Harsh Environment Sensor Cluster for Energy and Environment

Single-Chip, Self-Powered, Wireless Sensor Systems

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Harsh Environment Cluster Sensor

Harsh Environment Sensor Cluster

Energy Industries	Geothermal	Oil & Gas Exploration	Industrial Gas Turbines	Aircraft Engines	Automotive Engines
Required Sensing Temperatures	 375°C	 275°C	 600°C	 600°C	 300°C
Desired Sensing Measurands	• Pressure • Temperature • H_2S • Strain	• Pressure • Temperature • Hydrocarbon • Strain	• Pressure • Temperature • Flame speed • Acceleration	• Pressure • Temperature • Flame speed • Acceleration	• Pressure • Temperature • Flame speed • O_2

- **"Harsh environment" includes extremes of pressure, temperature, shock, radiation and chemical attack.**
- **Real-time sensing enables increased operation lifetimes, improved efficiency and reduced emissions.**

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Integrated SiC Sensors & Electronics

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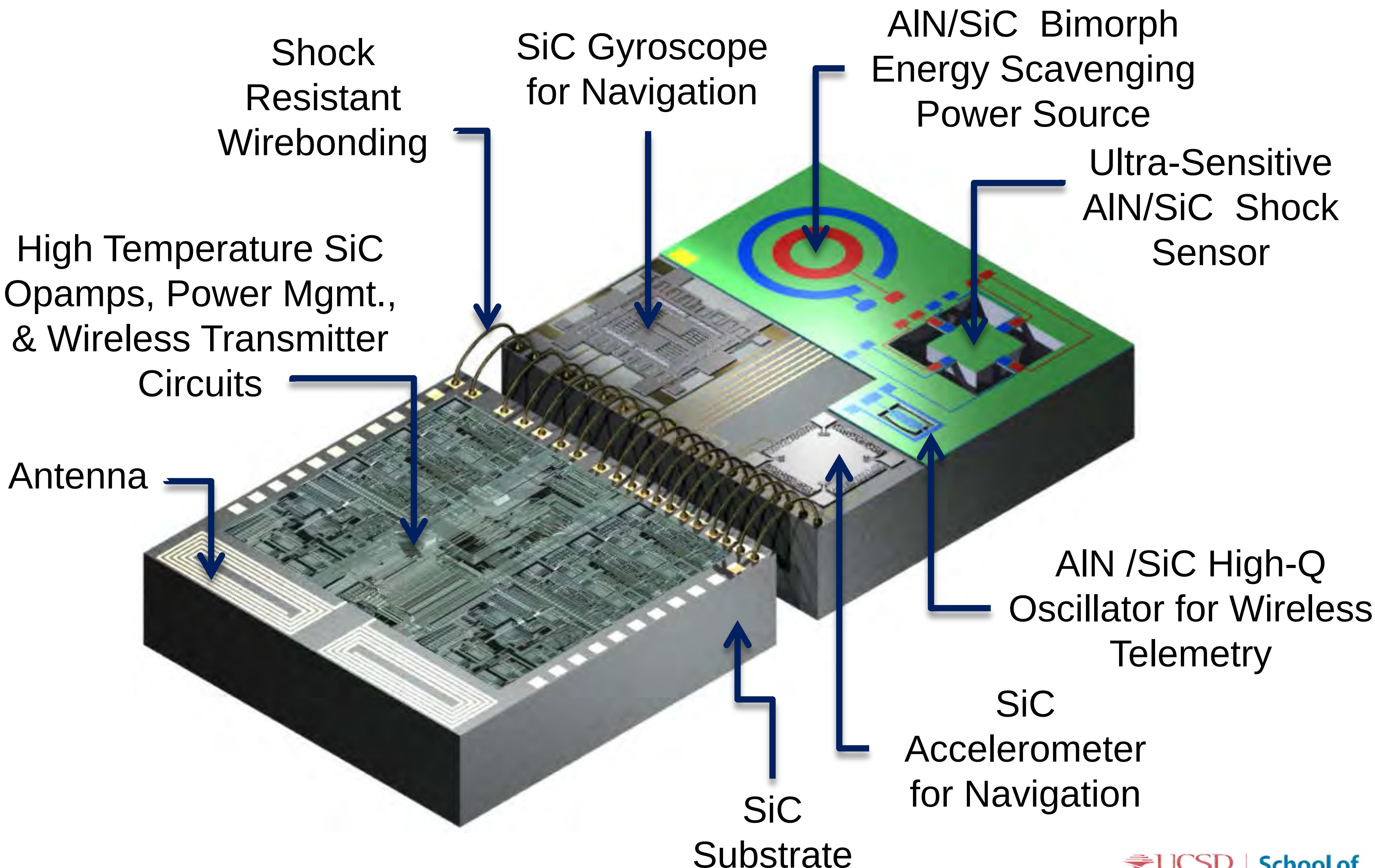

