Silicon Carbide Sensing Technology for Extreme Harsh Environments

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Berkeley Sensor & Actuator Center

SiC Sensing Technology for Extreme Harsh Environments

The National Science Foundation
Industry/University Cooperative Research Center on MEMS

*"BSAC conducts **industry-relevant, interdisciplinary research** on micro- and nano-scale sensors, moving mechanical elements, microfluidics, materials, and processes, and systems that take advantage of progress from integrated circuit, networking, bio, and polymer technologies."*

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Marvell Nano Lab

SiC Sensing Technology for Extreme Harsh Environments

Cory Hall Micro Lab moved to new "Nano Lab" in 2009

- ***Micro Lab achievements in the decade of CITRIS include:***
- 500 active users from 100 faculty PIs
- Enabled $320M research funding since 2000 (~ $40M/year)
- Trained work force for CA: > 2,000 MS/PhD/Postdocs and > 1,300 BS
- **Provided critical technology support for 86 companies (76 start-ups)**
- **Created 1,000 jobs in those start-ups**

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Presentation Outline

SiC Sensing Technology for Extreme Harsh Environments

- **Introduction**
  - New Requirements for Power and Propulsion Systems
- **Properties of Silicon Carbide (SiC)**
- **SiC Thin Film Encapsulation**
- **SiC Strain Sensors @ 600ºC**
- **SiC Wireless Combustion Monitoring System**
- **Conclusions**

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Introduction

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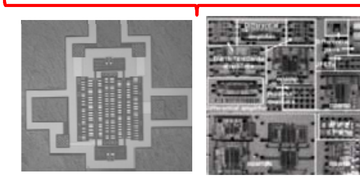
SiC Sensing Technology for Extreme Harsh Environments

- **Next generation power & propulsion systems require**
  - Increased efficiency
  - Reduced emissions
  - Fuel flexibility
- **Real-time sensing in harsh environments (e.g. combustion) can be used to obtain control data.**
  - Enable condition based monitoring
  - Predict failure of materials and critical components
  - Prevent combustion instabilities
  - Prevent stalling/surge
  - Reduce NO_x and CO_2 emissions



Harsh Environment (600ºC Operation) Sensors and ICs

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Harsh Environment Sensing

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SiC Sensing Technology for Extreme Harsh Environments

nergy dustries	Aircraft Propulsion	Automotive Engines	Industrial Gas Turbines	Geothermal	Oil & Gas Exploration
inimum ensing peratures	600ºC	300ºC	600ºC	374ºC	275ºC
esired ensing asurands	Pressure Temperature Flame Speed Acceleration	Pressure Temperature Flame Speed O_2	Pressure Temperature Hydrocarbon Acceleration	Pressure Temperature H_2S Strain	Pressure Temperature Hydrocarbon Strain

- **"Harsh environment" includes extremes of pressure, temperature, shock, radiation and chemical attack.**
- **Sensing within harsh environments enables real-time monitoring of <u>combustion</u>, <u>subsurface environments</u>, and <u>critical components</u>.**

