Testing and Analysis of Piezoresistive Signals from SiC MEMS Accelerometers with Application to Penetration Fuzing

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Outline

- Research Team
- Objectives
- Background
- Design and Fabrication
- Evaluation
- Results
- Accomplishments
- Future Work
- Conclusion

Research Team

- AFRL Munitions Directorate
  - Fuzes Branch: Dr. Alain Beliveau, Dr. Alex Cash, 1Lt. Ken Bradley, Mr. Jason Foley
  - Dr. Scott Roberson (now at SAF/AQ)
- NASA Glenn Research Center
  - Dr. Robert Okojie
- Cornell University
  - Prof. Kevin Kornegay, Dr. Andy Atwell (now at IDA)

Objectives

- **Develop a scientific understanding of…**
  - **Stress distribution and concentration**
  - **Microstructural transformation**

… for devices functioning in *harsh environments* to better predict failure and improve sensitivity

High Stress/Pressure

High Temperature (>250ºC)

High Power/Voltage (switches, μ–wave)

Corrosion

Erosion and Wear

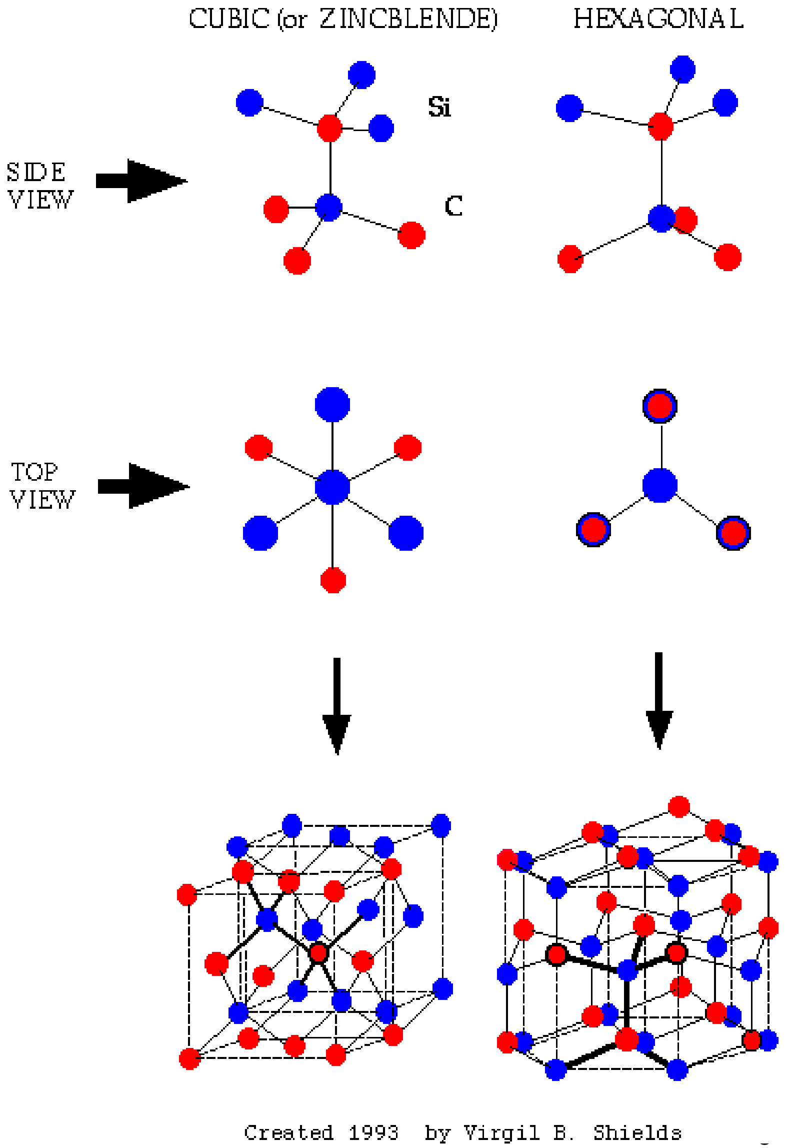
Radiation

Shock and Vibration

Background

SiC selected as material…

- **Wide Bandgap – 2 x Silicon**
- **High Thermal Conductivity**
- **Polytypic (3C, 6H, …)**
- **Chemically Inert**
- **Superior Mechanical Properties over Si**
  - **– 3 x Yield Strength**
  - **– 3.5 x Young's Modulus**
    - **Similar strains… due to greater max yield strength**

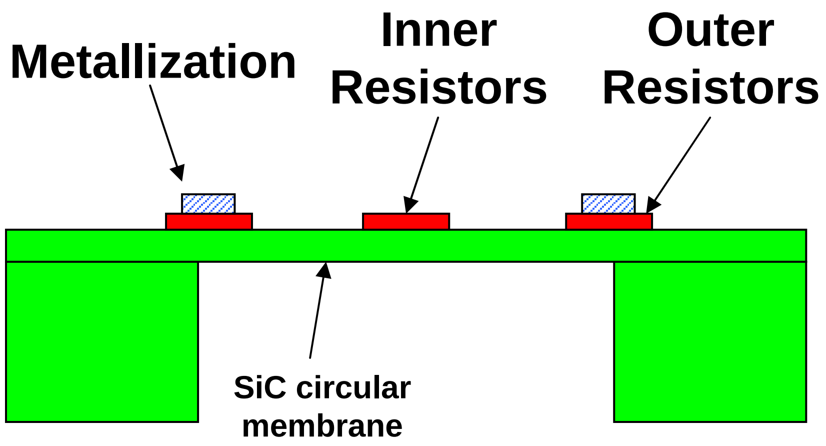


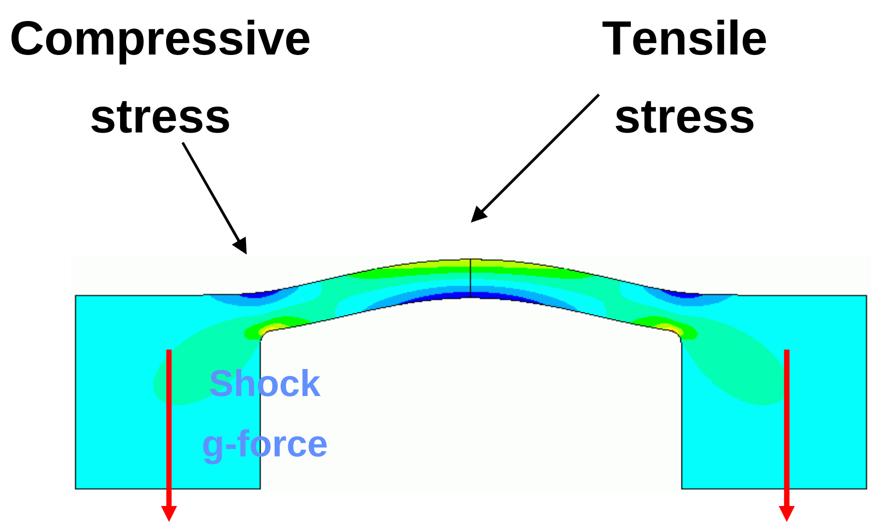
Design and Fabrication

Device Concept:

Suspended membrane with piezoresistive elements (mesas)

- Epilayer deposition
  - PECVD
- Bulk micromachining of silicon carbide
  - Reactive Ion Etch (Anisotropic)





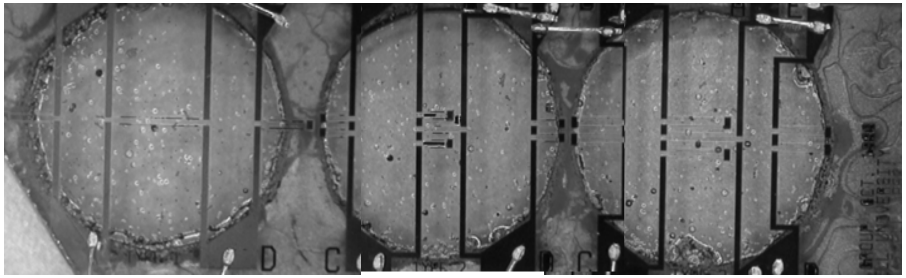
Stress contour plot

Source: K. Kornegay, Cornell U.

