Silicon Carbide Sensors and Electronics for Harsh Environment Applications

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Silicon carbide (SiC) semiconductor has been studied for electronic and sensing applications in extreme environment (high temperature, extreme vibration, harsh chemical media, and high radiation) that is beyond the capability of conventional semiconductors such as silicon. This is due to its near inert chemistry, superior thermomechanical 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.

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

- Microsystems block diagram
- Benefits to NASA
- Introduction
  - Electronic and sensing applications in extreme environments
  - SiC - advantages for harsh environment applications
- NASA GRC facilities
- NASA GRC advancements
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  - Overview
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- High Temperature SiC Electronics
  - Overview
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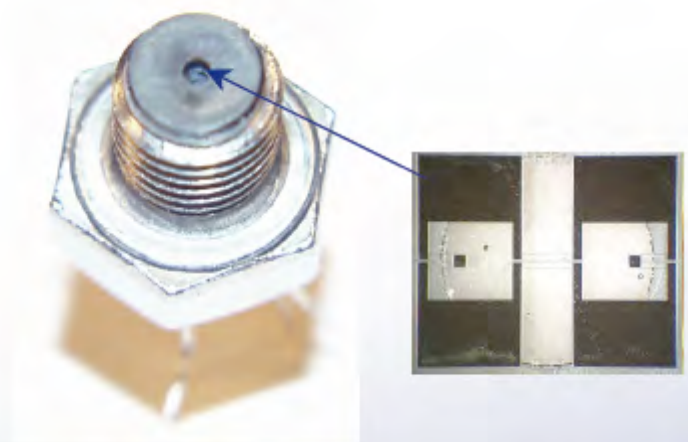
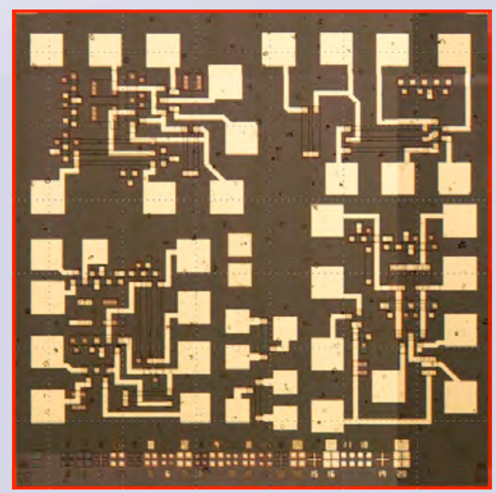
  - State-of-the-art at NASA GRC
- Conclusion
- Acknowledgements