SiC and AlN Material Properties

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Property	Silicon Carbide 3C-SiC (6H-SiC)	AlN	Silicon	Diamond
Melting Point (^{o}C)	**2830 (2830) sublimes**	**2470**	**1420**	**4000 phase change**
Energy Gap (eV)	**2.4 (3.0)**	**6.2**	**1.12**	**5.6**
Critical Field ($\times 10^6$ V/cm)	**2.0 (2.5)**	**10**	**0.25**	**5.0**
Thermal Conductivity (W/cm-K)	**5.0 (5.0)**	**1.6**	**1.5**	**20**
Young's Modulus (GPa)	**450 (450)**	**340**	**190**	**1035**
Acoustic Velocity (x10^3 m/s)	**11.9 (11.9)**	**11.4**	**9.1**	**17.2**
Failure Strength (GPa)	**21 (21)**	**-**	**7**	**53**
Coeff. of Thermal Expansion (^{o}C $\times 10^{-6}$)	**3.0 (4.5)**	**4.0**	**2.6**	**0.8**
Chemical Stability	**Excellent**	**Good**	**Fair**	**Fair**

Material properties of SiC, AlN and other semiconductor materials.

SiC and AlN are mechanically robust, chemically inert and electrically stable wide-band gap semiconductor materials.