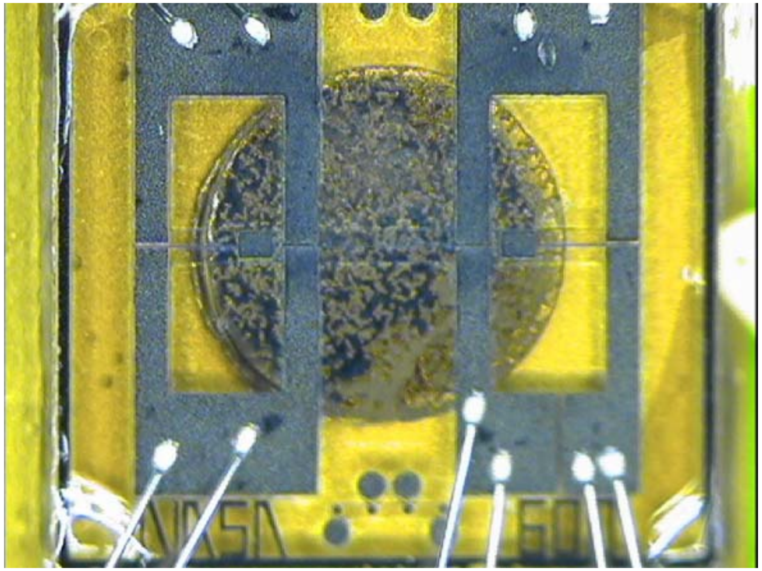
Design and Fabrication

- **Device series:**
  1. **Cornell Types 1-3**
  2. **NASA Generation 1**
  3. **NASA Generation 2**