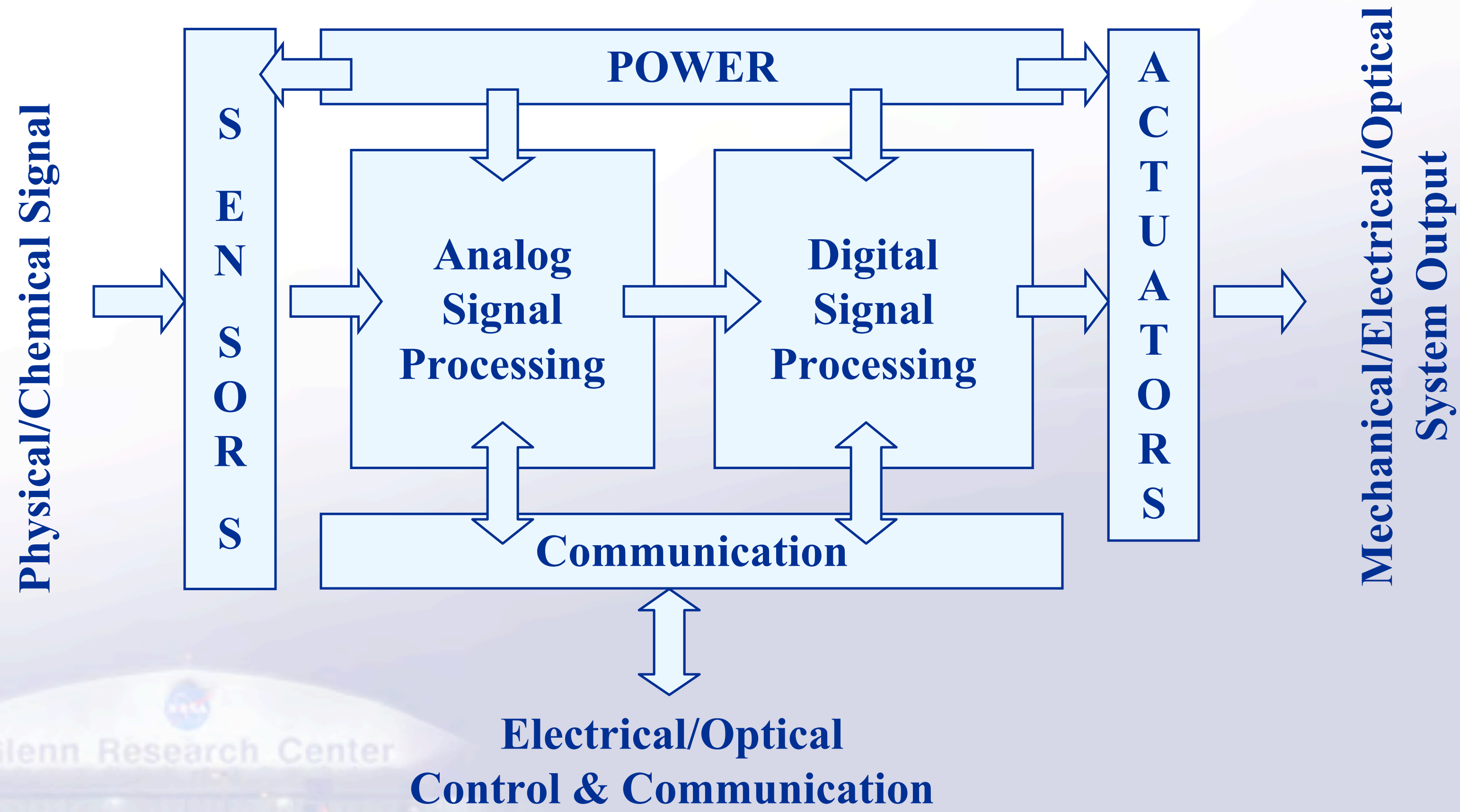


Micro-Electro-Mechanical Systems (MEMS)



High Temperature SiC Electronics

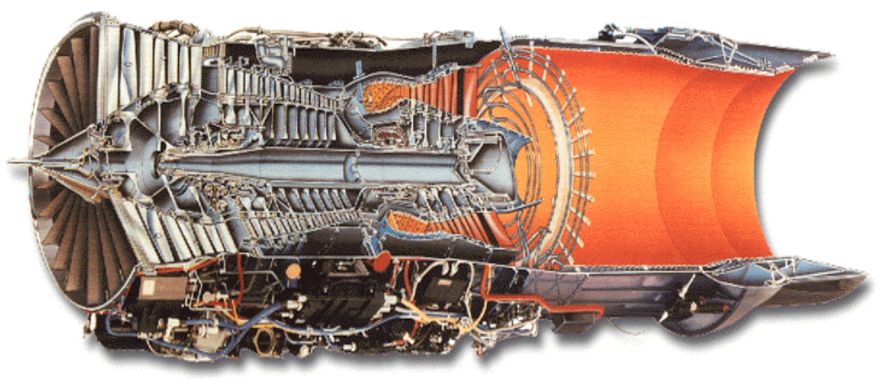
Microsystem Block Diagram



Large-scale integrated electronics 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

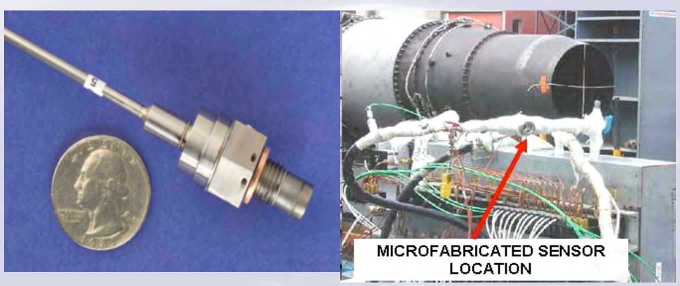
Venus Exploration

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

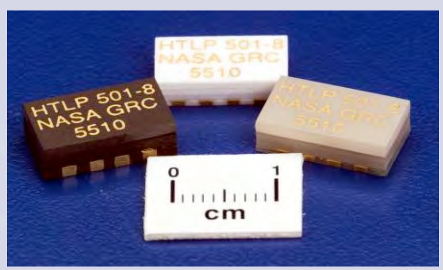
Applications

- 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

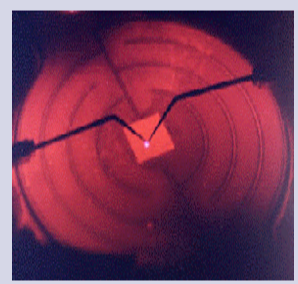
Range of Physical and Chemical Sensors for Harsh Environments