LPCVD Polycrystalline 3C-SiC

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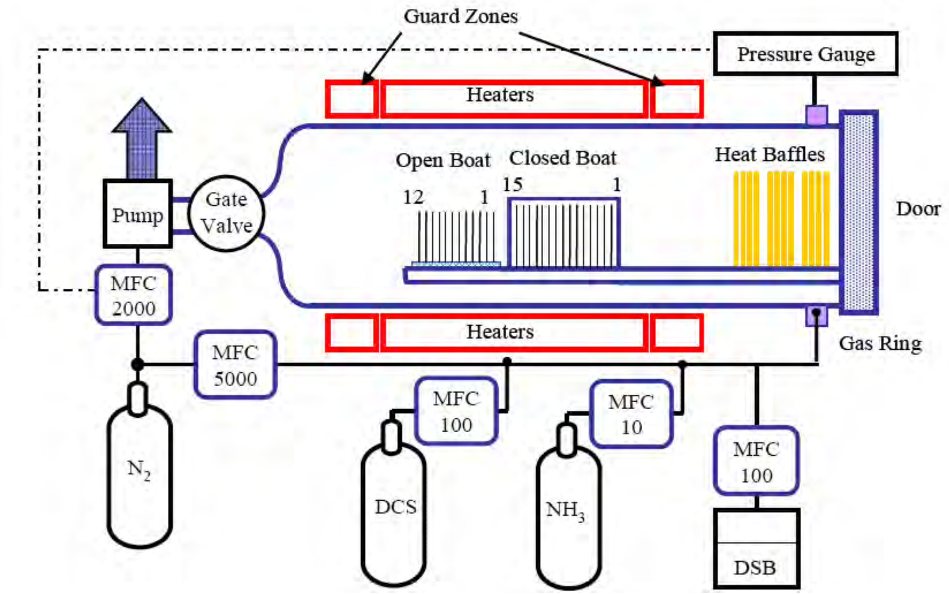
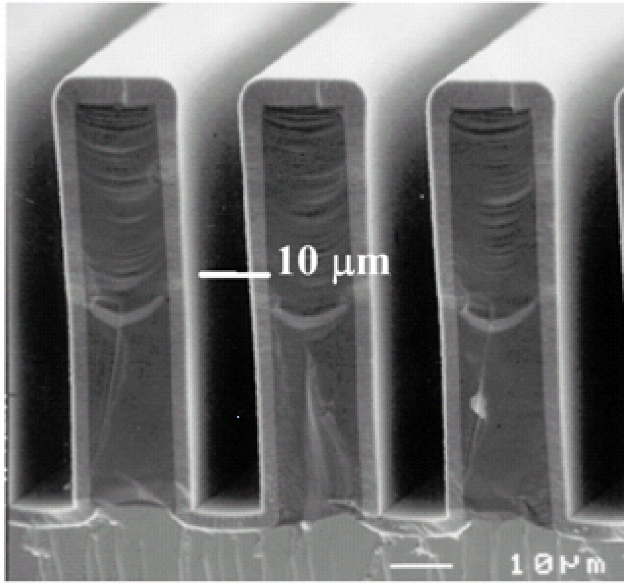
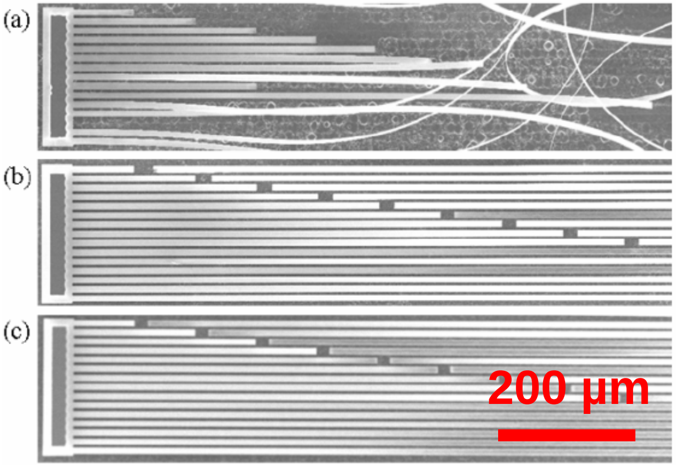




- **Low pressure chemical vapor deposition (LPCVD) of polycrystalline 3C-SiC**
  - 4 in (100 mm) & 6 in (150 mm) compatible
  - Deposition temperature = 800°C
  - Precursors
    - 1,3-Disilabutane ($CH_3SiH_2CH_2SiH_3$)
    - Ammonia (NH_3)
- **Process was optimized to obtain low stress, strain gradient and resistivity films.**



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

LPCVD Cost Reduction

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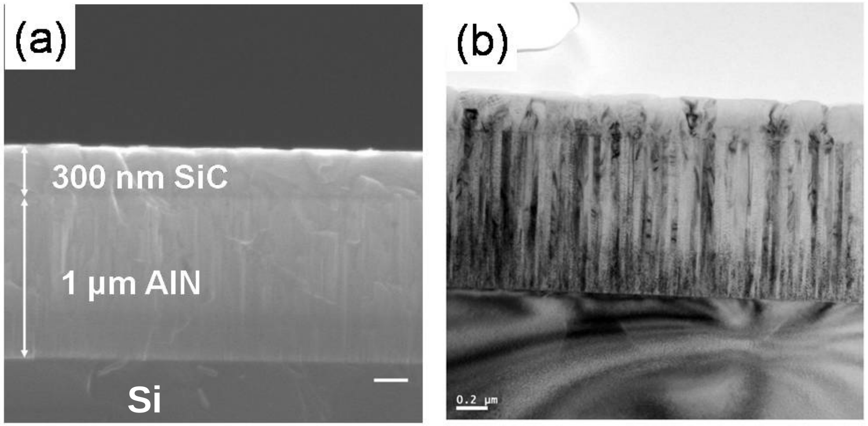
Precursor	Purity	State	Price per gram	Price per mol of SiC	Deposition Temperature (℃)
1,3-Disilabutane*	98%	Liquid	$ 22	$ 990	750-850
Methylsilane**	99.9%+	Gas	$ 17	$ 798	750-850
Methyltrichloro-silane**	99%	Liquid	$ 0.062	$ 9.24	1000-1200

