areas of harsh environment electronics and sensors.

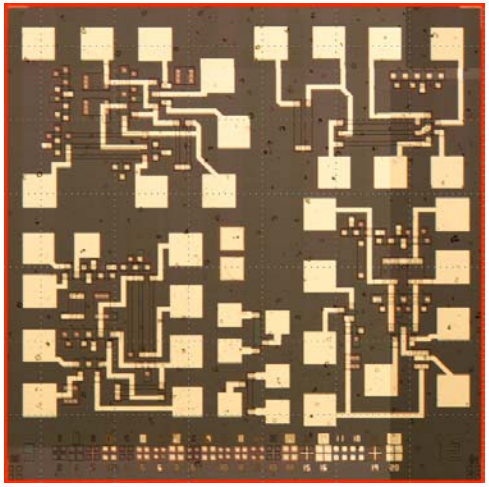
http://www.grc.nasa.gov/WWW/SiC

Outline

- Microsystems overview
- Benefits to NASA
- Electronic and sensing applications in extreme environments
- SiC - advantages for harsh environment applications
- Facilities
- NASA GRC advancements
- Harsh Environment Pressure Transducers
  - Overview
  - Concept
  - State-of-the-art at NASA GRC
- High Temperature SiC Electronics
  - Overview
  - Testing
  - Junction Field Effect Transistor
  - Semiconductor IC: Amplifiers
  - State-of-the-art at NASA GRC
- Conclusion
- Acknowledgements