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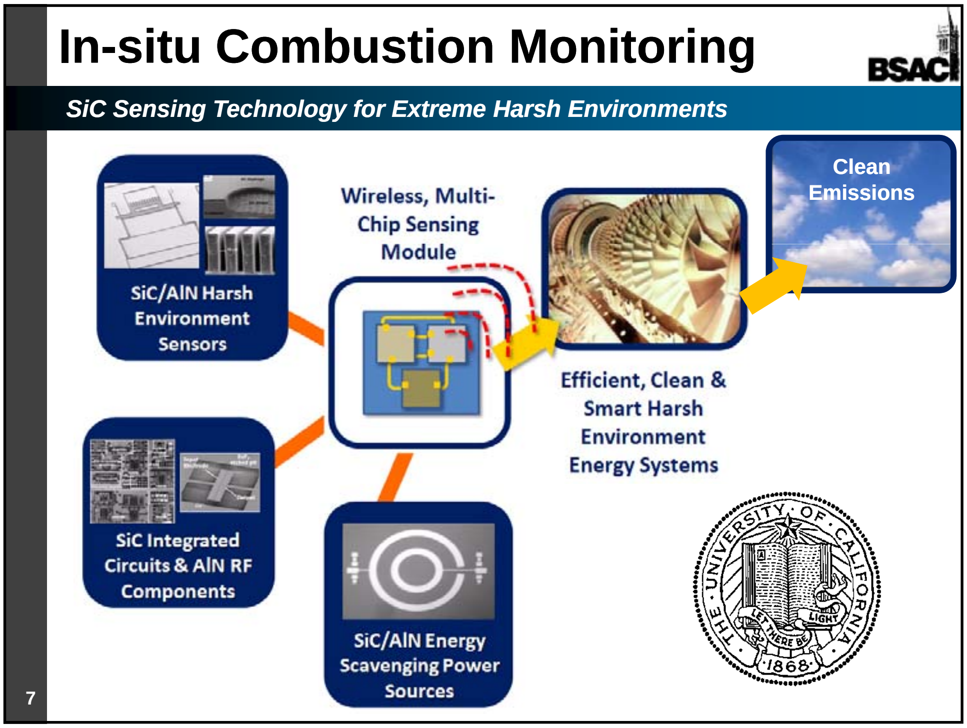
In-situ Combustion Monitoring
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SiC Sensing Technology for Extreme Harsh Environments
SiC/AlN Harsh Environment Sensors
Wireless, Multi-Chip Sensing Module
Efficient, Clean & Smart Harsh Environment Energy Systems
Clean Emissions
SiC Integrated Circuits & AlN RF Components
SiC/AlN Energy Scavenging Power Sources
THE UNIVERSITY OF CALIFORNIA LET THERE BE LIGHT 1868
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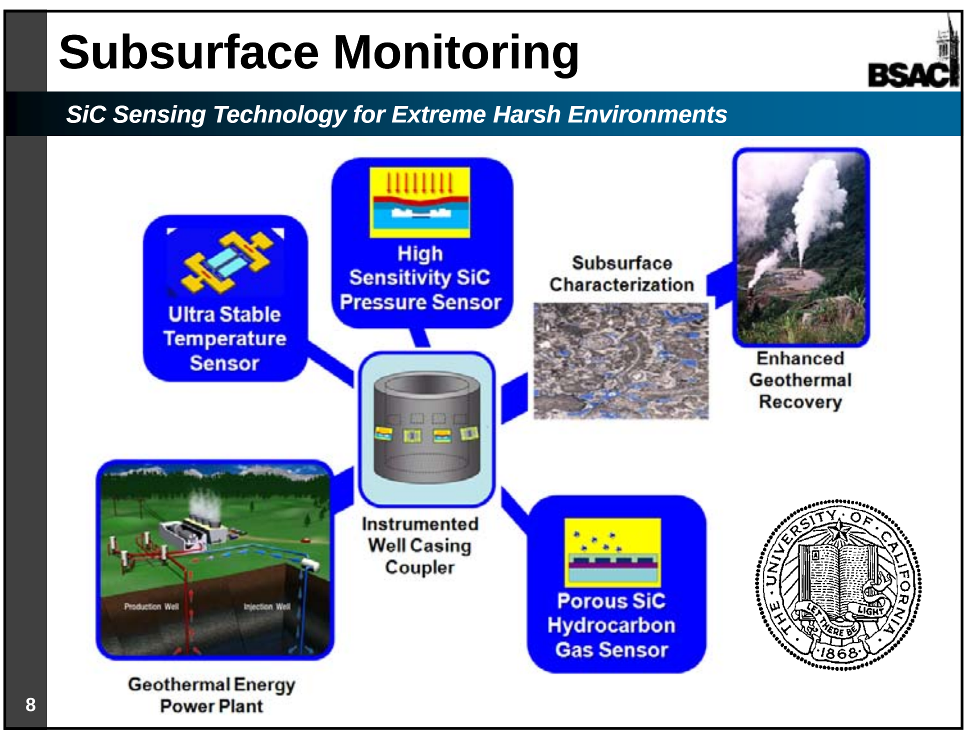
Subsurface Monitoring
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Ultra Stable Temperature Sensor
High Sensitivity SiC Pressure Sensor
Subsurface Characterization
Enhanced Geothermal Recovery
Instrumented Well Casing Coupler
Porous SiC Hydrocarbon Gas Sensor
Geothermal Energy Power Plant
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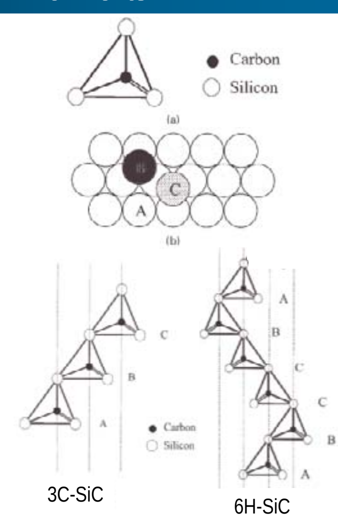
Silicon Carbide (SiC)

SiC Sensing Technology for Extreme Harsh Environments

- **Semiconductor material**
  - p-type with Al doping
  - n-type with N doping
- **200+ polytypes have been identified**
  - Commonly used polytypes are 3C-SiC, 4H-SiC & 6H-SiC



Schematic of atomic arrangement and stacking order of SiC (Mehregany et al.).

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Lightweight SiC

SiC Sensing Technology for Extreme Harsh Environments

Herschel telescope: The Herschel telescope is almost entirely made of silicon carbide, a highly polishable, stable, and lightweight ceramic material and coated with a very thin layer of aluminum, for reflectivity. (Credit: European Space Agency, ESA)

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Material Properties

SiC Sensing Technology for Extreme Harsh Environments

Material properties of SiC and other materials used by the semiconductor industry.

Property	Silicon Carbide 3C-SiC (6H-SiC)	Silicon	Diamond
Melting Point (ºC)	2830 (2830) sublimes	1420	4000 phase change
Energy Gap (eV)	2.4 (3.0)	1.12	5.6
Critical Field ($\times10^6$ V/cm)	2.0 (2.5)	0.25	5.0
Thermal Conductivity (W/cm-K)	5.0 (5.0)	1.5	20
Young's Modulus (GPa)	450 (450)	190	1035
Acoustic Velocity (x10^3 m/s)	11.9 (11.9)	9.1	17.2
Yield Strength (GPa)	21 (21)	7	53
Coeff. of Thermal Expansion (ºC $\times10^{-6}$)	3.0 (4.5)	2.6	0.8
Chemical Stability	Excellent	Fair	Fair

→ SiC is a mechanically robust, chemically inert and electrically stable ceramic semiconductor material.