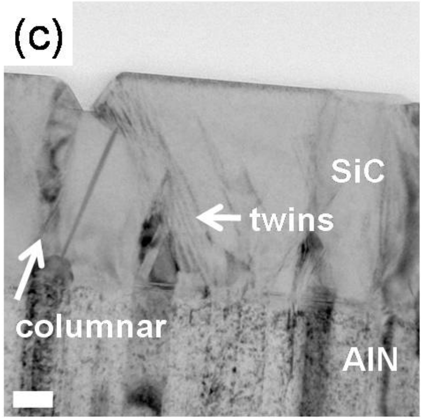
* - Current technology which previously demonstrated low stress, low resistivity films for sensor fabrication.

** - Proposed technology to be developed and characterized for improved cost.

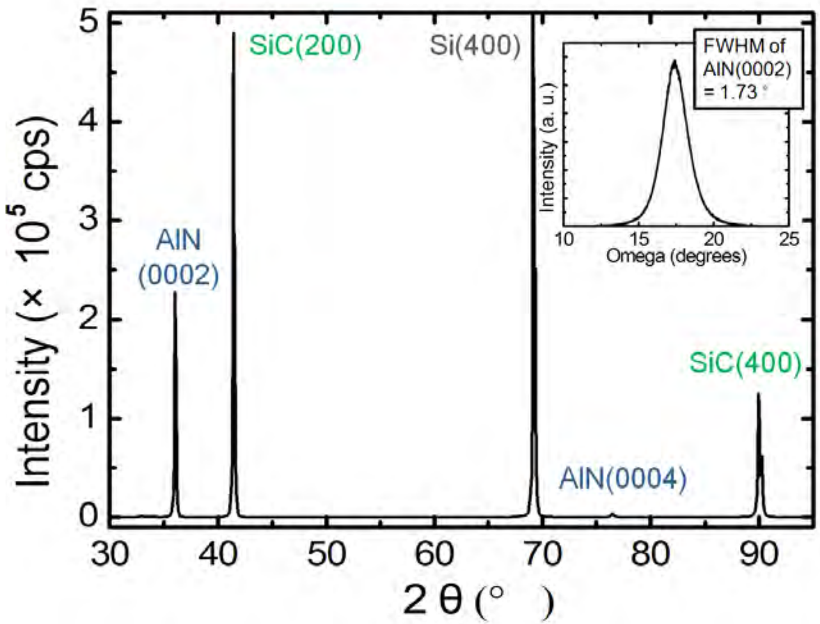
Heteroepitaxial 3C-SiC on AlN

Structural layers for AlN/SiC Devices - 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 (2010)