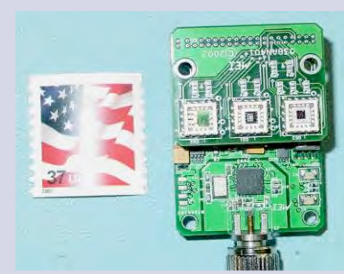
Harsh Environment Packaging (2000 hours at 500 °C)



High Temperature Signal Processing and Wireless



Long Term: High Temperature "Lick and Stick" Systems



Technologies for Harsh Environments

- 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

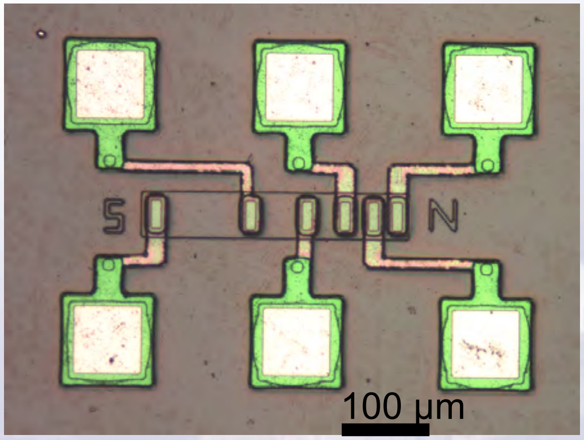
Microsystems Fabrication Clean Rooms: Class 100 and 1000

Microdevices Characterization Facilities

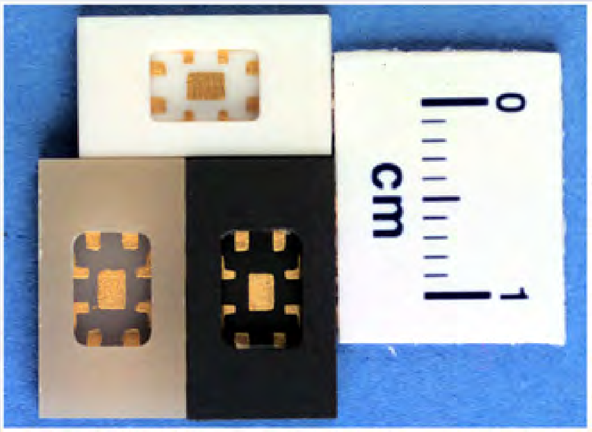
Previous Key NASA Glenn Advancements

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

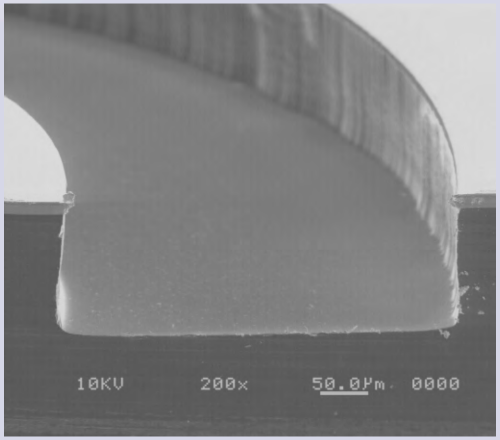
500 °C Durable Metal-SiC Contacts
(R. Okojie, 2000 GRC R&T Report)



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

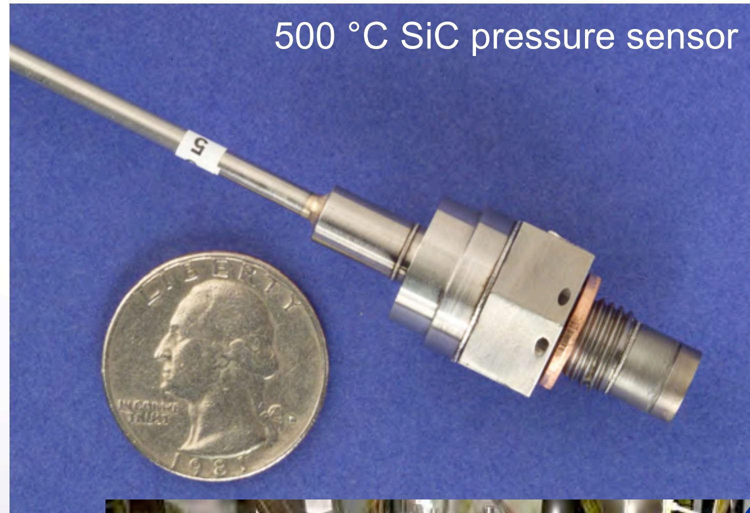
Objective:

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

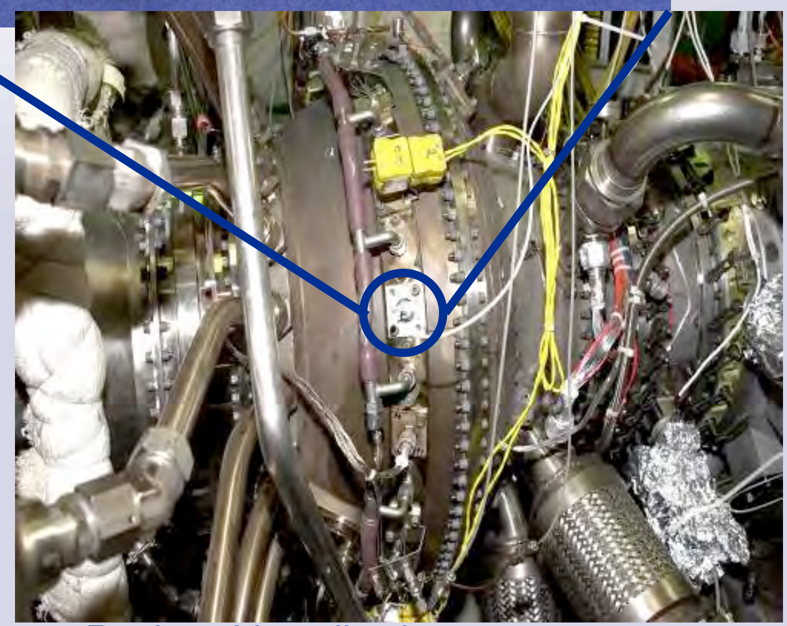
- Engine health monitoring with wireless data transmission
- Active combustion control