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SiC Resistance Testing

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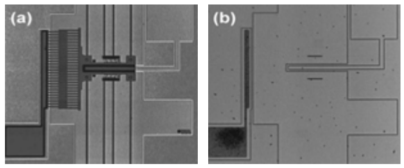
Chemical Resistance:

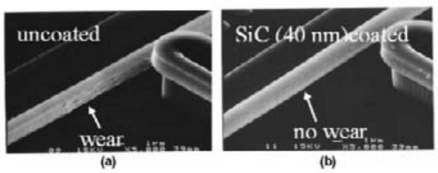


Optical images of (a) SiC-coated and (b) uncoated polysilicon structures following immersion in 65ºC KOH for 1 minute

Mechanical Toughness:

Material	Fracture Strain	Fracture Stress (GPa)
Poly-Si	1.5%	2.5
Poly-SiC	3.3%	23

Wear Resistance:



SEM images of (a) poly-Si after 250,000 cycles and (b) SiC-coated beam after 1 million cycles of high contact pressure rubbing.

Oxidation Resistance:

Material	Oxide Thickness after 100 hours in Air at 850ºC
Diamond-like Carbon (DLC)	Completely burned out after 24 hours
Si	300 nm
Poly-SiC	50 nm

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M.B.J. Wijesundara, D. Gao, A.P. Pisano & R. Maboudian

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SiC TAPS Project

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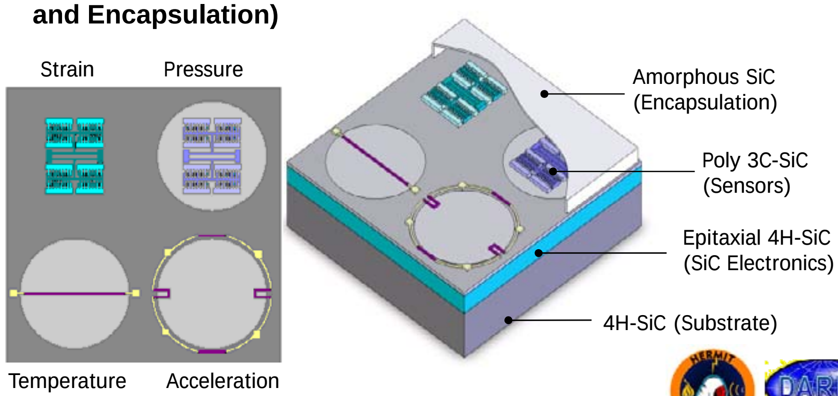
SiC Sensing Technology for Extreme Harsh Environments

- **Development of extreme harsh environment TAPS (<u>T</u>emperature, <u>A</u>cceleration, <u>P</u>ressure, and <u>S</u>train) sensors on a single chip that can operate at 600ºC and survive shocks above 10,000 g.**
- **Silicon carbide (SiC) as a platform material (Electronics, Sensors, and Encapsulation)**



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Thin Film Encapsulation

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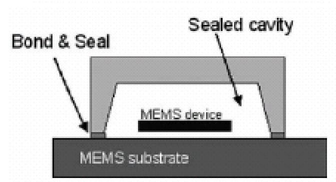
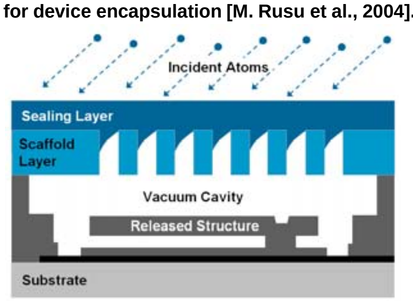


Schematic diagram of bond and seal method for device encapsulation [M. Rusu et al., 2004].



Schematic diagram of wafer-level thin film encapsulation method displaying the sealing and scaffold layers.

- **Thin film sputtering in high vacuum enables <u>line-of-sight</u> deposition**
  - Long mean free path (λ) in high vacuum

$$\lambda = \frac{k_B T}{\sqrt{2}\pi d^2 P}$$

λ = Mean free path
k_B = Boltzmann Constant
T = Temperature
P = Pressure
d = Diameter of particle

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Ion Beam Sputtering System

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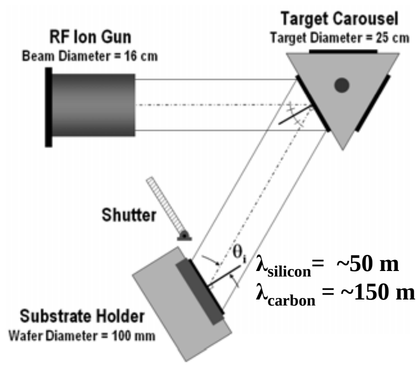

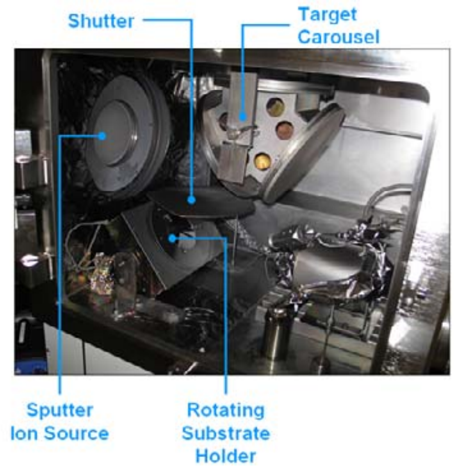

Parameter	Value
Pressure	~3x10^{-6} Torr
Temperature	25^{o}C to 430^{o}C
Substrate Size	4 inch and 6 inch
Angle of Incidence	0^{o} to 60^{o}

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Schematic illustration (left) and picture (right) of the ion beam sputtering system.