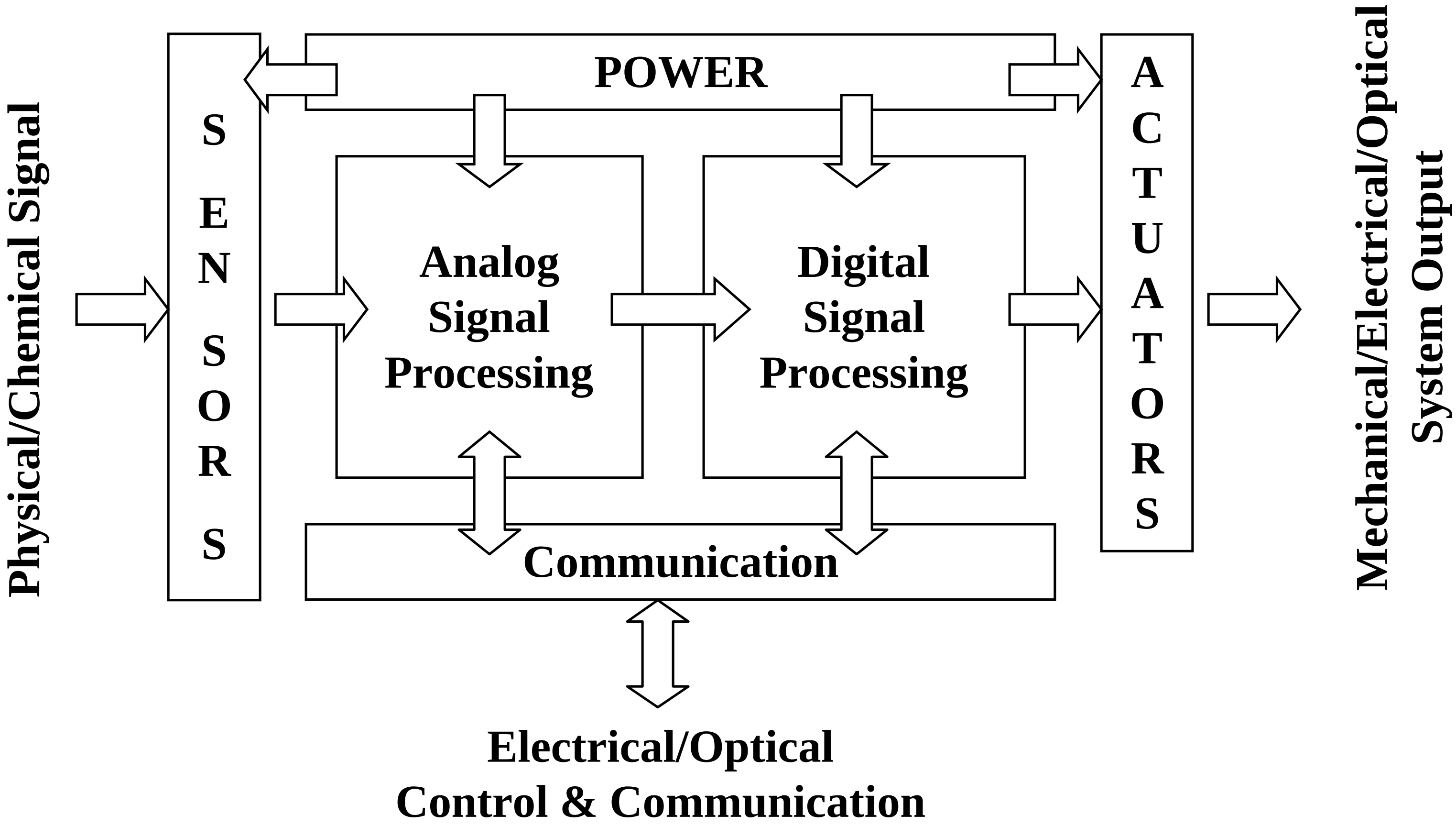


Harsh Environment Pressure Transducer



High Temperature SiC Electronics

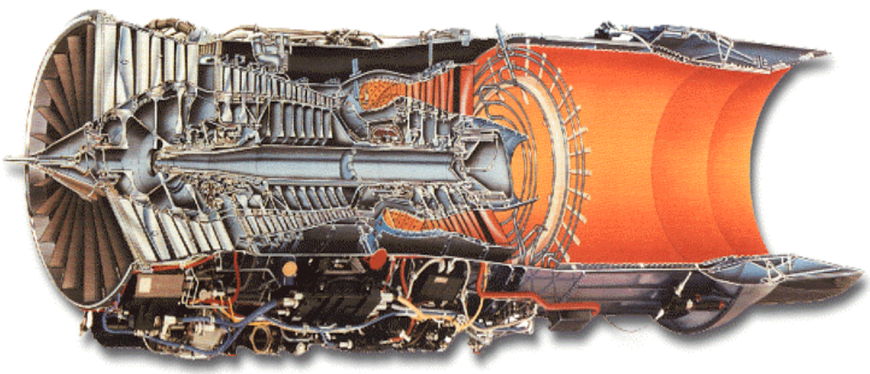
Microsystems Overview



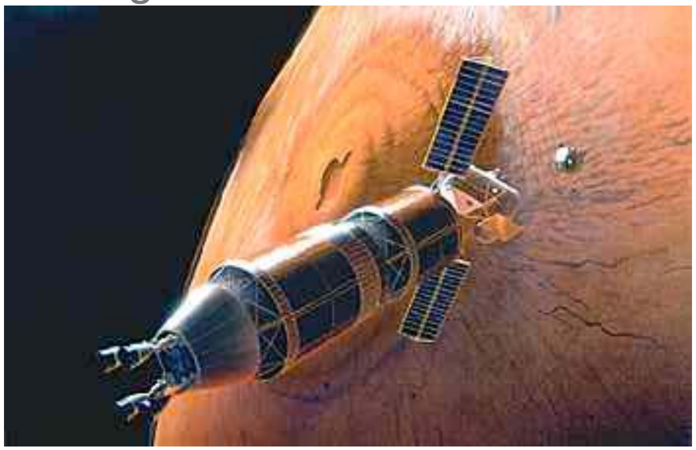
Large-scale integrated electronics are crucial to highly advanced MEMS.

High Temperature MEMS and Electronics Benefits to NASA

Intelligent Propulsion Systems

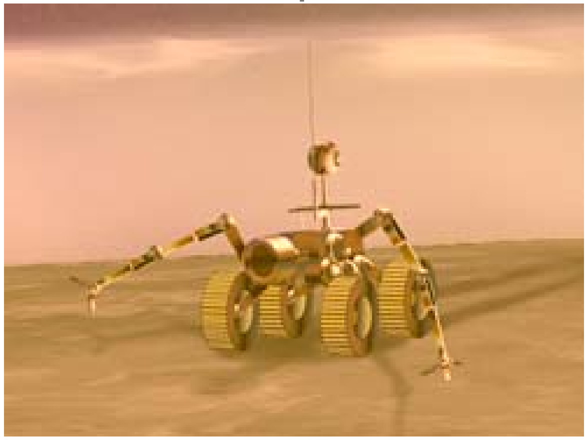


Space Exploration Vision: Power Management and Distribution



More Electric + Distributed Control Aircraft

Venus Exploration

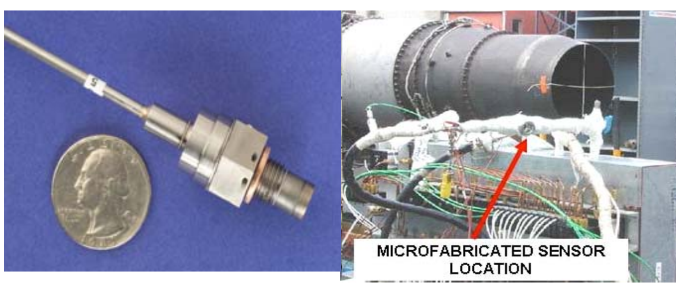


Some of these applications require prolonged T > 400 °C operation

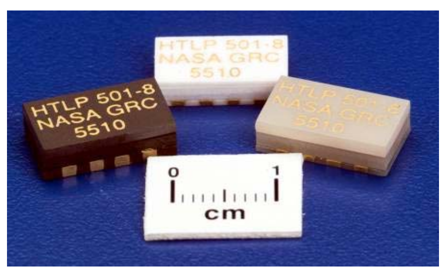
Applications for Harsh Environment Sensors and Electronics

- Applications in environments of high temperature, extreme vibration, harsh chemical media, high radiation
  - Measurement and control of challenging systems
    - Aircraft engines
    - Automotive
    - Well drilling
  - Enhanced tools for exploration systems
- Requires development of integrated sensors, electronics, and packaging

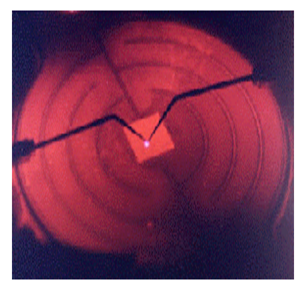
Range of Physical and Chemical Sensors for Harsh Environments



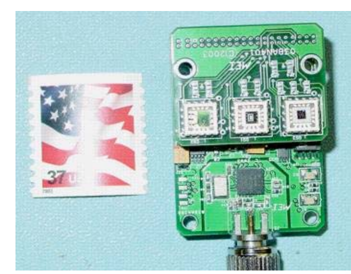
Harsh Environment Packaging (2000 hours at 500 °C)



High Temperature Signal Processing and Wireless



Long Term: High Temperature “Lick and Stick” Systems



SiC - advantages for harsh environment applications

- Current technology - suitable up to 350 °C:
  - T < 150 °C (302 °F), silicon is used in almost all integrated circuits in use today.
  - T < 300 °C (572 °F), well-developed Silicon-On-Insulator (SOI) IC's available for low-power logic and signal processing functions.
  - T > 350 °C (662 °F), other wide-bandgap semiconductors such as SiC, GaN, or diamond are needed.
- Why SiC for harsh environments?
  - Near inert chemistry due to high bonding energy
  - Similar processing as silicon
  - Technology at a level where single crystal wafers can be purchased
  - Superior thermomechanical properties (greater hardness, higher Young's modulus, high thermal conductivity)
  - Superior electronic properties (wide bandgap, high breakdown electric field, high carrier saturation velocity)
- Benefits:
  - Improved reliability
  - Reduced cooling system: reduced cost, volume, and weight of control systems, reduction in fuel consumption and pollution
  - Direct sensing and control in harsh environment e.g., turbine engine

NASA Glenn SiC Microsystem Development Facilities

- Significant in-house capabilities for a range of micro/nano sensor and electronics development
- Capabilities range from semiconductor material growth to micro-device fabrication to packaging and testing

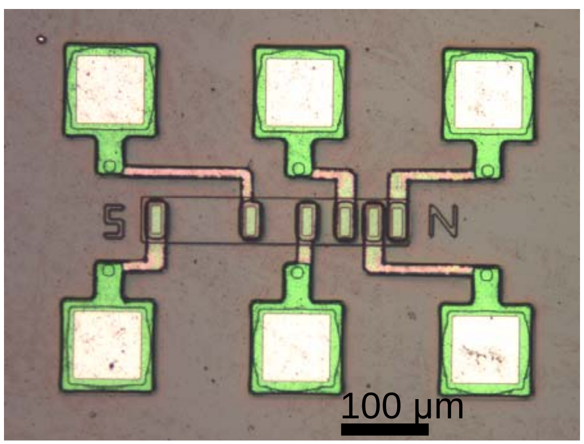
Microsystems Fabrication Clean Rooms: Class 100 and 1000