High-T Metallization on 3C-SiC

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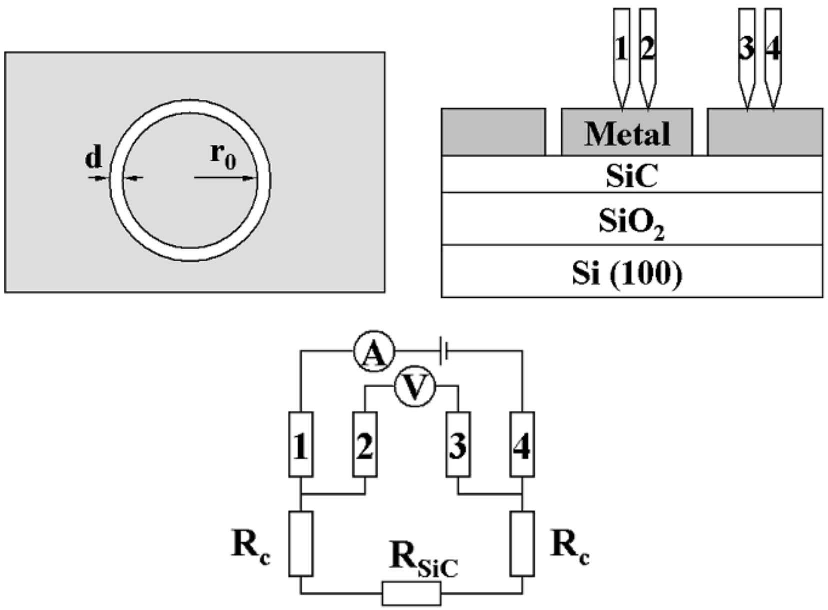
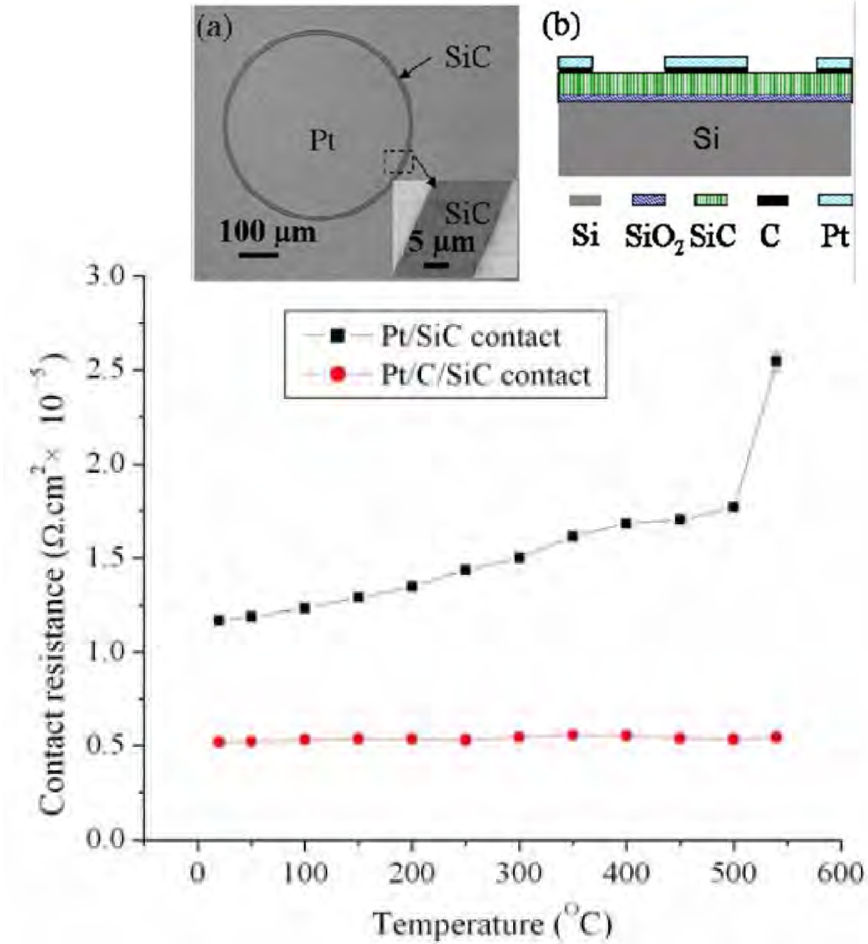


Schematics of the Circular Transmission Line Method (CTLM) structure.