Film Characterization

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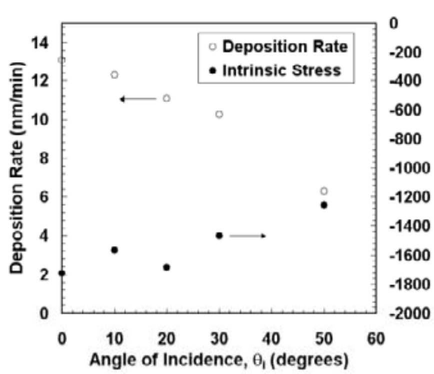
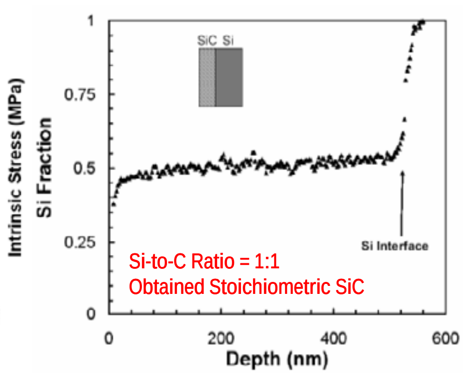


Plot of the film stress and deposition rate vs. angle of incidence for low-temperature deposited films



Results from Rutherford Backscattering Spectroscopy (RBS) of sputter deposited amorphous SiC film without substrate heating

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D.G. Jones (Senesky) et al., IEEE MEMS Conference (2007)

Line-of-Sight Topography

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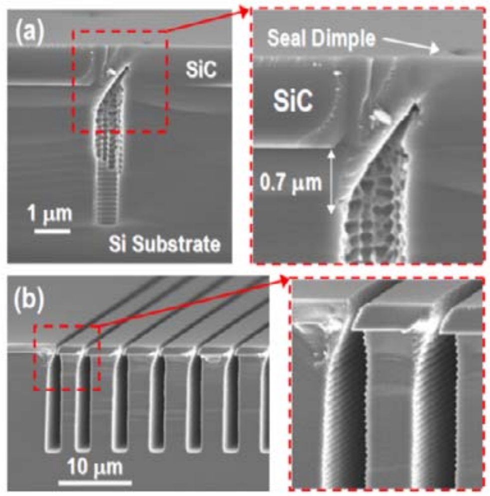

D.G. Jones (Senesky) et al., IEEE MEMS Conference (2007)

SEM images of deposit topography for an angle of incidence of 50°.

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Amorphous SiC Sealing Layers

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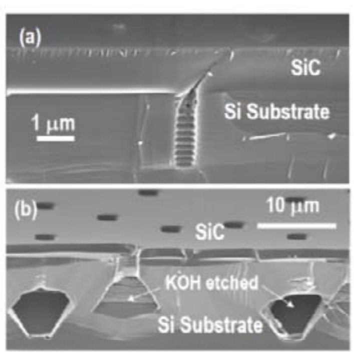
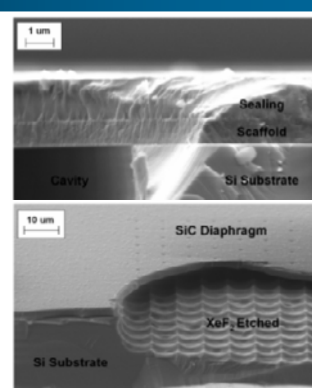


SEM images of structures upon exposure to hot (80 °C) KOH for 15 minutes.



SEM images of sealed diaphragms to be utilized for device encapsulation.

- **Ion beam sputter deposition of amorphous SiC for low temperature sealing layers for device encapsulation diaphragms.**
- **Film deposition to seal structures was demonstrated and film characterization was performed.**

D.G. Jones (Senesky) et al., IEEE MEMS Conference (2007)

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LPCVD Polycrystalline 3C-SiC

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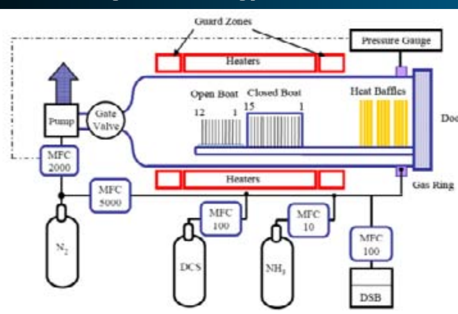