Microdevices Characterization Facilities

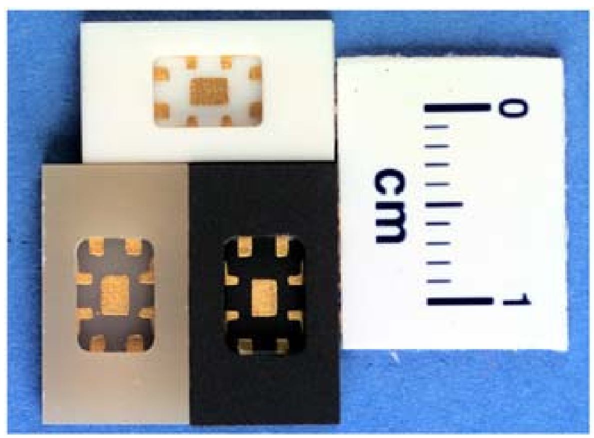
Previous Key NASA Glenn Advancements

Key fundamental high temperature electronic materials and processing challenges have been faced and overcome by systematic basic materials processing research (fabrication and characterization).

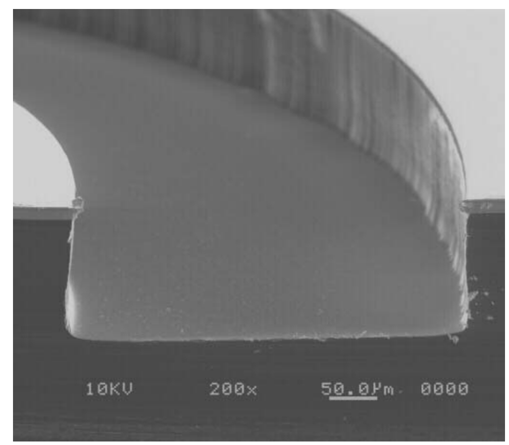
500 °C Durable Metal-SiC Contacts
(R. Okojie, 2000 GRC R&T Report)



500 °C Durable Chip Packaging
And Circuit Boards
(L. Chen, 2002 GRC R&T Report)



Improvements in SiC Microfabrication Processes
(L. Evans, 2006 GRC R&T Report)



Additional advancements in device design, insulator processing, etc., also made.

Harsh Environment SiC Pressure Sensors: an Overview

Objective:

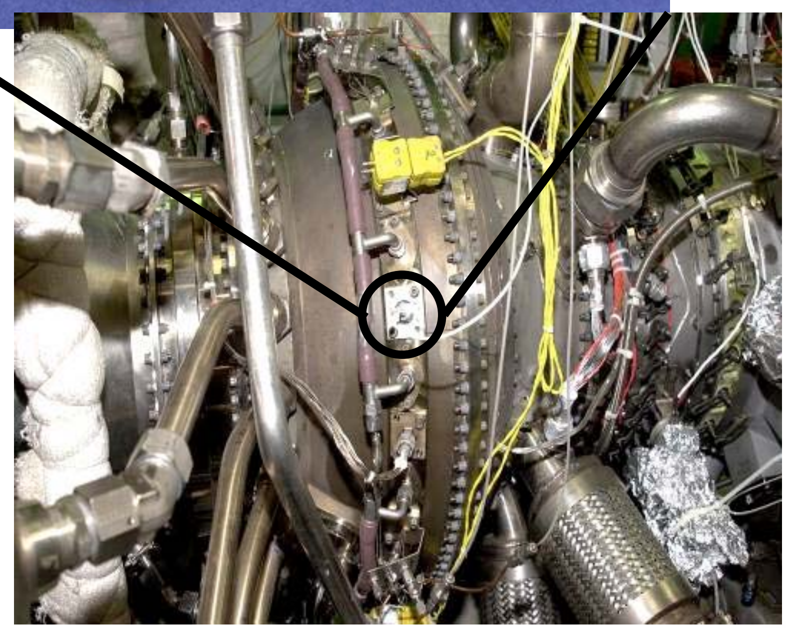
Develop high temperature (500 to 600 °C) SiC pressure sensors for:

- Engine health monitoring with wireless data transmission
- Active combustion control

Challenges:

- Reliable device packaging: failure at wire bonds
- Failure due to strains/stresses caused by CTE mismatch during heating/cooling
- Premature failure of diaphragms due to stress concentration

The developed technology that has solved these packaging challenges has been licensed to Endevco Corporation, San Juan Capistrano, CA



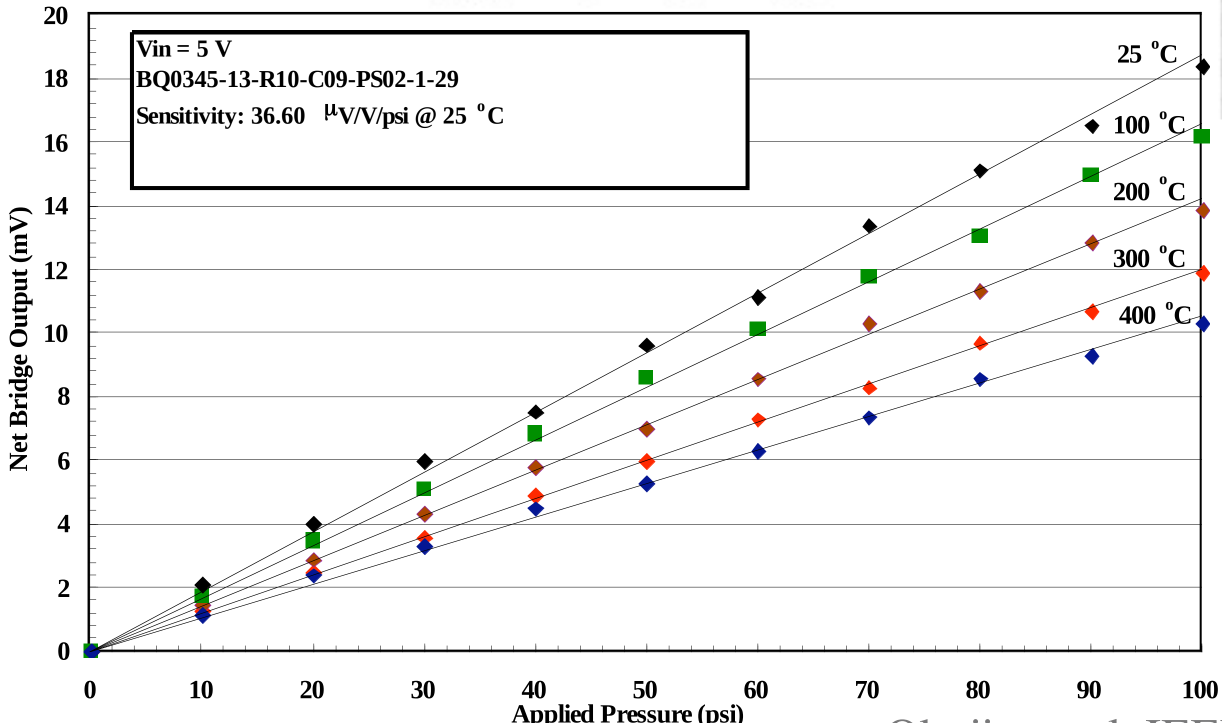
Real world application: pressure sensor installed in engine test