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

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

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SiC Resistance Testing

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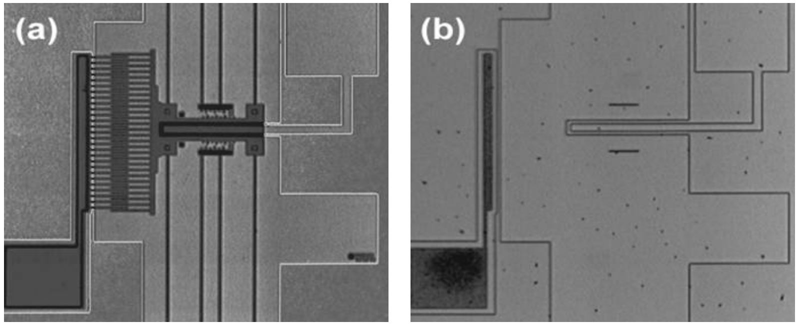
Chemical Resistance:

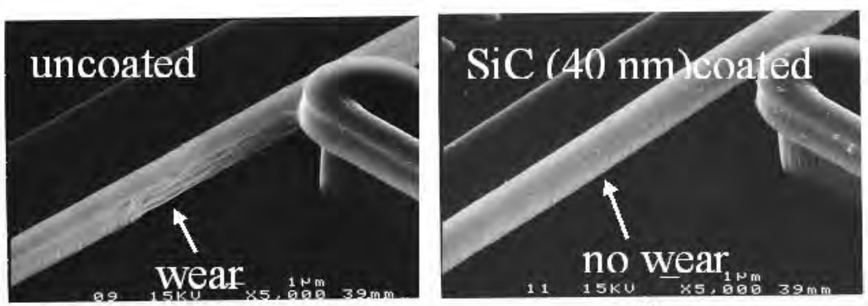


Optical images of (a) SiC-coated and (b) uncoated polysilicon structures following immersion in 65ºC KOH for 1 minute

Mechanical Toughness:

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

Wear Resistance:



(a) (b)

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 850^{O}C
Diamond-like Carbon (DLC)	Completely burned out after 24 hours
Si	300 nm
Poly-SiC	50 nm

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

SiC Sensor Operation at 600°C

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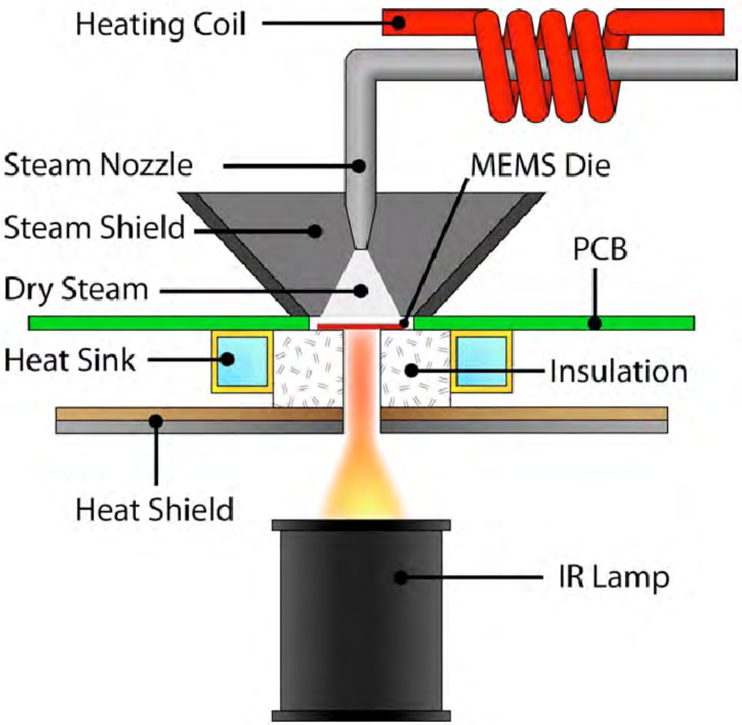