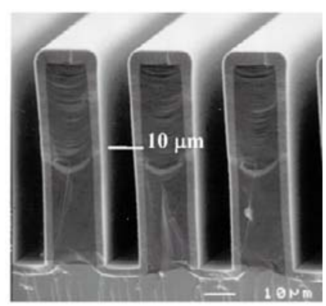

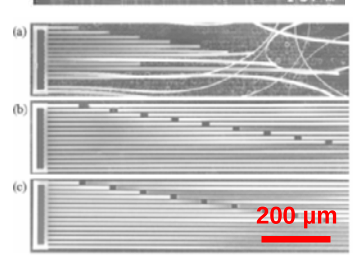

- **Low pressure chemical vapor deposition (LPCVD) of polycrystalline 3C-SiC**
  - 4 inch and 6 inch wafers
  - Deposition temperature = 800ºC
  - Precursors
    - Disilabutane ($CH_3SiH_2CH_2SiH_3$)
    - Ammonia (NH_3)
- **Process was optimized to obtain low stress, strain gradient and resistivity films.**

C.S. Roper et al., Electrochemical and Solid-State Letters (2008)

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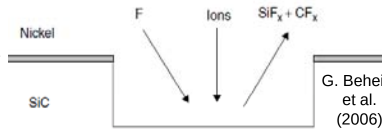
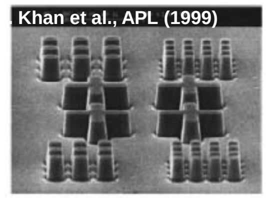
Plasma Etching of SiC

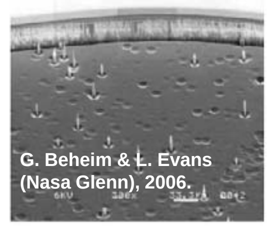
SiC Sensing Technology for Extreme Harsh Environments

- **Plasma etching is typically utilized to pattern SiC features**
  - Fluorinated gases (CHF_3, CF_4, SF_6 and NF_3) in combination with O_2
    - Si + 4F → SiF_4
    - C + xO → (CO, CO_2)
    - C + xF → CF_x
  - Metal masks etch masks
    - High selectivity (> 50:1)
    - Micromasking defects
    - Degrades health of etch tools
  - Typically slow etch rates are observed (< 0.2 µm/min)
  - Higher etch rates have been obtained in custom etch tools (2.1 µm/min)



G. Beheim et al. (2006)





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Plasma Etching of SiC

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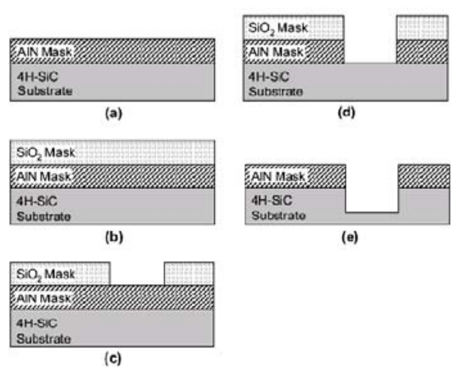
Material	Product	Boiling Point (°C)
SiC	SiF_4	-95.7
	CF_4	-128
	CO_2	-78.5
	CO	-191.5
	SiO_2	2590
AlN	AlF_3	1275
	Al_2O_3	3000

Table of the boiling points of possible by-products formed by etching SiC and AlN in SF_6/O_2



Schematic diagram of the fabrication process used to create samples for the etch study utilizing AlN as a masking material for etching SiC in SF_6/O_2 etch chemistries.

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D.G. Senesky & A.P. Pisano, IEEE MEMS Conference (2010)

SiC Etch (SF_6/O_2) Results

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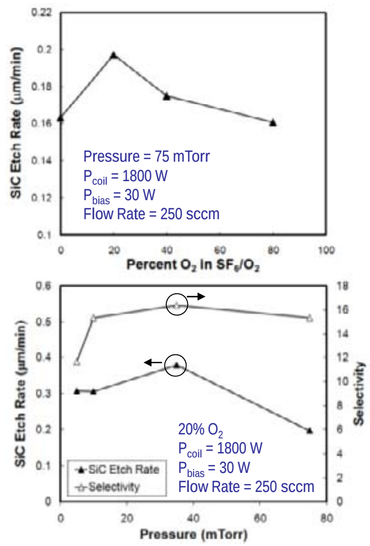

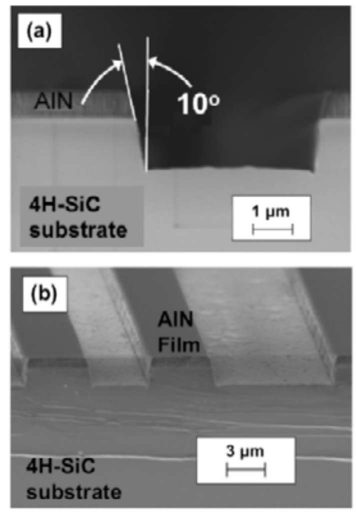

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D.G. Senesky & A.P. Pisano, IEEE MEMS Conference (2010)