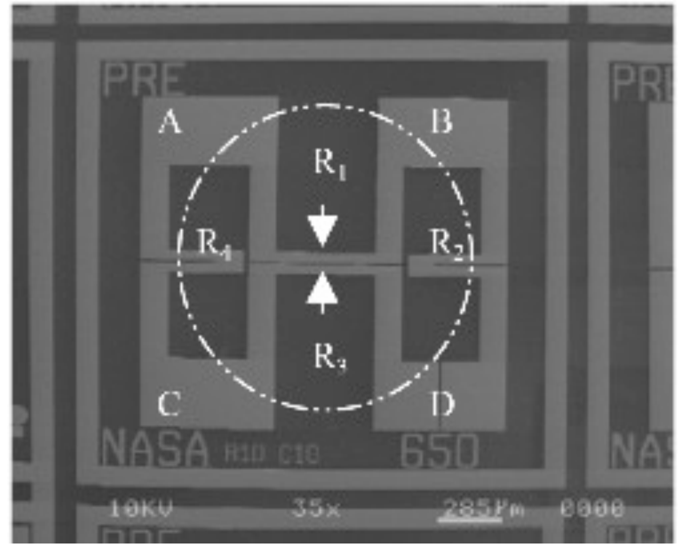
Concept

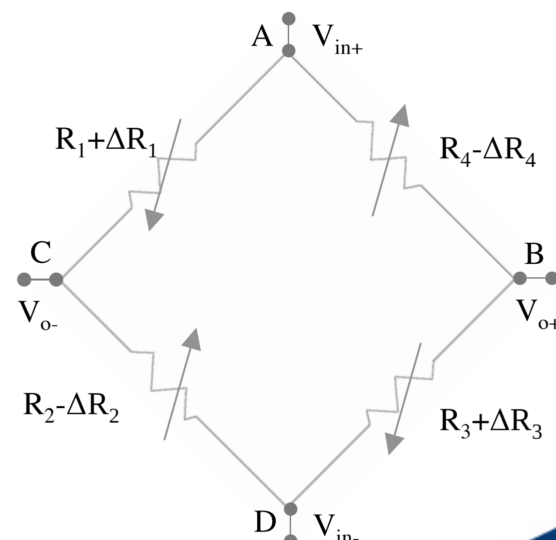
- Piezoresistive SiC Pressure Sensor

$$\Delta R_{\varepsilon}(T) = R_o G_o \left[1 + (\beta + \gamma)\Delta T + \gamma\beta(\Delta T)^2\right](\varepsilon + \delta)$$

$$V_{oz} = V_{in}\,\frac{1}{2}\left(\frac{R_2 - R_1}{R_1 + R_2} + \frac{R_4 - R_3}{R_3 + R_4}\right)$$