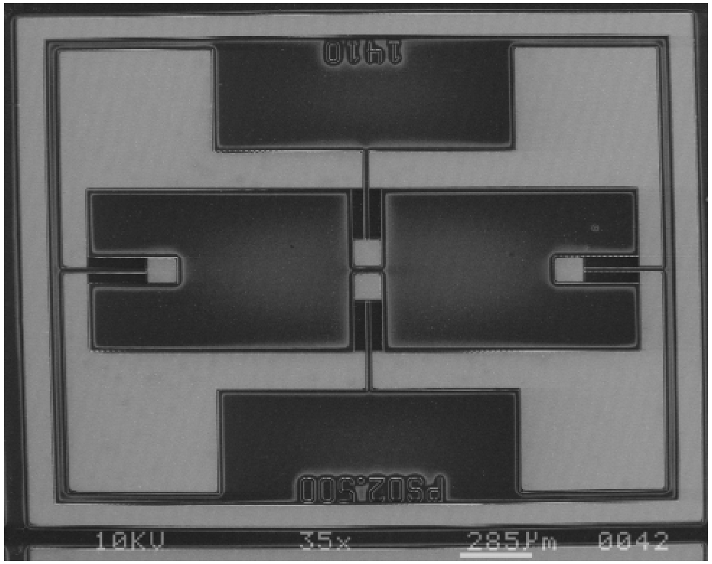
TYPE 1 TYPE 2 TYPE 3



1. SEM micrographs of the Cornell designs

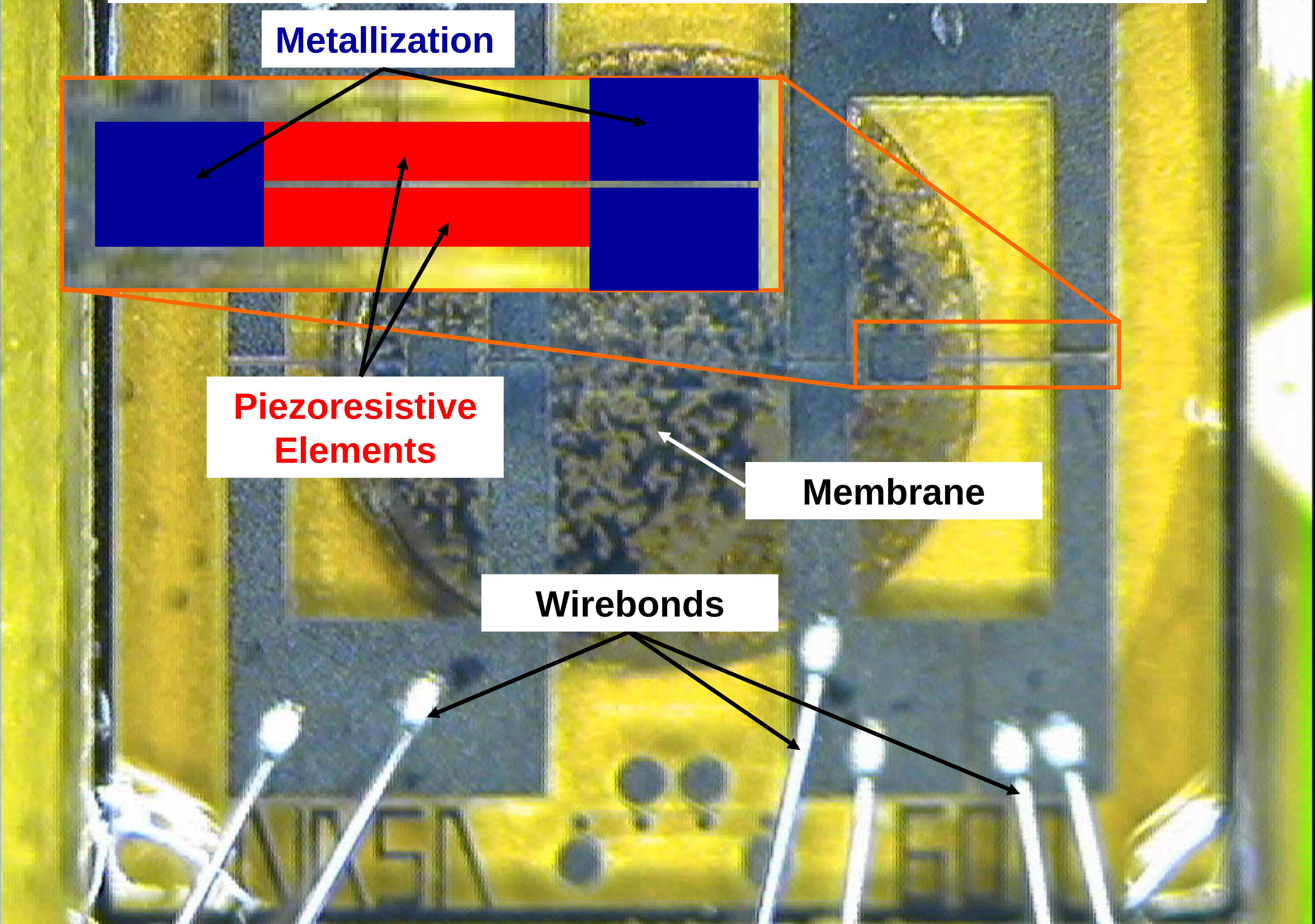


2. Optical micrograph of Gen 1 NASA sensor (no boss)

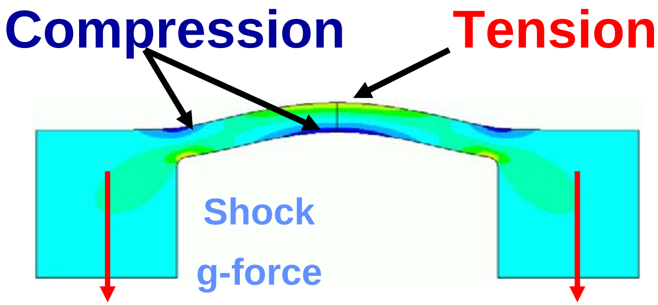


3. SEM micrograph of Gen 2 NASA sensor (with boss)

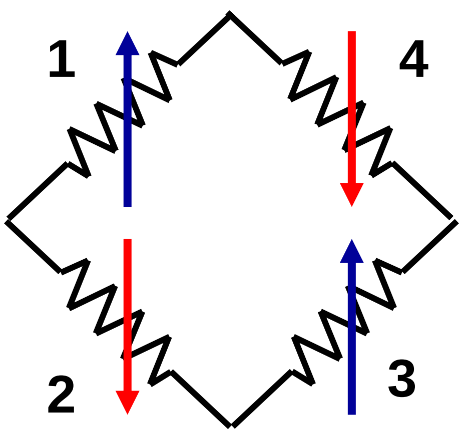
Sample SiC MEMS Layout (NASA Generation 1)



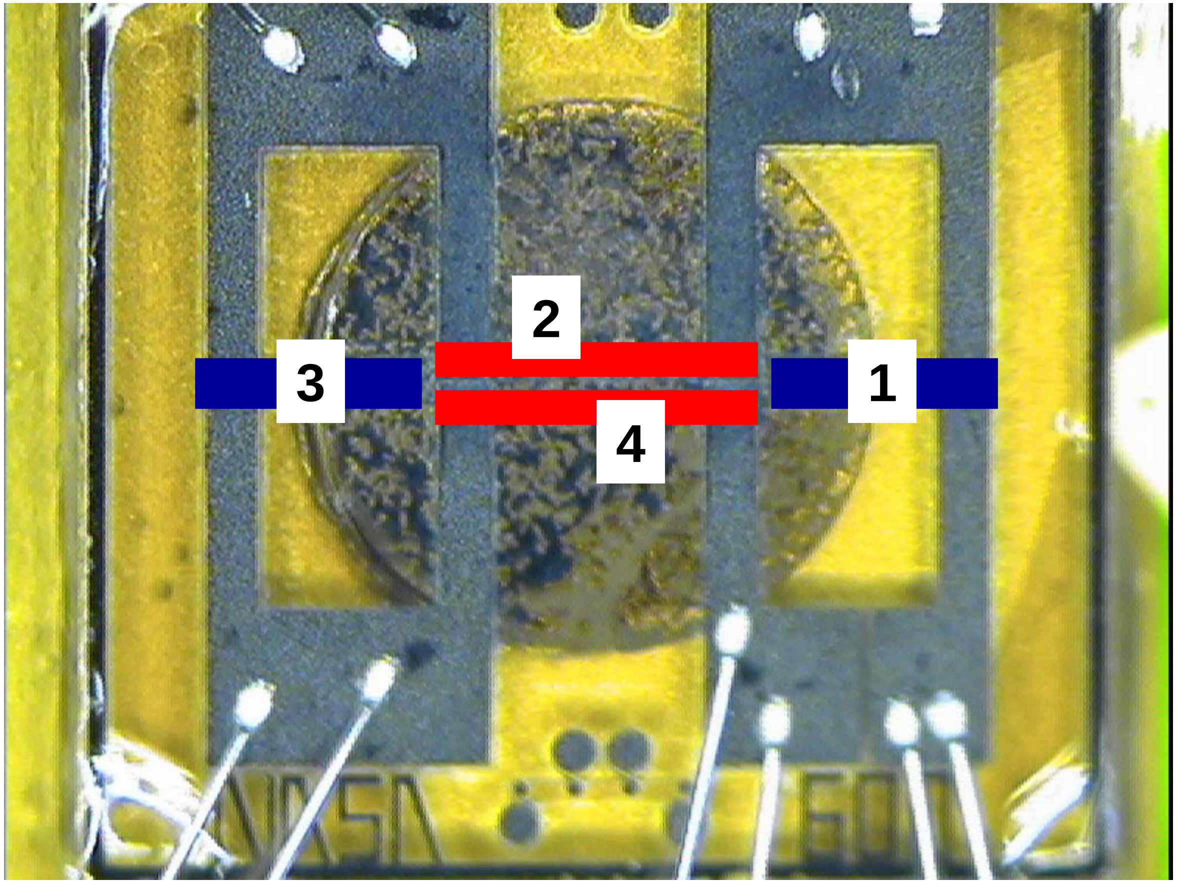
Sample SiC MEMS Operation (NASA Generation 1)



Stress contour plot

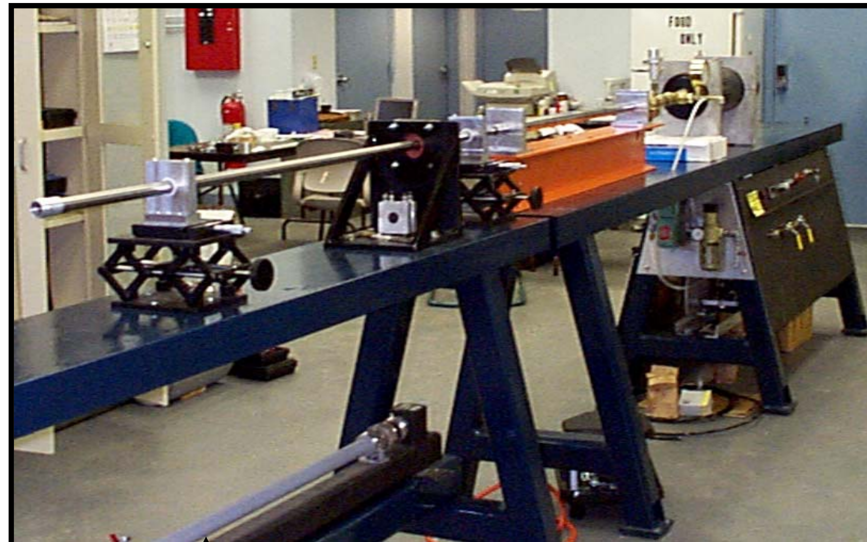


Wheatstone Bridge



Evaluation

- Microcharacterization
  - SEM, XRD, etc.
- Stress Evaluation (Accelerometers)
  - Steady State (Centrifuge): Calibration
  - Dynamic (Shock Machine): Real Time Data
  - Temperature: Internal Stress Development
- Develop feedback for future designs, understanding of fundamental mechanisms