Resonant Strain Gauge

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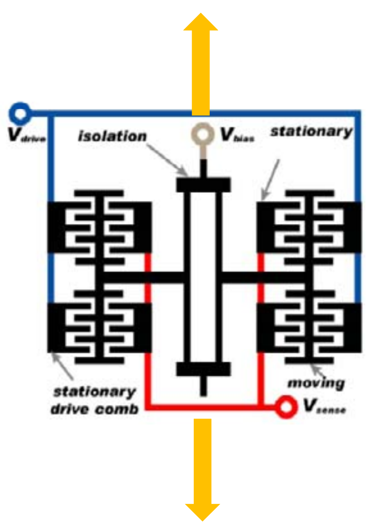

Natural frequency of fixed-fixed beam with lumped mass (m_1) at center:

$$f_n = \sqrt{\frac{k}{m}}$$

$$f_n = \frac{1}{2\pi}\sqrt{\frac{198.6EI_{xz}}{L^3(0.397\rho AL + m_1)} + \frac{4.85EA\varepsilon}{L(0.397\rho AL + m_1)}}$$

f_n = natural frequency
k = spring constant
ε = strain
m = mass
ρ = density
E = Young's Modulus
I_{xz} = Moment of Inertia
A = area
L = length

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R.G. Azevedo, D.G. Jones (Senesky), A. V. Jog, B. Jamshidi, D. R. Myers, L. Chen, X. Fu, M. Mehregany, M. B. J. Wijesundara, & A.P. Pisano, IEEE Sensors Journal (2007)

SiC Resonant Strain Gauge

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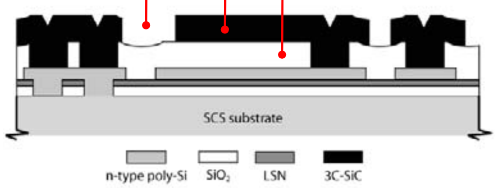
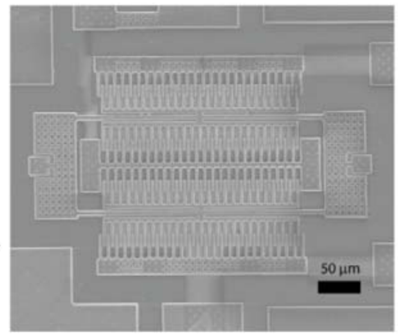


Cross-sectional image of the SiC strain sensor fabrication process.



SEM image of polycrystalline 3C-SiC (7um thick) resonant strain sensor.

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R.G. Azevedo, D.G. Jones (Senesky), A. V. Jog, B. Jamshidi, D. R. Myers, L. Chen, X. Fu, M. Mehregany, M. B. J. Wijesundara, & A.P. Pisano, IEEE Sensors Journal (2007)

SiC Sensor Operation at 600˚C

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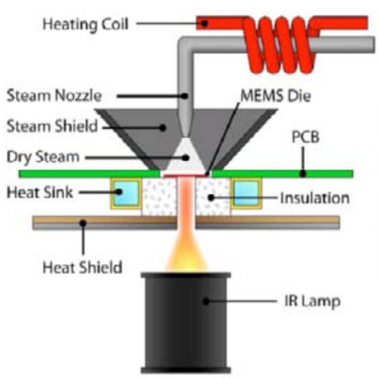
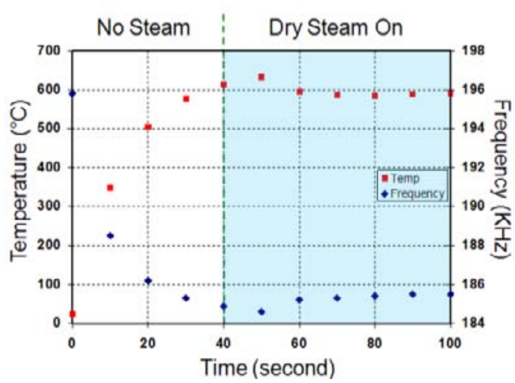
SiC Sensing Technology for Extreme Harsh Environments





- **The polycrystalline 3C-SiC sensor resonates in air and can operate at 600°C in dry steam**
- **The strain sensor has a sensitivity of 66 Hz/με and resolution of 0.045 με in a 10 kHz bandwidth**
- **This poly-SiC sensor utilizes a fabrication process that can be utilized realize other harsh environment sensors.**

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D. R. Myers et al., J. Micro/Nanolith. MEMS MOEMS (2009)

G-Shock Testing at 64,000 g

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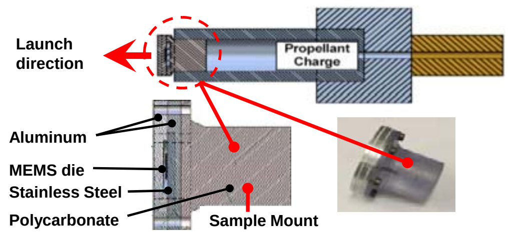
SiC Sensing Technology for Extreme Harsh Environments

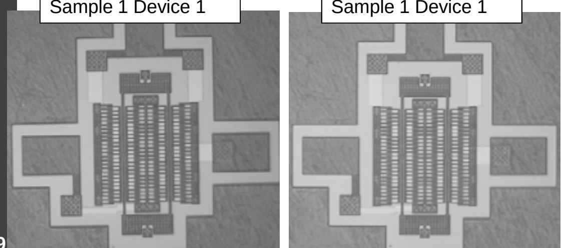
Gas Gun Schematics



- G-shock Testing carried out at Aerophysics Research Center at University of Alabama in Huntsville
- Hard-launch soft-catch method
- Initial G-load is 64,000 g.