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

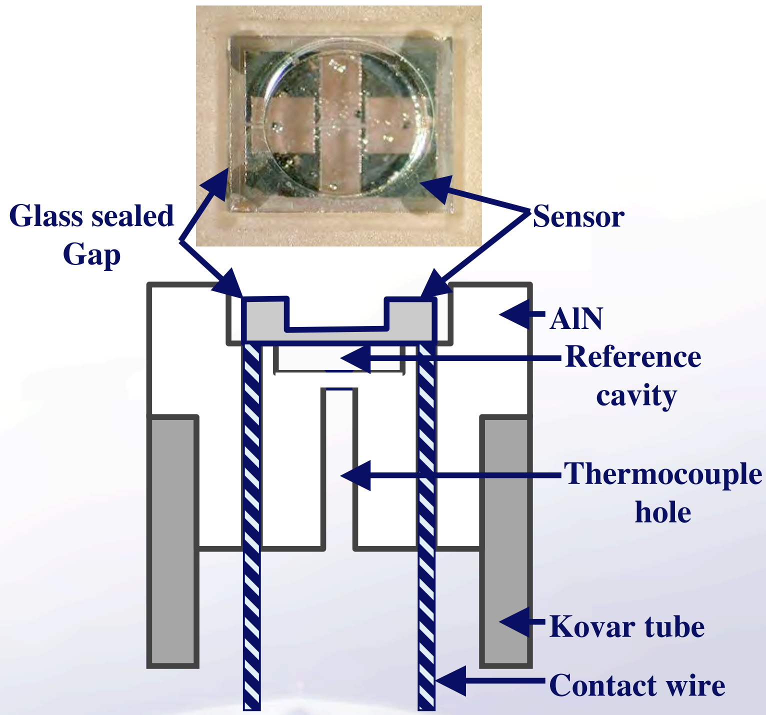


500 °C SiC pressure sensor



Real world application: pressure sensor installed in engine test

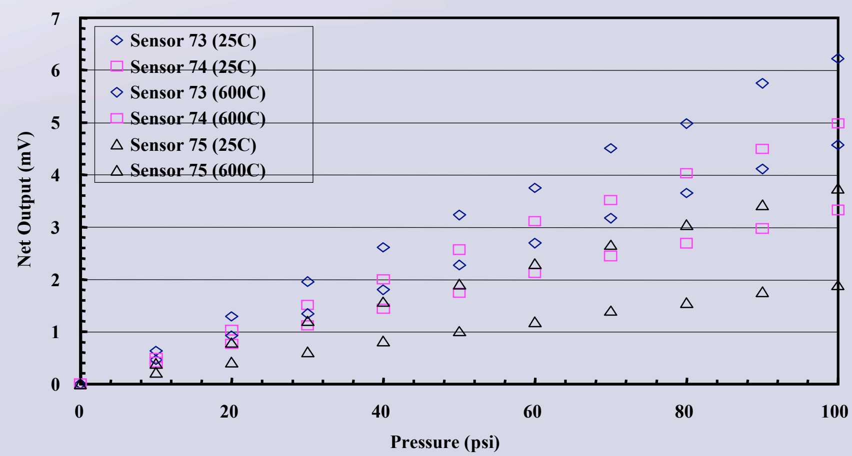
Harsh Environment SiC Pressure Sensors



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

MEMS-DCA Sensor Attributes:

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



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

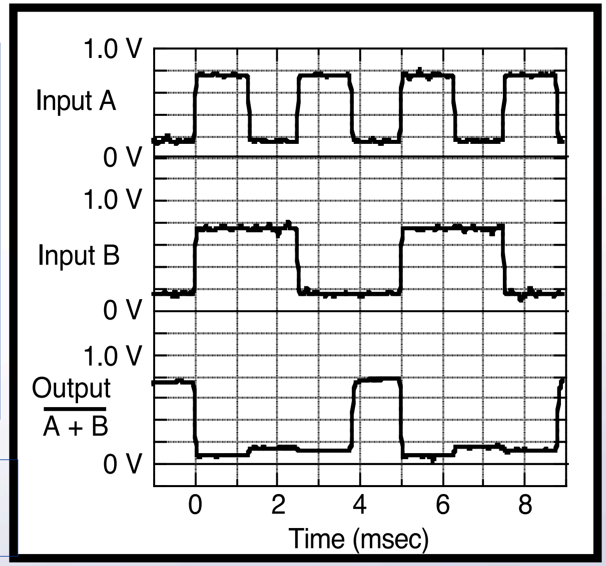
High Temperature SiC Electronics: an Overview

Objective:

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

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

A	B	$\overline{A+B}$
0	0	1
0	1	0
1	0	0
1	1	0

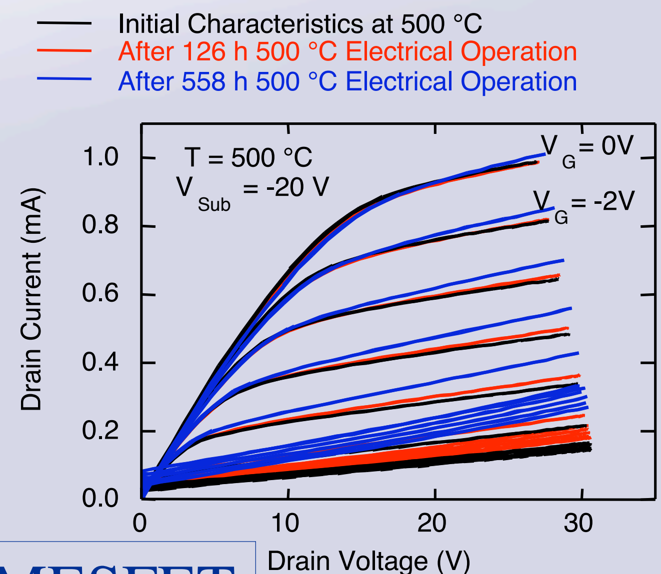


1997 NOR gate

Previous Accomplishments:

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

- 1997 - 6H-SiC Junction Field Effect Transistor (JFET) NOR Gate <u>hour long</u> test at 600 °C on probe station
- 2004 - <u>Record setting</u> demonstration of SiC Metal-Semiconductor Field Effect Transistor (MESFET) at 500 °C for <u>500 hours</u> – failure (10% degradation) due to annealing of metal-semiconductor gate interface, incomplete turn-off