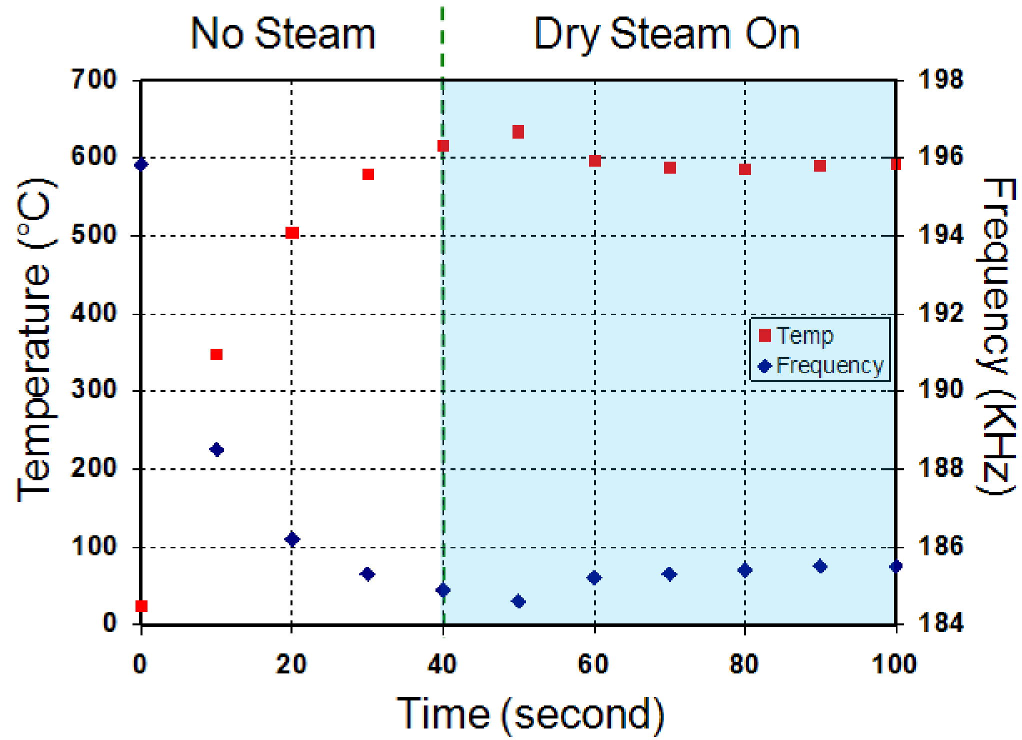

- **The polycrystalline 3C-SiC sensor resonates in air and can operate at 600°C in dry steam**
- **The strain sensor has a sensitivity of 66 Hz/με and resolution of 0.045 με in a 10 kHz bandwidth**
- **This poly-SiC sensor utilizes a fabrication process that can be utilized realize other harsh environment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

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

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G-Shock Testing at 64,000 g

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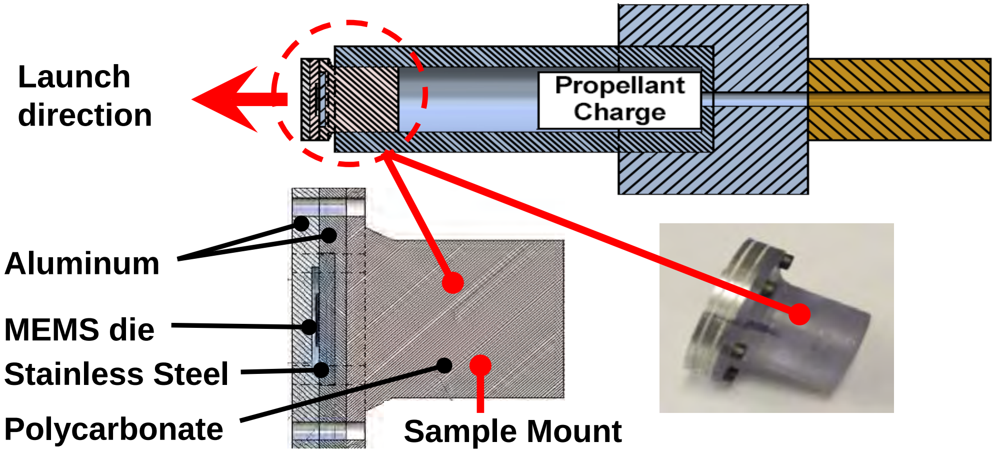
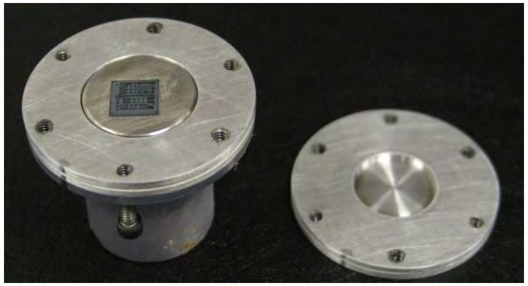
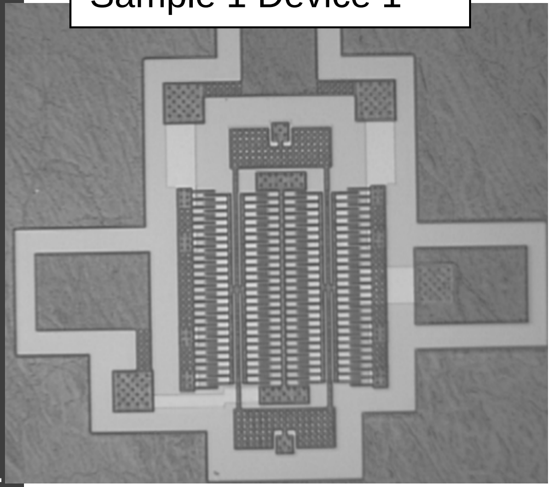
Gas Gun Schematics