Hopkinson Bar

VHG

Evaluation

Very High-*g* (VHG) Machine

- Dynamic Test to Failure
- Determine Real-Time Stress from Centrifuge Data
- Separation of Design and Material Properties Failures
- Serves as Baseline for Empirical Modeling
- VHG allows determination of failure due to mechanical stress and resonance frequency phenomenon

Evaluation

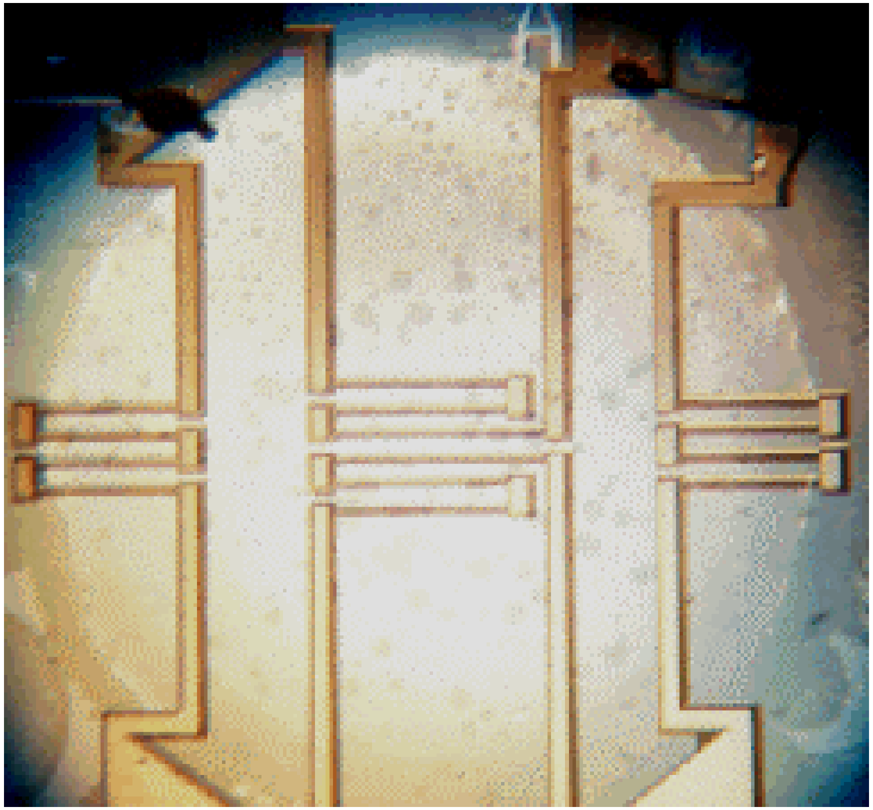
Baseline: Endevco 7270A

- **Peak mag up to 200k x *g***
- **Survivable**

Results

Cornell University Types 1-3

Simple membrane devices

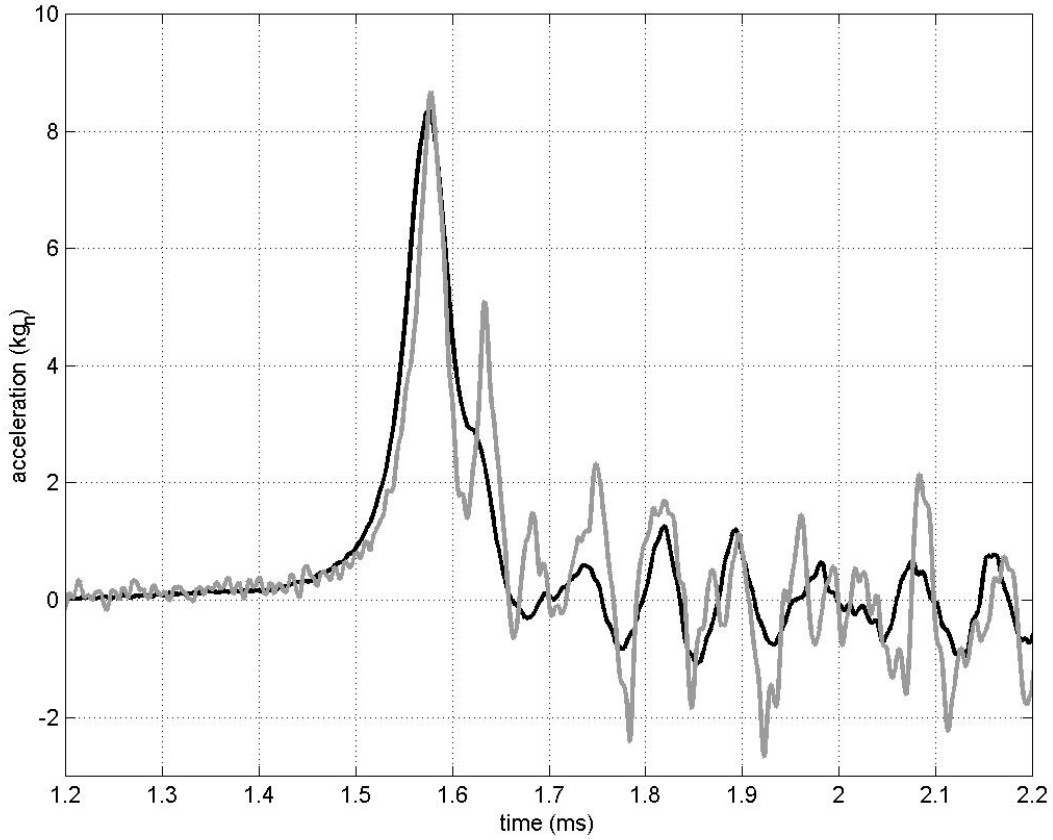


Results

- **SiC MEMS device matched output of Industry Standard Endevco 7270 Accelerometer within 5% up to 20k x *g***

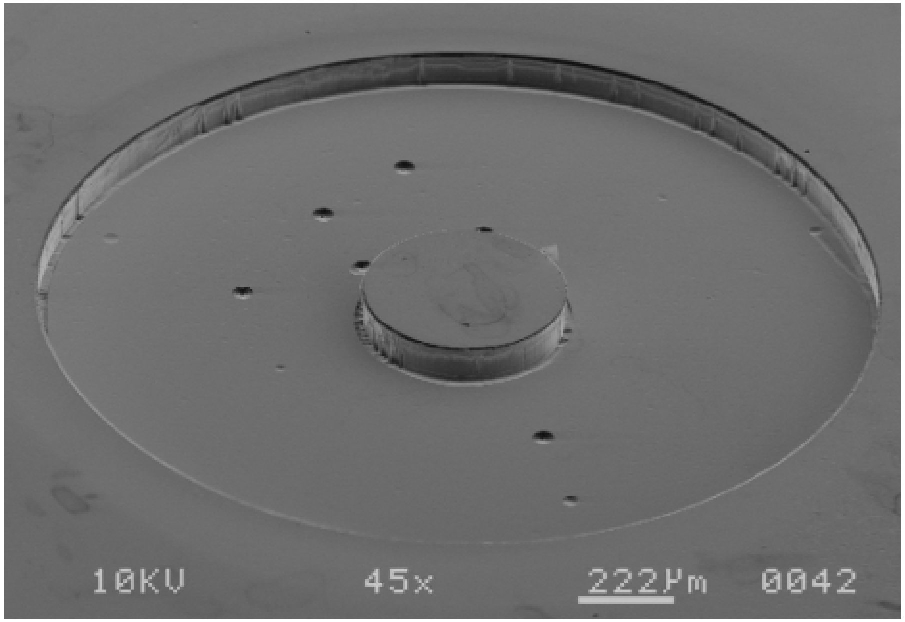
- **Very low sensitivity (75 nV/*g*) compared to Endevco (4 μV/*g*)**