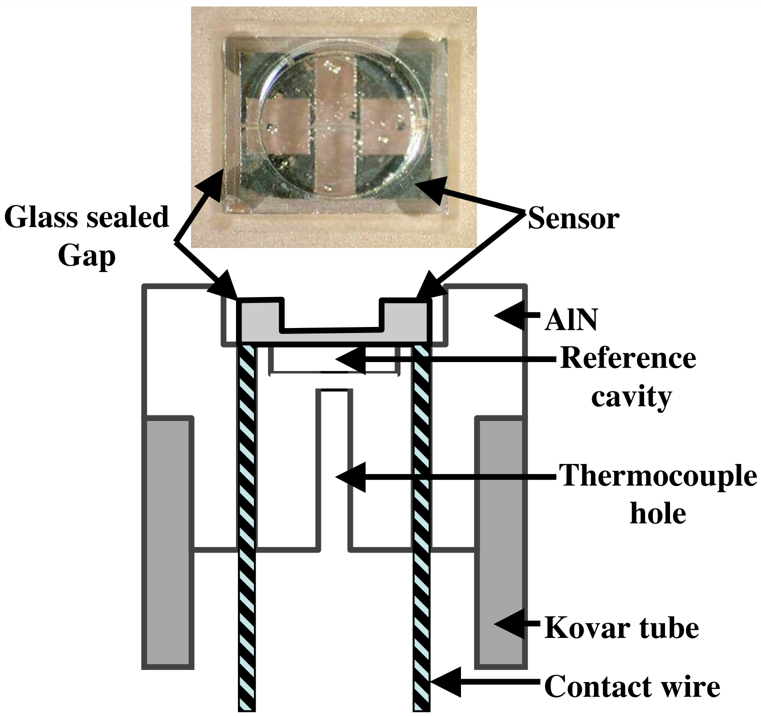




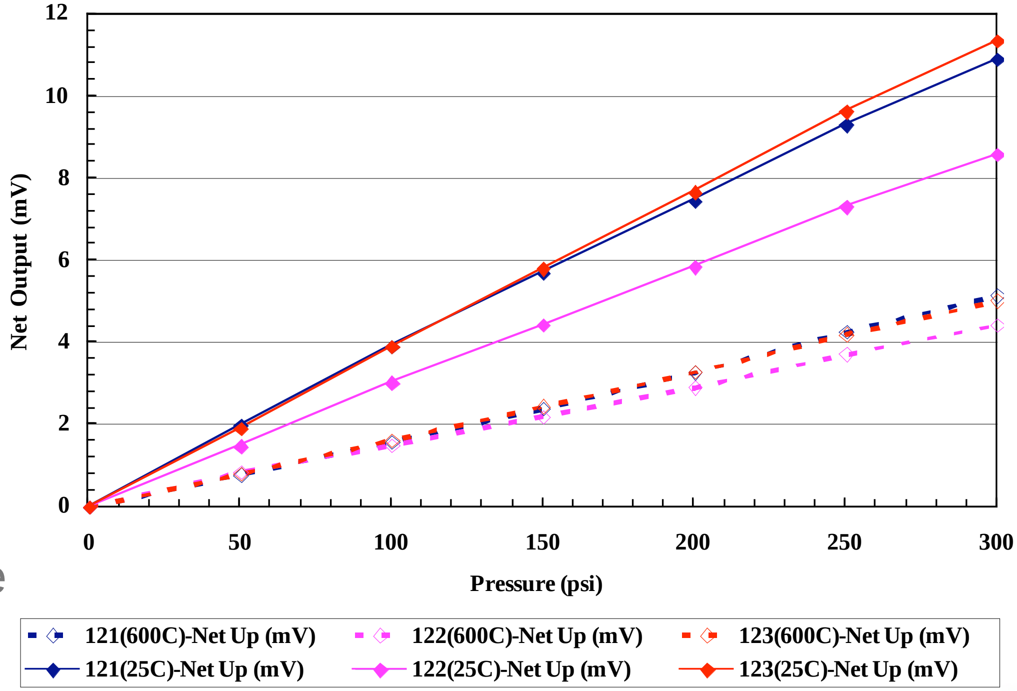


Okojie et. al. IEEE Sensors, Oct 2004

Harsh Environment SiC Pressure Sensors



MEMS-DCA (Direct Chip Attach) packaged SiC pressure sensor



Net output voltage of three SiC pressure sensors tested up to 600 °C

MEMS-DCA Sensor Attributes:

- Eliminates failures associated with wire bonds at high temperature
- Reduces thermomechanical stress by decoupling sensor from package

High Temperature SiC Electronics: an Overview

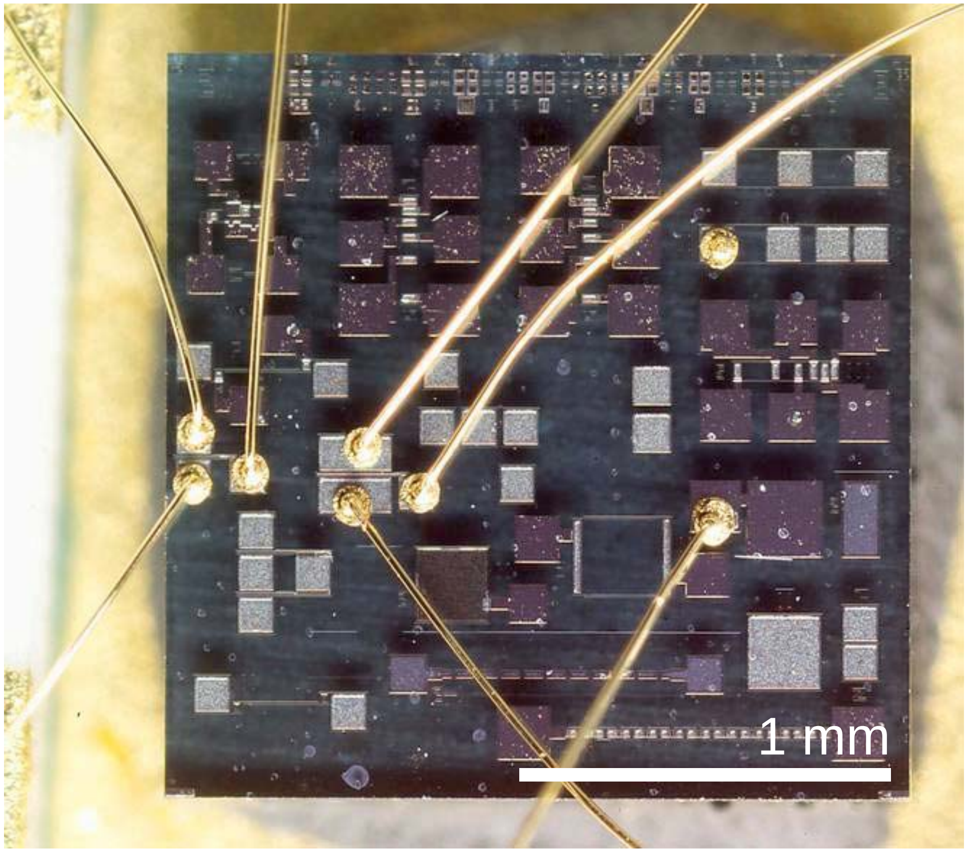
Objective:

Develop high temperature (500 °C) SiC electronics for:

- Wireless sensors
- Sensor signal conditioning – amplifier for SiC pressure sensor
- Distributed engine control – sensor multiplexing

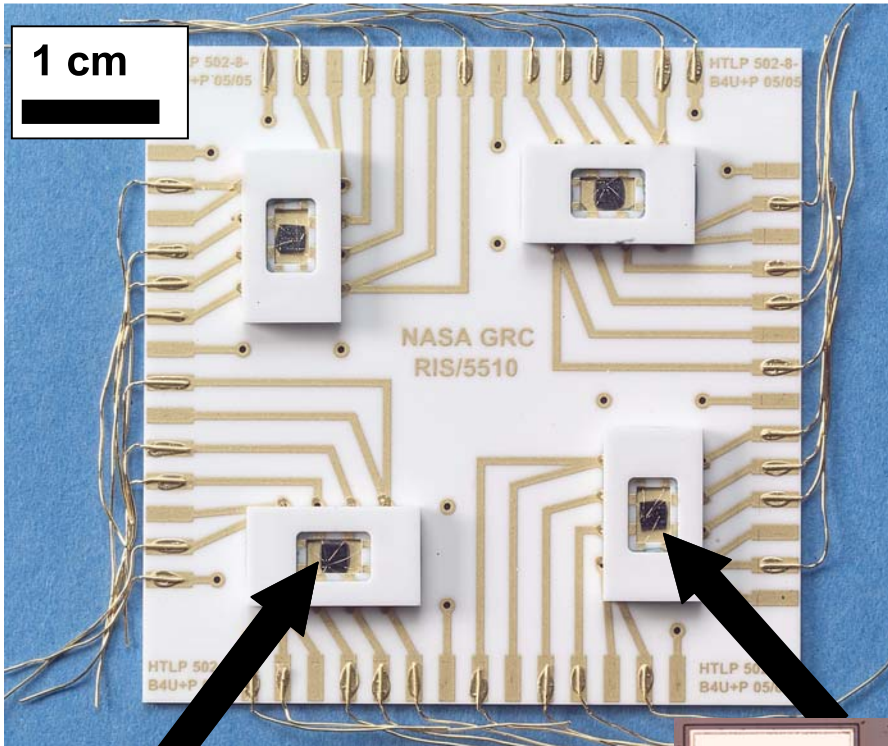
Challenges:

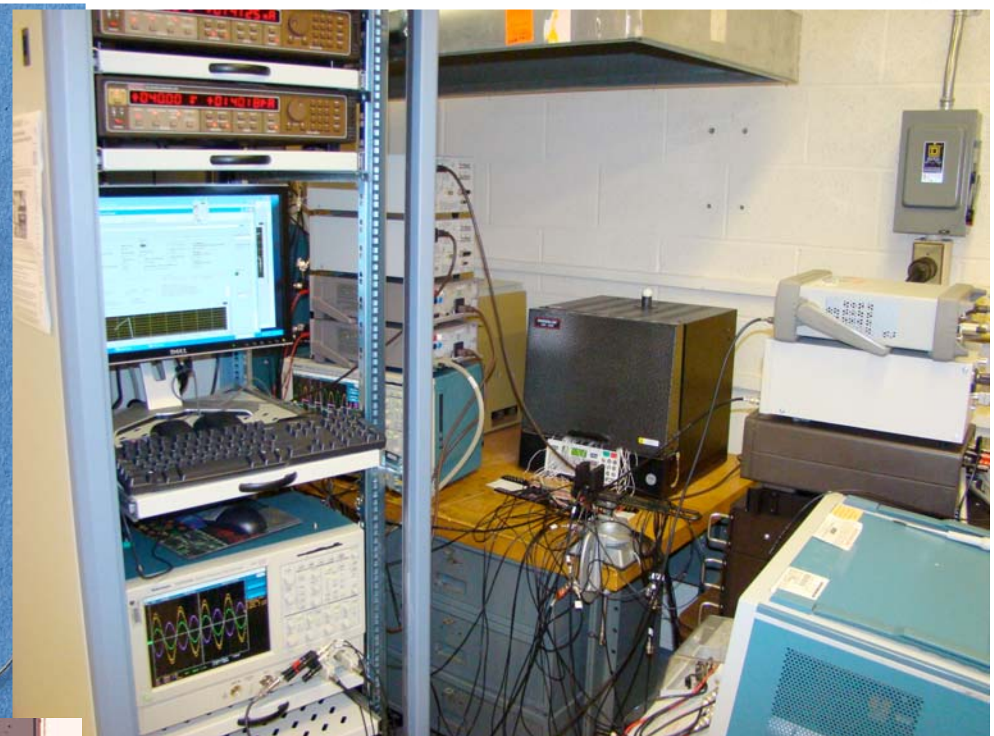
- Electronic structure robust against high temperature degradation
- Thermally activated degradation mechanisms at interfaces
    - Metal-SiC
    - Insulator-SiC
- Thermally activated degradation mechanisms at system level
    - Metals (e.g., contacts)
    - Insulators
    - Packaging

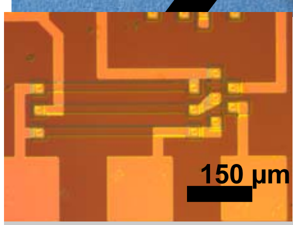


Testing of SiC JFET and SiC amplifiers. Packaging described in L.Y. Chen et. al., IMAPS Int. Conf. High Temp. Electronics, 2006

High Temperature SiC Electronics: Testing







Differential Amplifier

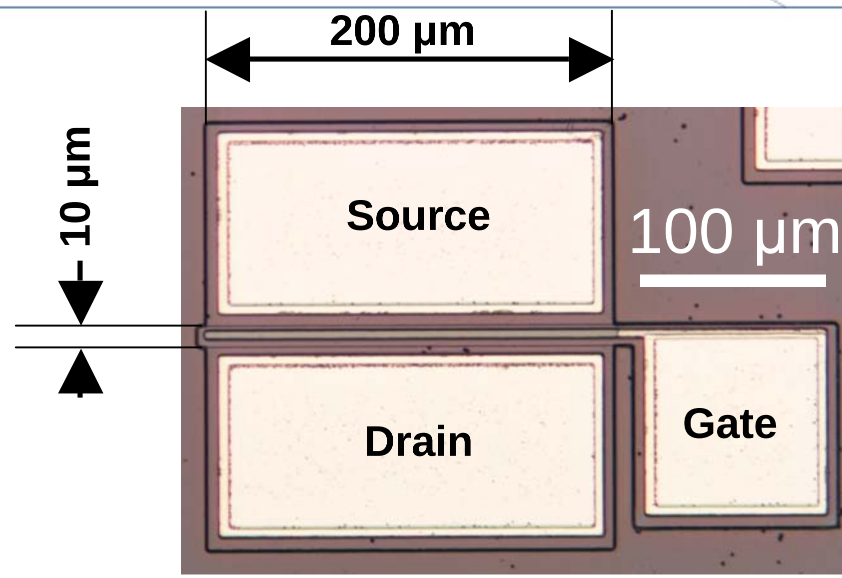
200µm/10µm 6H-SiC JFET

Boards with chips reside in ovens.
Oxidizing room air ambient.
Wires to test instrumentation.
Continuous electrical testing at 500 °C.