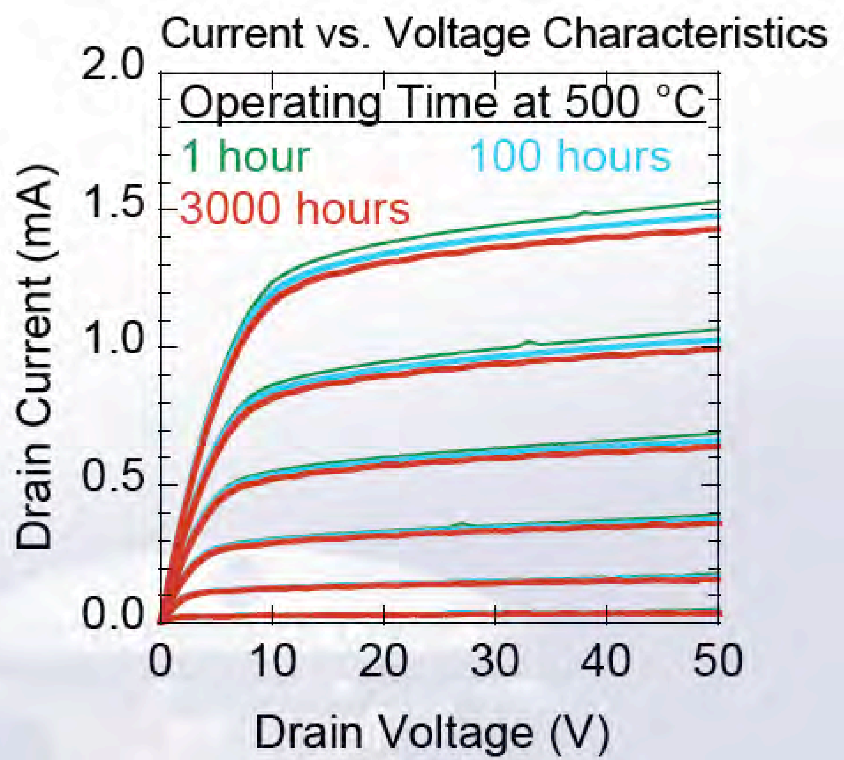


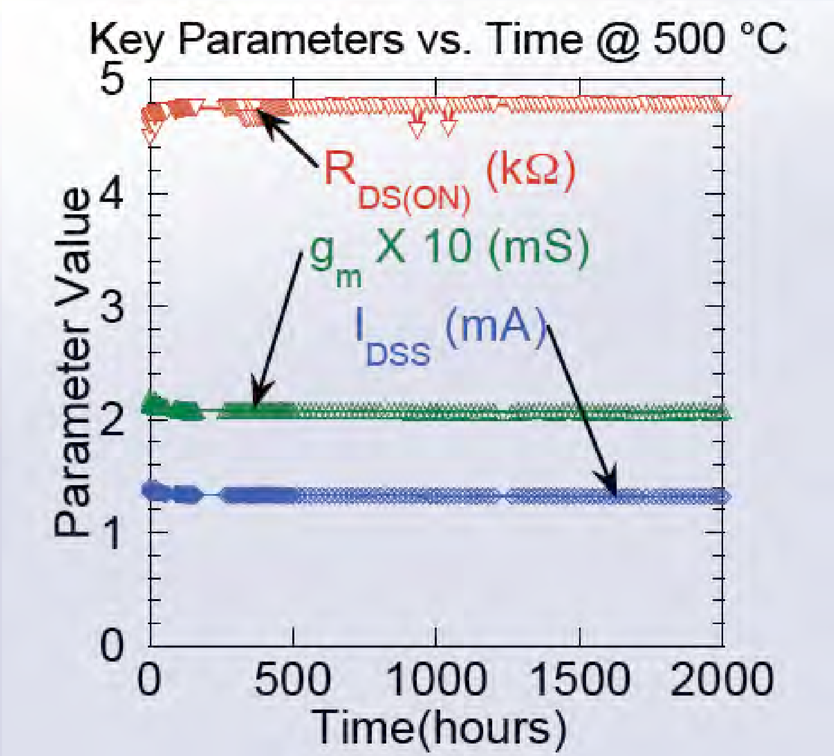
2004 MESFET

NASA Glenn Discrete SiC JFET Transistors: First to Surpass 3000 Hours of Stable Electrical Operation at 500 °C

Current-voltage characteristics are very good and stable after 3000 hours
- Enables realization of analog integrated circuits (amplifiers, oscillators)