Black – Endevco 7270
Gray – SiC MEMS (CU1)



NASA Generation 1

Innovative design with boss for increased sensitivity

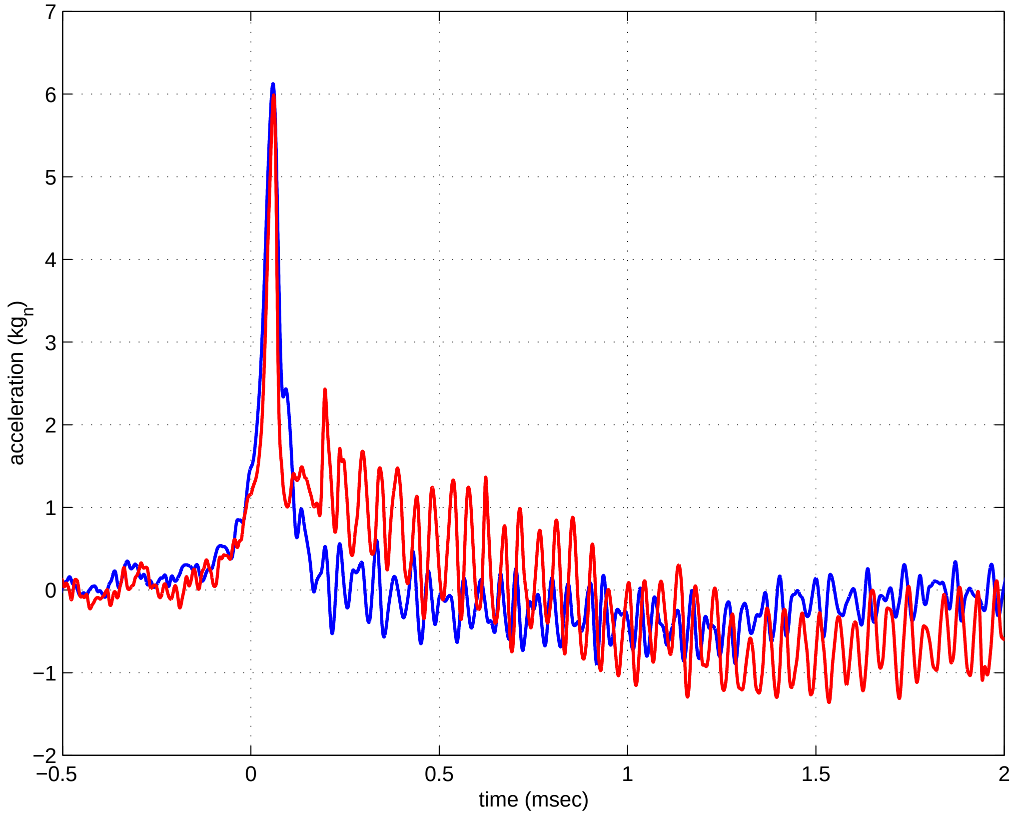


A SEM micrograph of the backside deep reactive ion etch for the NASA bossed sensor.

Results

- **NASA SiC MEMS matched output of Endevco 7270 to 8k x *g***
- **Survived to 80k x *g***
- **Sensitivity: 0.125 μV/*g***

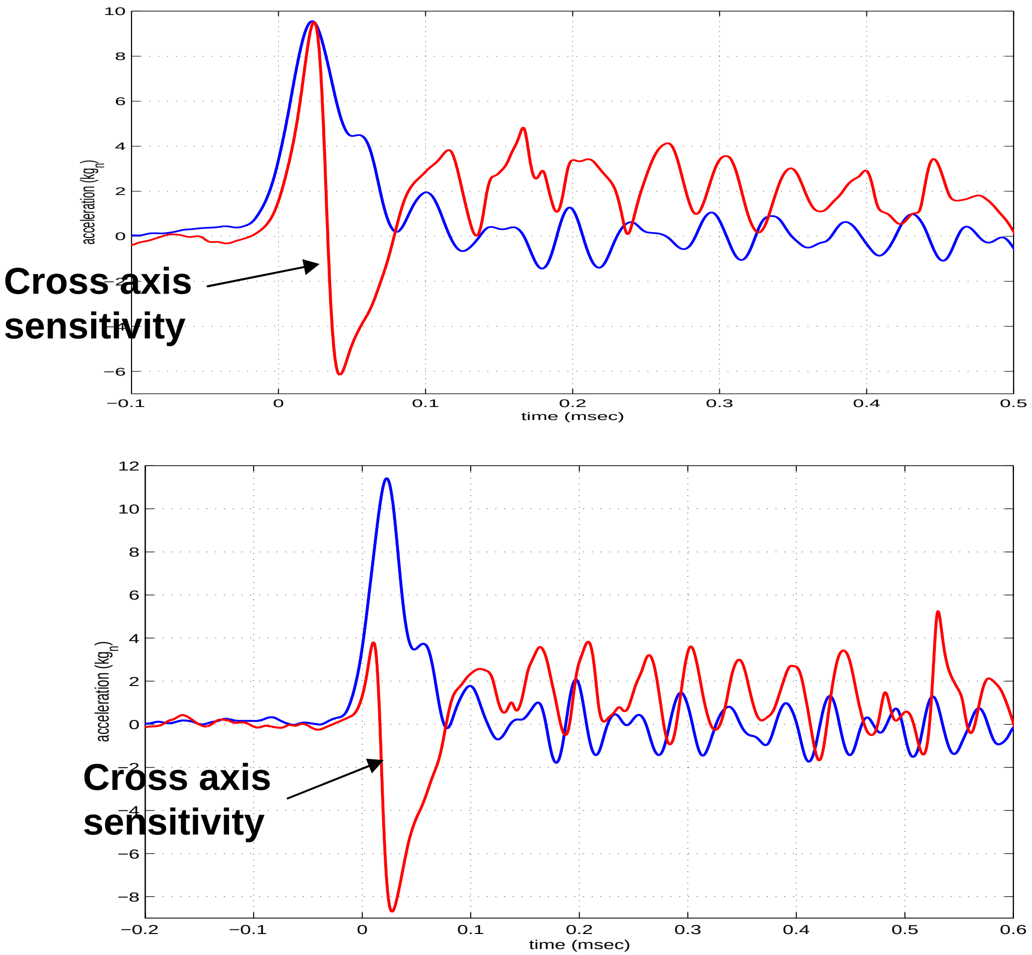
Blue– Endevco 7270
Red – SiC MEMS (NASA1)



Results

- **Strong "cross axis" sensitivity or cross axis resonance mode was observed ~9k x *g***
- **Cross axis sensitivity increased with increasing axial *g*'s, dominating signal**
- **New design: no boss**