Before G-shock
Sample 1 Device 1

After G-shock
Sample 1 Device 1



- **No structural damage after g-shock at 64,000g**
- **Successfully operates (resonates) after enduring a 64,000 g shock**

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Wireless Combustion Monitoring

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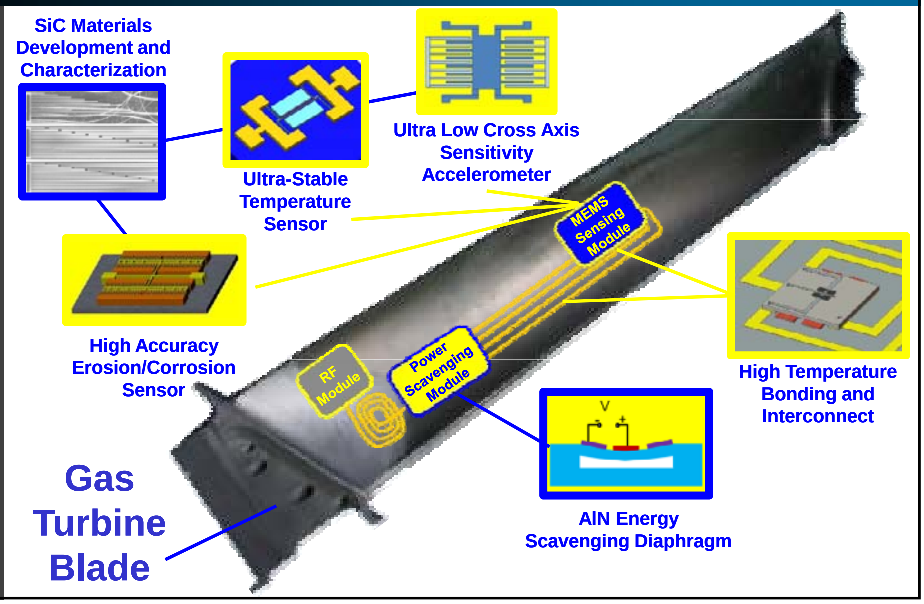

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Heteroepitaxial 3C-SiC on AlN

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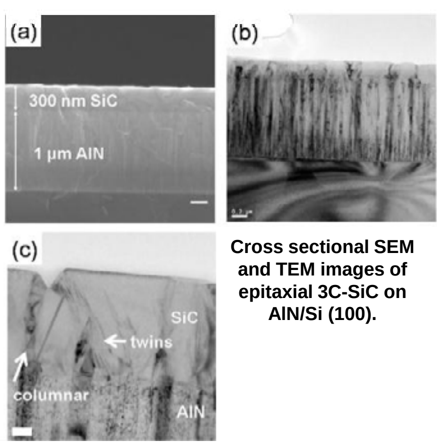
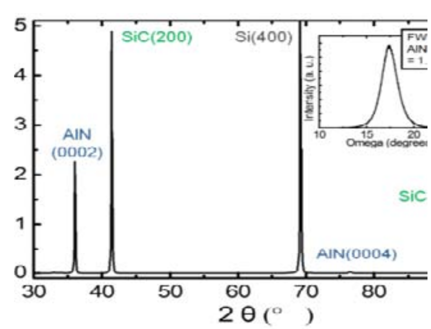
3C-SiC deposited on aluminum nitride (AlN) with Methyltrichlorosilane (CH_3SiCl_3) precursor



Cross sectional SEM and TEM images of epitaxial 3C-SiC on AlN/Si (100).



XRD spectrum of epitaxial 3C-SiC on AlN/Si (100).

W.C. Lien, K.B. Cheng, D.G. Senesky, C. Carraro, A.P. Pisano & R. Maboudian, Electrochemical and Solid-State Letters (accepted)

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High-T Metallization on 3C-SiC

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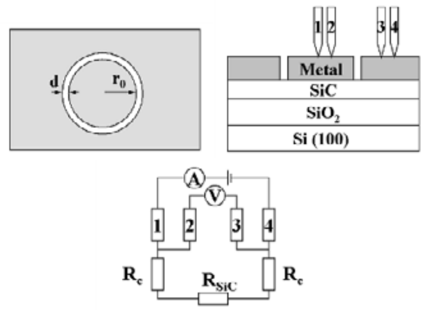
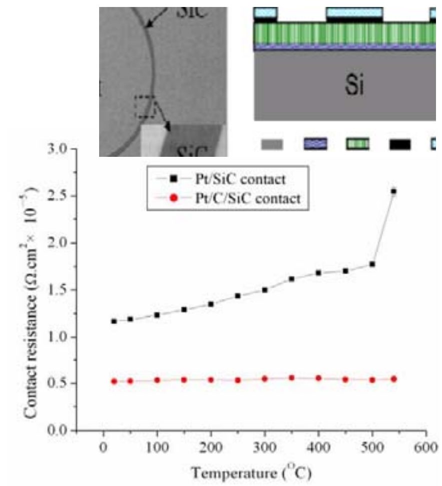


Schematics of the Circular Transmission Line Method (CTLM) structure.