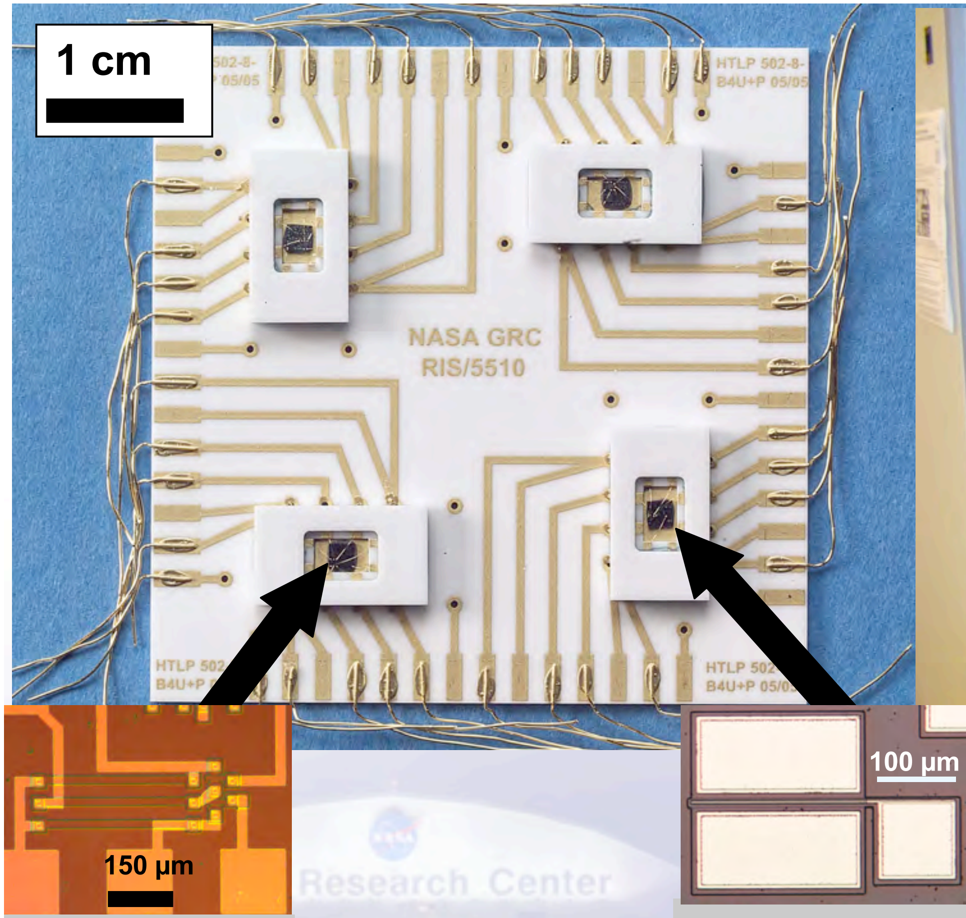
Excellent turn-off characteristics, ON to OFF current ratio
- Enables realization of digital circuits.





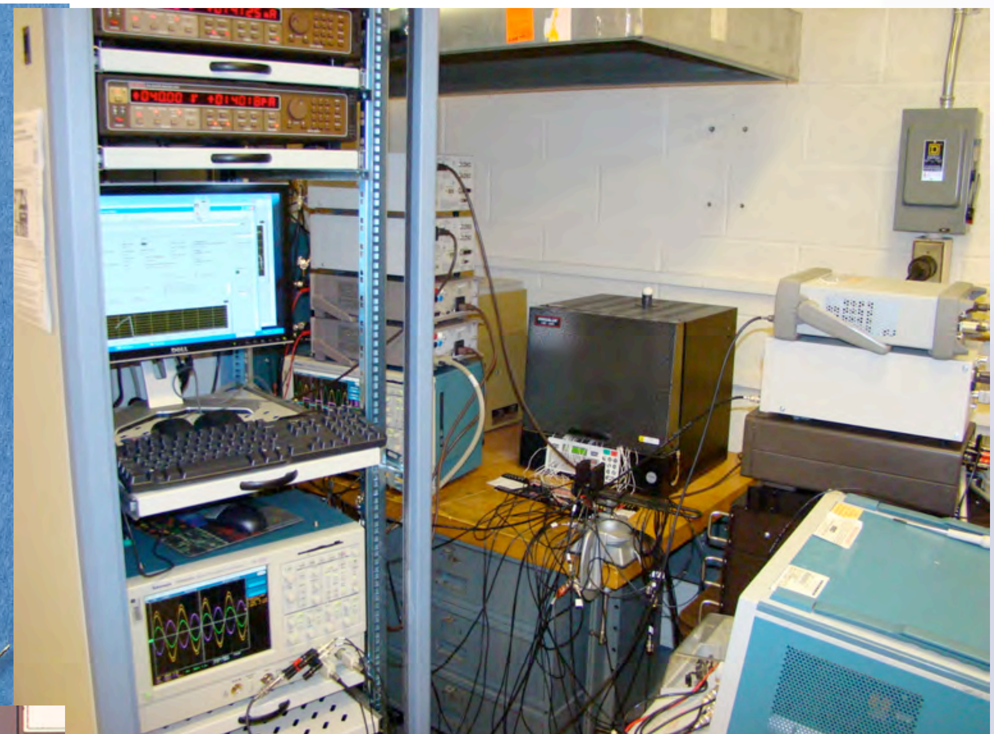
Less than 7% change occurs during 3000 hours at 500 °C.
- 7% change is smaller than listed on most silicon transistor specs sheets.