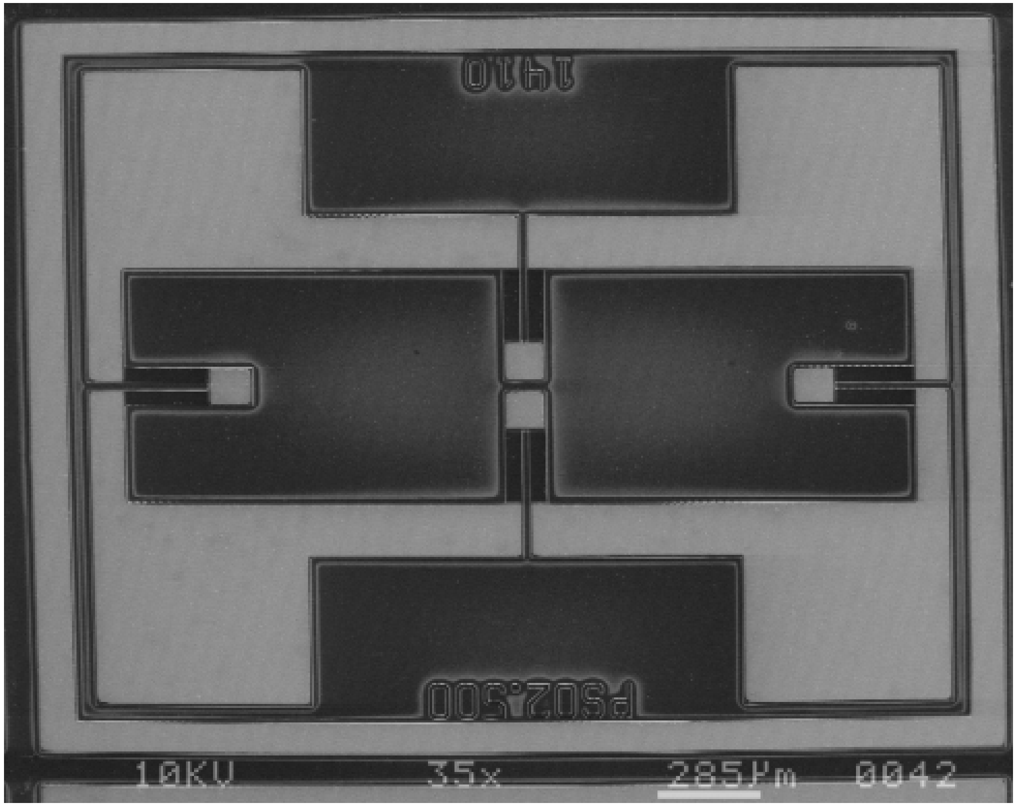
Blue– Endevco 7270
Red – SiC MEMS (NASA1)



Results

NASA Generation 2

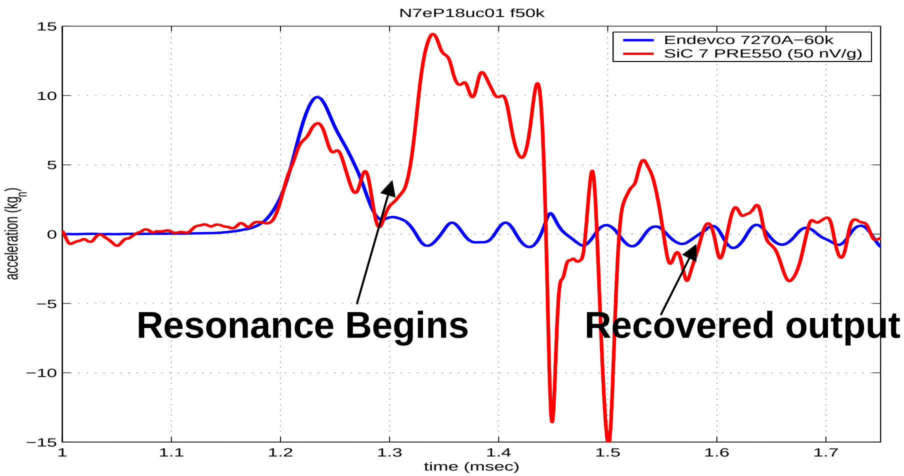
No boss for decreased cross-axis sensitivity

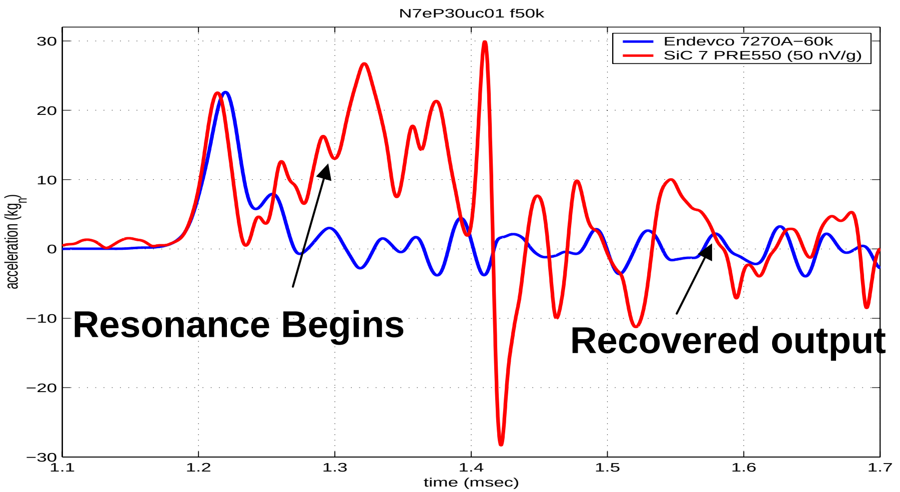


Results

- **Matched output of Endevco 7270 until a dominating resonance mode around 1.3 msec**
- **Output recovered around 1.6 msec and matched that of the Endevco 7270**

Blue – Endevco 7270
Red – SiC MEMS (NASA2)