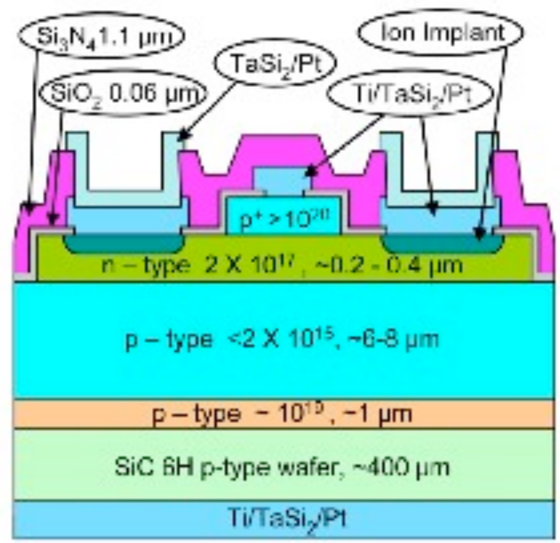
Testing discrete JFETs and integrated circuits at same time.

Junction Field Effect Transistor (JFET)

- Epitaxial pn-junction gate structure
- Low operating gate current - more robust at high temperatures
- Mesa-etched p$^+$ epi-gate structure to avoid defects and extreme activation temp of high-dose p-type implants



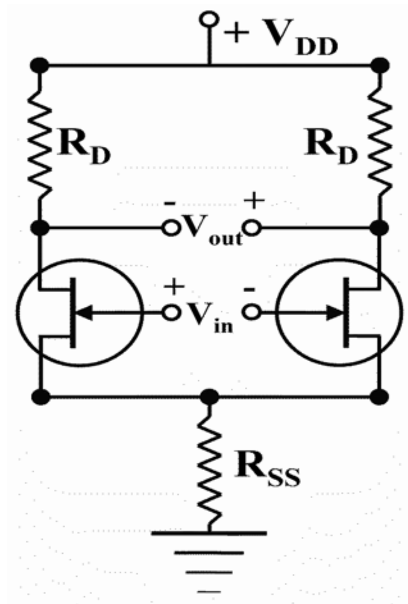
Cross-section of JFET



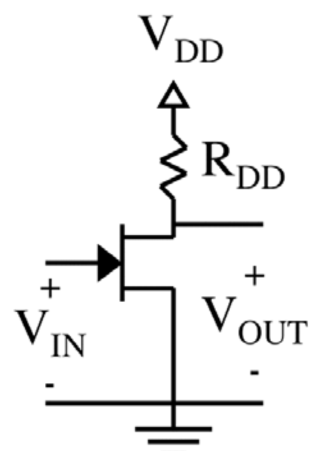
Spry et. al. Mater. Sci. Forum, 2008

Differential and Inverting Amplifiers (diff-amp and inv-amp)

- Amplifiers:
  - Control of motors or servos
  - Signal amplification applications
- Diff-amp:
  - Two source-coupled 20μm/10μm JFET
  - Three epitaxial load resistors (545 Ω)
- Inv-amp:
  - 80μm/10μm JFET
  - 20-square(516 kΩ @ 500 °C) epitaxial load resistor
- Goal: more complex analog and digital ICs, using multiple metal interconnect layers



Differential Amplifier

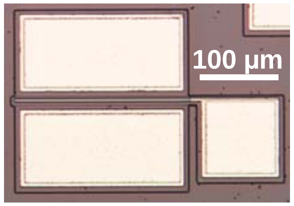


Inverting Amplifier

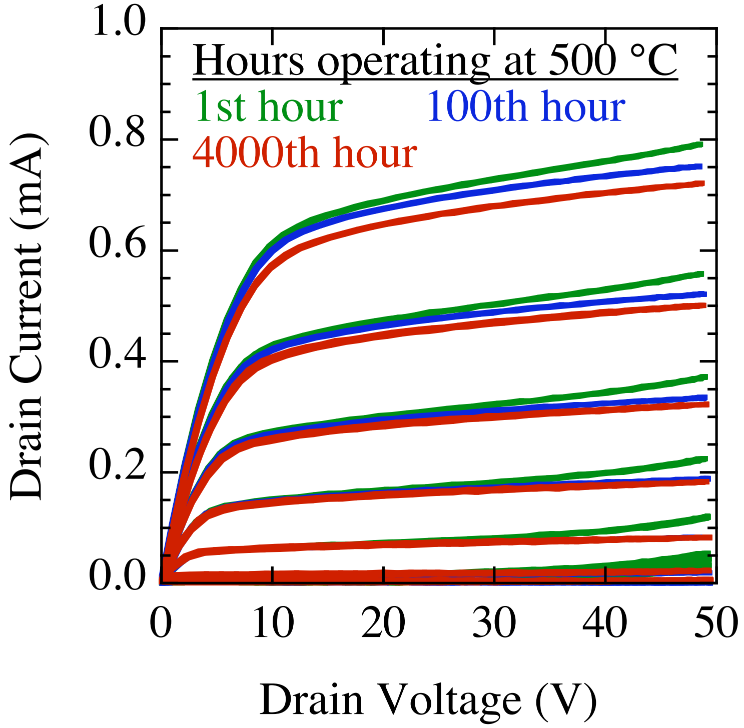
NASA Glenn Discrete SiC JFET Transistors: First to surpass 4000 hours of stable electrical operation at 500 °C

Current-voltage characteristics are very good and stable after 4000 hours
- Enables realization of analog integrated circuits (amplifiers, oscillators)

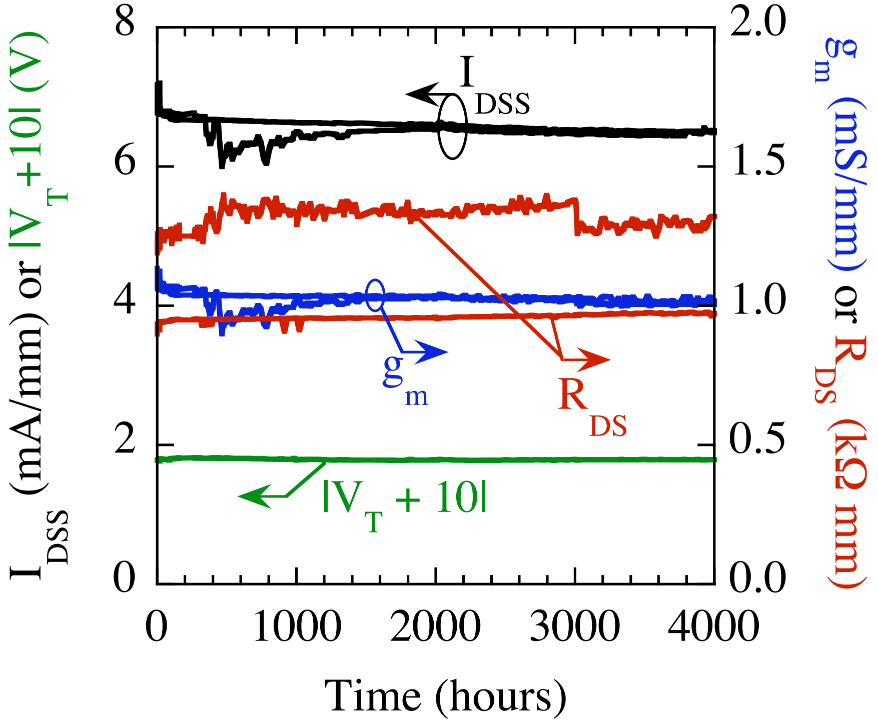
Excellent turn-off characteristics, ON to OFF current ratio
- Enables realization of digital circuits.