Contact resistance (R_c) from room temperature to 550ºC for Pt/3C-SiC and Pt/C/3C-SiC

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F. Liu, B. Hsia, D.G. Senesky, C. Carraro, A.P. Pisano & R. Maboudian, Hilton Head Conference (2010)

SiC JFET at 600ºC

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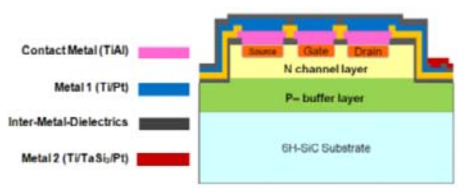

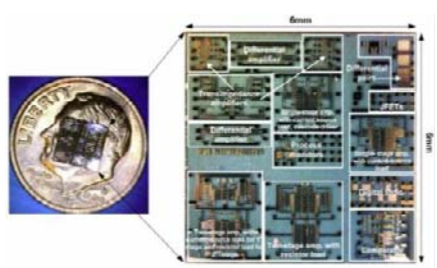

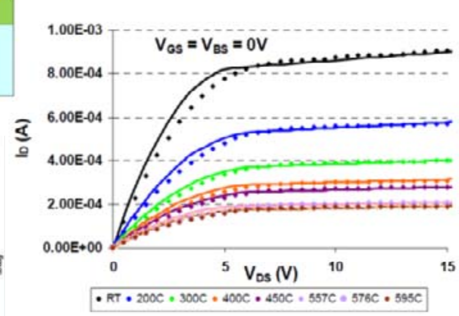

Measured I-V of JFET with W/L = 100 μm/10 μm for temperatures up to 600ºC. Symbols mark measured values while solid curves show fit to the 3/2-power model.

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A. Patil, M. Mehregany and S. Garverick, Ph.D. Thesis (2009)

AlN Resonator from 25-600°C

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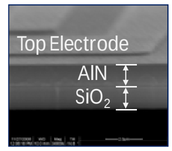
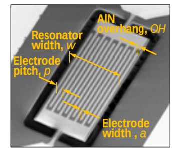
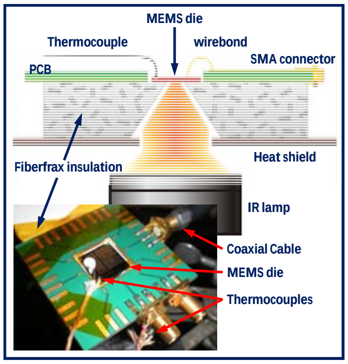
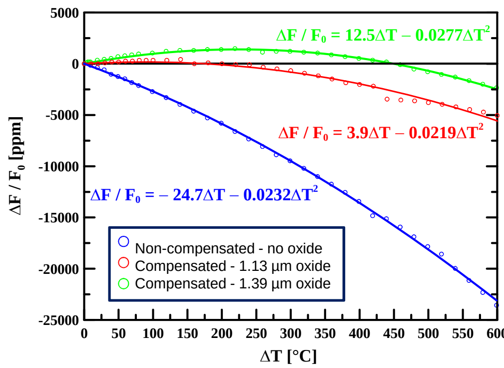
- **A specific thickness of SiO_2 is used for temperature compensation, and total frequency variation is reduced by over 90%.**









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T.-T. Yen *et al.*, IEEE MEMS Conference (2010)

High Temperature Active Platforms

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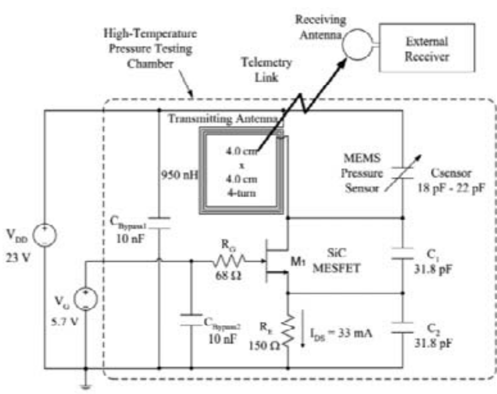

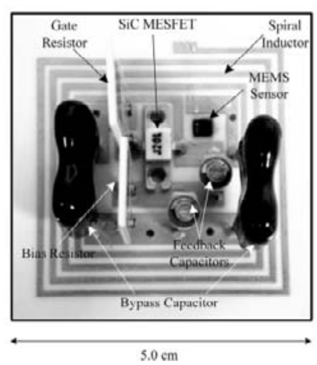

Telemetry module (Colpitts circuit) utilizing a SiC MESFET operated up to 400˚C with a telemetry distance of approximately 1.0 m.

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R. Wang, W. H. Ko, and D. J. Young, IEEE Sensors Journal (2005)

Conclusions

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SiC Sensing Technology for Extreme Harsh Environments

- **Advanced power and propulsion systems (e.g. aircraft propulsion, industrial gas turbines and automotive engines) can utilize robust sensors for increased fuel efficiency, increased operation lifetimes and reduced emissions.**
- **Development of advanced ceramic semiconductors (materials & processes) has enabled a new class of sensors and electronics that can operate in hostile conditions.**
- **Future research includes systems integration to realize a wireless sensing module. This will require novel packaging and interconnect technology.**

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