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.

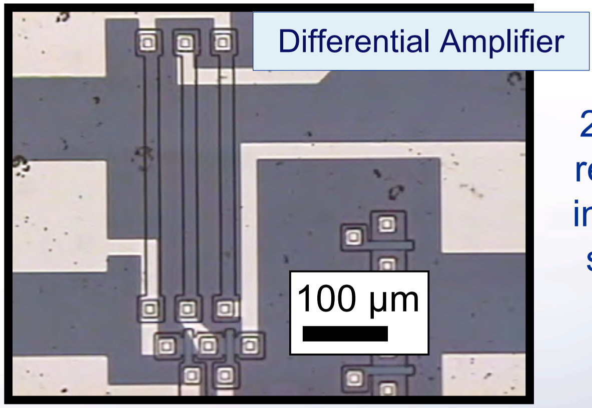
Testing discrete JFETs and integrated circuits at same time.

NASA Glenn Silicon Carbide Amplifiers

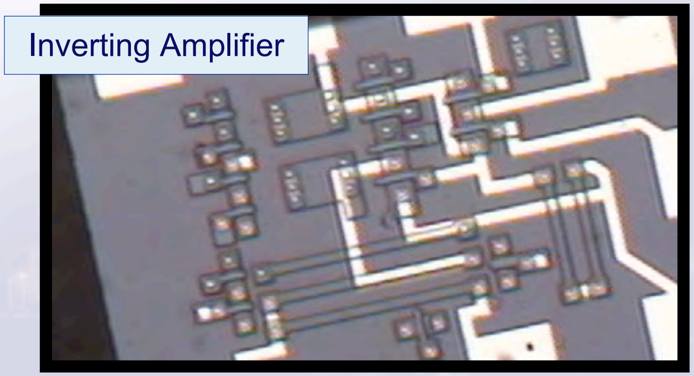
World's First Semiconductor IC to Surpass 3000 Hours of Electrical Operation at 500 °C

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

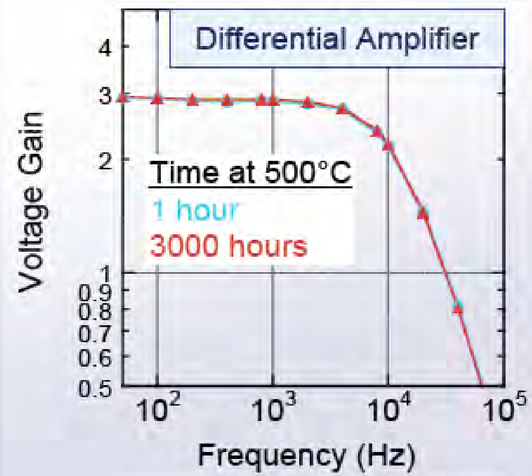


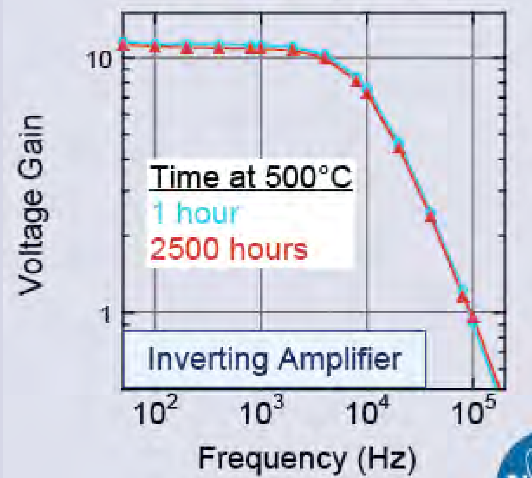
2 transistors and 3 resistors integrated into less than half a square millimeter.



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

Gain vs. Frequency at 500 °C





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 in progress for SiC Pressure Transducer work
  - 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

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- Supersonics
- Hypersonics
- Subsonic Fixed Wing
- Subsonic Rotary Wing

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