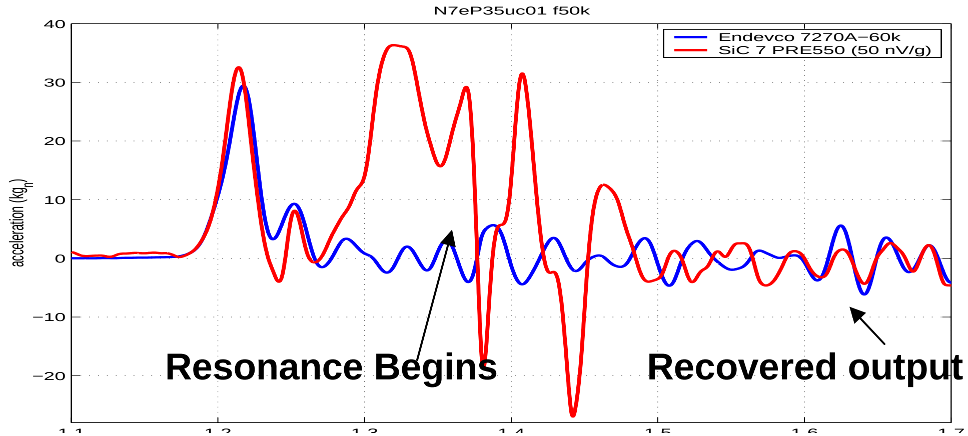


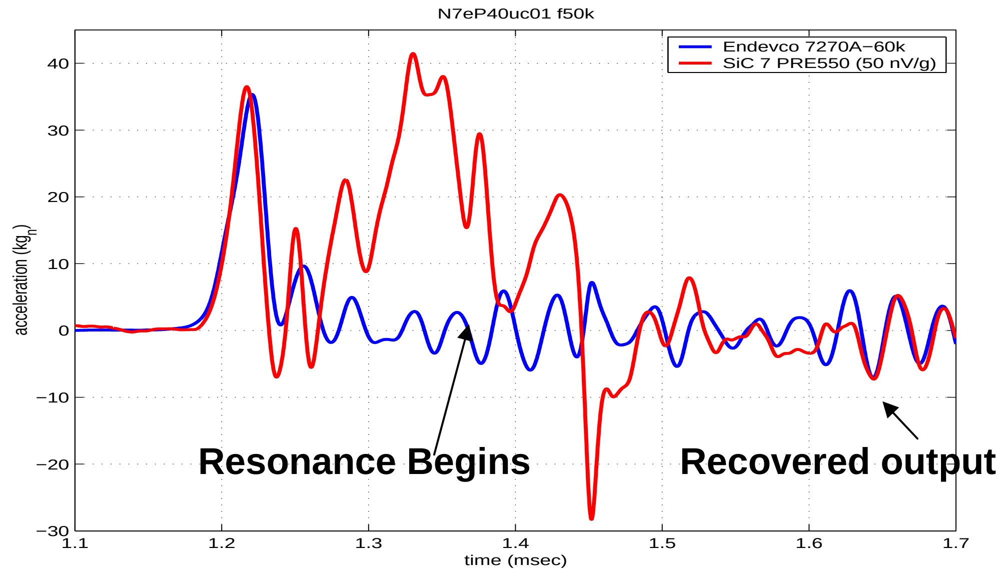
Results

- **Repeatable results**
- **Matched the Endevco 7270 first peak intensity very well**

Blue – Endevco 7270

Red – SiC MEMS (NASA2)





Results Summary

- **Three Generations of SiC MEMS have been modeled, fabricated and evaluated for Stress development**
  - **Cornell University Types 1-3**
    - Simple Round Membrane
      - Easy to model, fabricate and interpret scientific data
  - **NASA Glen Research Center Generation 1**
    - Complex designs for Improved Sensitivity
      - More Difficult to Interpret Data but more sensitive
  - **NASA Glen Research Center Generation 2**
    - Redesigned to avoid problems from gen 1

Program Accomplishments

- **Established MOA with NASA Glenn Research center for Long-Term, Joint SiC MEMS Collaboration**
- **First Published Peer Reviewed Journal Article on SiC MEMS: *IEEE Journal of Sensors and Actuators A 104, 2003 (11-18)***
- **First Conference Paper on Operating SiC MEMS: *Jan 02 IEEE Conference, Las Vegas, NV***
- **PhD Dissertation at Cornell University by Dr. Andy Atwell: *Modeling,Simulation, and Fabrications of SiC MEMS***
  - **Funded by AFOSR and NASA Glenn**

Future Work

- **Material effects of thermomechanical cycling**
  - **Thermal cycling coupled with mechanical cycling**
- **Improving device function and reliability**
  - **Increasing axial sensitivity**
  - **Decreasing cross-axial sensitivity**
  - **Reducing bias**
- **Enhanced "nondestructive" evaluation *in situ***
  - **Velocity interferometer (VISAR)**

Future Work

- Investigating microstructural changes
  - Defects
  - Hysteresis
  - Phase changes
- Initial shock tests of 1st generation NASA GRC accelerometers
- 2nd generation NASA GRC accelerometers (4Q04)

Summary

- SiC MEMS that function in harsh environments have been demonstrated
  - Fabricated (Cornell, NASA Glenn)
  - Tested (AFRL/MN)
- Improvements necessary to achieve desired functionality
  - Problems with cable noise, sensitivity, cross-axis
- Continuing investigation by focusing on fundamental mechanisms will enhance effort

End of Presentation

Backup Slides

Publication List

1. **Atwell, Andrew R., Okojie, Robert S., Kornegay, Kevin T., Roberson, Scott L., and Beliveau, Alain, 2003, "Simulation, fabrication and testing of bulk micromachined 6H-SiC high-g piezoresistive accelerometers," Sensors and Actuators A, 104, pp. 22-18.**

Atwell et al, 2003, Sens Act A, 104, pp 11-18.pdf

2. **Okojie, Robert S., Atwell, Andrew R., Kornegay, Kevin T., Roberson, Scott L., and Beliveau, Alain, 2002, "Design Considerations for Bulk Micromachined 6H-SiC High-g Piezoresistive Accelerometers," Tech. Digest 15th IEEE Intl. Conf. on MEMS, Las Vegas, Nevada (Jan. 20-24, 2002), pp. 618-622.**

Okojie et al, 2002, Tech Dig 15th IEEE Conf MEMS, pp 618-622.pdf

SiC: Mechanical Properties

Property Table

Percentages in parentheses denote estimated combined relative standard uncertainties of the property values.
For example, 3.0(5%) is equivalent to 3.0 +/- 0.15. Property values in parentheses are extrapolated values.

Property [unit]	20 °C	500 °C	1000 °C	1200 °C	1400 °C	1500 °C
Bulk Modulus [GPa]..................	203(3%)	197	191	188	186	184
Creep Rate [10^{-9} s^{-1}] at 300 MPa.....	0	0	0	0.004(17%)	0.27	1.6
Density [g/cm^3].....................	3.16(1%)	3.14	3.11	3.10	3.09	3.08
Elastic Modulus [GPa]...............	415(3%)	404	392	387	383	380
Flexural Strength [MPa].............	359(15%)	359	397	437	446	446
Fracture Toughness [MPa $m^{1/2}$]........	3.1(10%)	3.1	3.1	3.1	3.1	3.1
Friction Coefficient [], 0.2 m/s,5 N	0.7(21%)	0.4	0.4			
Hardness (Vickers, 1 kg) [GPa]......	32(15%)	17	8.9	(6.9)	(5.3)	(4.6)
Lattice Parameter a(polytype 6H) [Å]	3.0815(0.01%)	3.0874	3.0950	(3.0984)	(3.1021)	(3.1040)
Lattice parameter c(polytype 6H) [Å]	15.117(0.02%)	15.144	15.179	(15.194)	(15.210)	(15.218)
Poisson's Ratio [].................	0.16(25%)	0.159	0.157	0.157	0.156	0.156
Shear Modulus [GPa].................	179(3%)	174	169	167	166	165
Sound Velocity, longitudinal [km/s].	11.82(2%)	11.69	11.57	11.52	11.47	11.44
Sound Velocity, shear [km/s]........	7.52(2%)	7.45	7.38	7.35	7.32	7.31
Specific Heat [J/kg·K]..............	715(5%)	1086	1240	1282	1318	1336
Tensile Strength [MPa]..............	250(6%)	250	250	250	250	250
Thermal Conductivity [W/m·K]........	114(8%)	55.1	35.7	31.3	27.8	26.3
Thermal Diffusivity [cm^2/s].........	0.50(12%)	0.16	0.092	0.079	0.068	0.064
Thermal Expansion from 0 °C [$10^{-6}K^{-1}$]	1.1(10%)	4.4	5.0	5.2	5.4	5.5
Wear Coefficient(Log10)[],0.2 m/s,5 N	-4.0(5%)	-3.6	-3.6	...	...	...
Weibull Modulus [].................	11(27%)	11	11	11	11	11