Current vs. Voltage Characteristics



Key Parameters vs. Time @ 500 °C



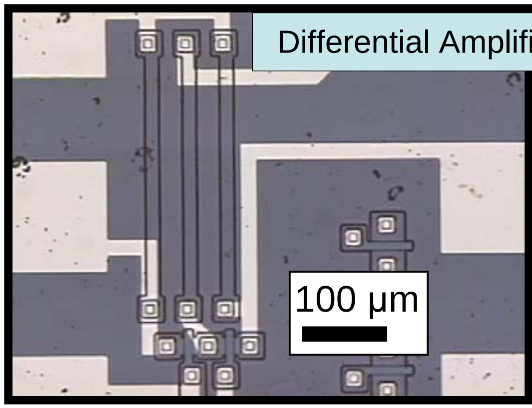
Less than 10% change occurs during 4000 hours operation at 500 °C.
- Most silicon transistor specs sheets list larger parameter variations.

NASA Glenn SiC Amplifiers: First semiconductor IC to surpass 3000 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.

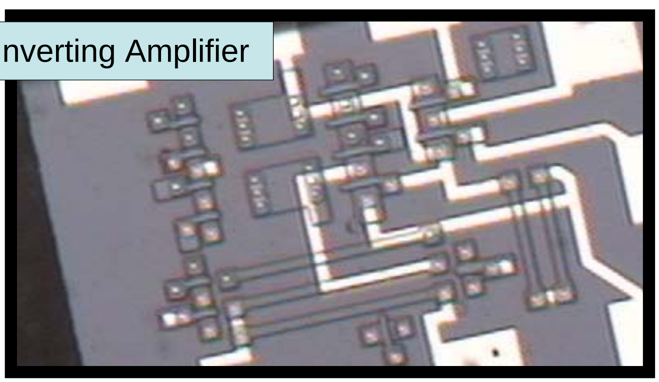
Optical micrograph of demonstration amplifier circuit before packaging

Differential Amplifier



2 transistors and 3 resistors integrated into less than half a square millimeter.

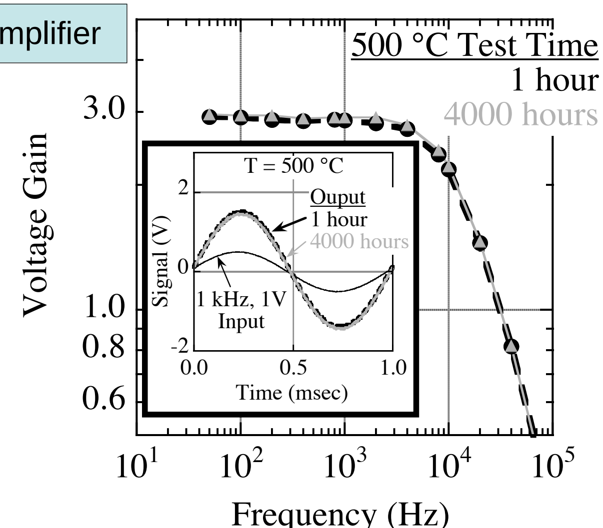
Inverting Amplifier



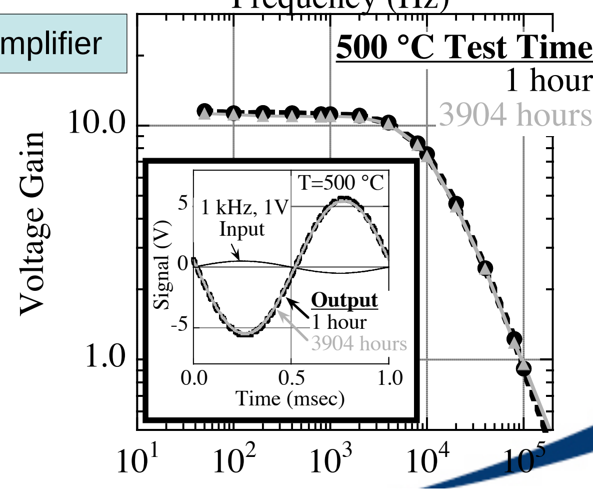
Less than 3% change in operating characteristics during 3000 hours of 500 °C operation.

Gain vs. Frequency at 500 °C

Differential Amplifier



Inverting Amplifier



Conclusion

- Future work:
  - Continuation of high temperature testing
  - Continued improvement of fabrication procedures
  - Fabrication of improved devices based on knowledge gained
- Long term goals:
  - Technology transfer for SiC electronics work
  - Complete integration of electronics and sensors for total harsh environment sensing capability
  - Continue to push the envelope of what is possible in high temperature electronics and sensors, e.g., smart wireless sensor systems

Acknowledgments

Work is carried out at NASA GRC by:

- Glenn M. Beheim
- Carl W. Chang
- Liang-Yu Chen
- Gary W. Hunter
- Dorothy Lukco
- Philip G. Neudeck
- Robert S. Okojie
- David J. Spry

- Charles A. Blaha
- Robert Buttler
- Jose M. Gonzalez
- Kimala L. Laster
- Lawrence G. Matus
- Kelley M. Moses
- Michelle M. Mrdenovich
- Beth A. Osborn
- Andrew J. Trunek

NASA Funding

The work in this talk has been supported by NASA's Aeronautics Research Mission Directorate:

- IVHM: Integrated Vehicle Health Management
- Supersonics
- Hypersonics
- Subsonic Fixed Wing
- Subsonic Rotary Wing

Recent press releases:

http://www.nasa.gov/centers/glenn/news/pressrel/2007/07-053_patents.html

http://www.nasa.gov/centers/glenn/news/pressrel/2007/07-035_Electric_Chip.html