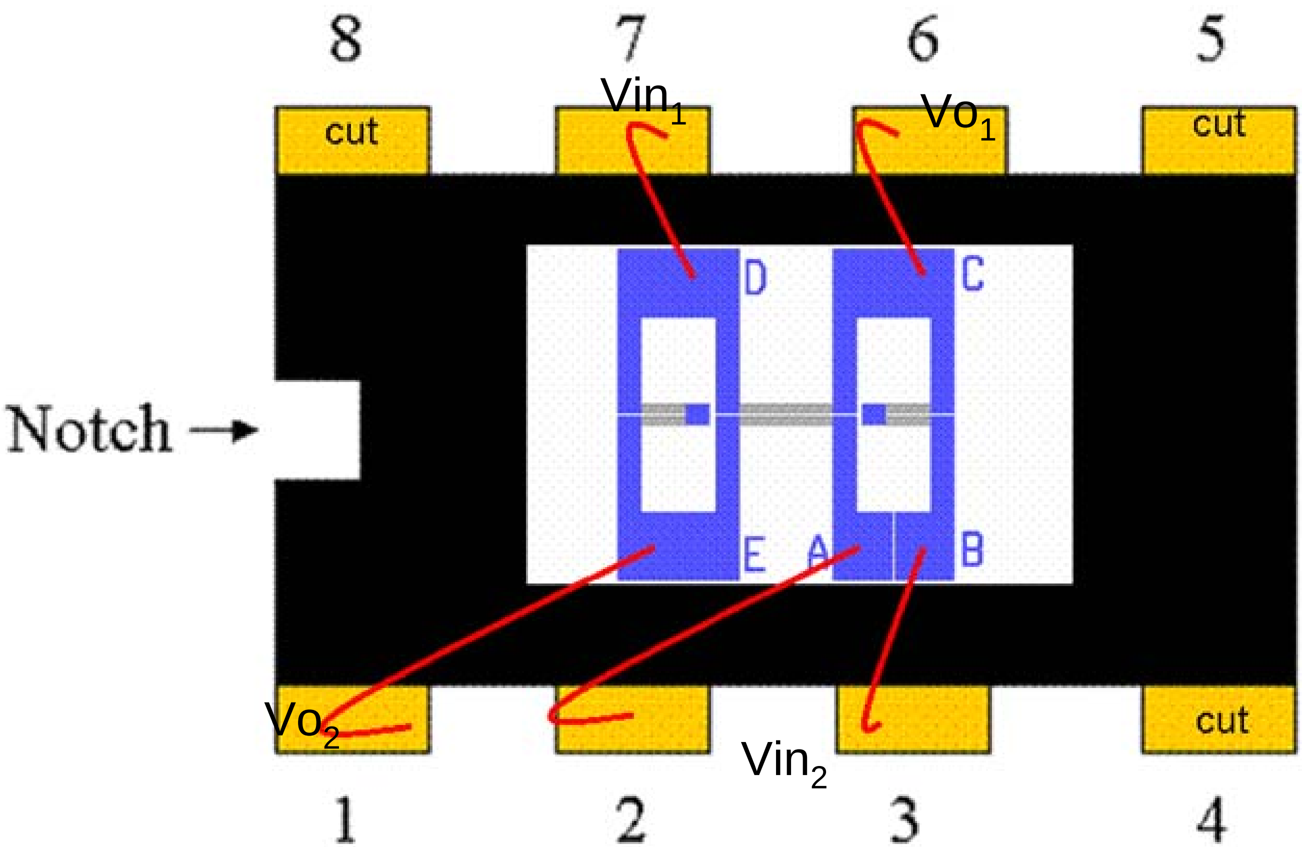
Source: NIST SRM

SiC: Electrical Properties

PROPERTY	3C-SiC	6H-SiC
Bandgap (eV) at 300 K	2.3	2.9
Maximum operating temperature (°C) 300	873	873
Melting point (°C)	Sublimes >1800	Sublimes >1800
Physical stability	Excellent	Excellent
Electron mobility (cm^2/V-s)	1000	600
Hole mobility (cm^2/V-s)	40	40
Breakdown field, E_b (10^{-6} V/cm)	4	4
Thermal conductivity, σ_T (W/cm-°C)	5	5
Sat. elect. drift velocity, v_{sat} (10^7 cm/s)	2.5	2.5
Dielectric constant, ε	9.7	9.7

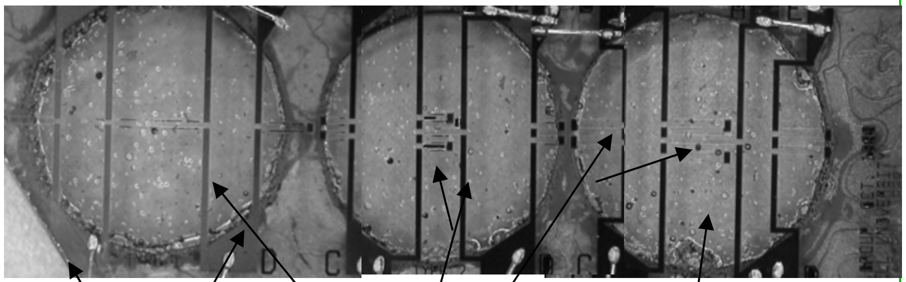
Source: V. Shields, JPL (NASA)

Accelerometer Circuit Configuration



The above configuration makes the Wheatstone Bridge an open one. It allows each resistor element BC, CD, DE, and EA to be measured independently. When 2/3 is connected together, the bridge is closed. To be consistent, the power supply Vin_1 and Vin_2 should be connected at pin 7 and 2/3, respectively. The output Vo_1 and Vo_2 should be tapped at pin 6 and 1, respectively.

SILICON CARBIDE MEMS



OBJECTIVE

- UNDERSTAND STRESS DEVELOPMENT AND DETERMINE FUNDAMENTAL FAILURE MECHANISMS OF SILICON CARBIDE MEMS ACCELEROMETERS UNDER HIGH SHOCK AND HIGH TEMPERATURE LOADING TO ENABLE USE IN HARSH ENVIRONMENTS

PAST ACCOMPLISHMENTS

- FIRST GENERATION ACCELEROMETERS FABRICATED AND EVALUATED - DATA TO BE PUBLISHED
- THREE TYPES OF DEVICES WERE DESIGNED AND FABRICATED TO ALLOW FOR ACCURATE DETERMINATION OF STRESSES
- SECOND GENERATION DEVICES HAVE BEEN DESIGNED AND EVALUATED

TECHNICAL MILESTONES

- INITIAL FEASIBILITY STUDY IN SIC MEMS 2Q99
- INITIAL DESIGN OF SIC MEMS ACCELEROMETER 4Q99
- INITIAL FABRICATION OF SIC MEMS 2Q00
- EVALUATION OF FIRST GENERATION DEVICES 3Q00

OPR: DR.SCOTT ROBERSON, DSN 872-2006, X257

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