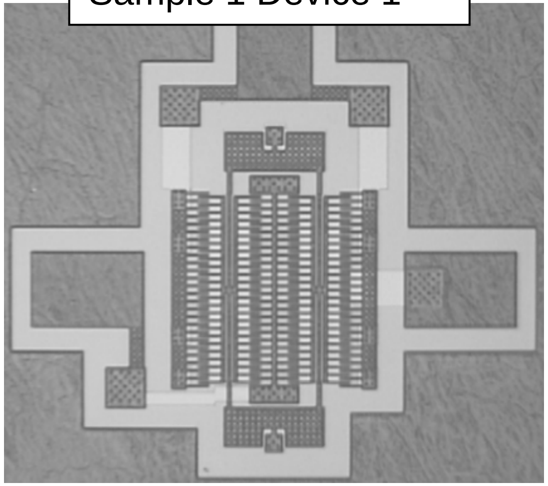
- G-shock Testing carried out at Aerophysics Research Center at University of Alabama in Huntsville
- Hard-launch soft-catch method
- Initial G-load is 64,000 g



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**

Bonding for In-chamber Operation

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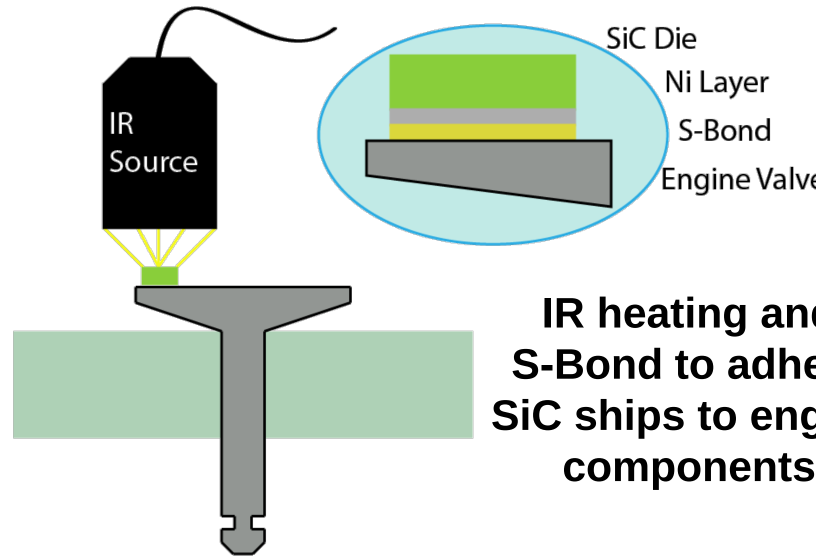
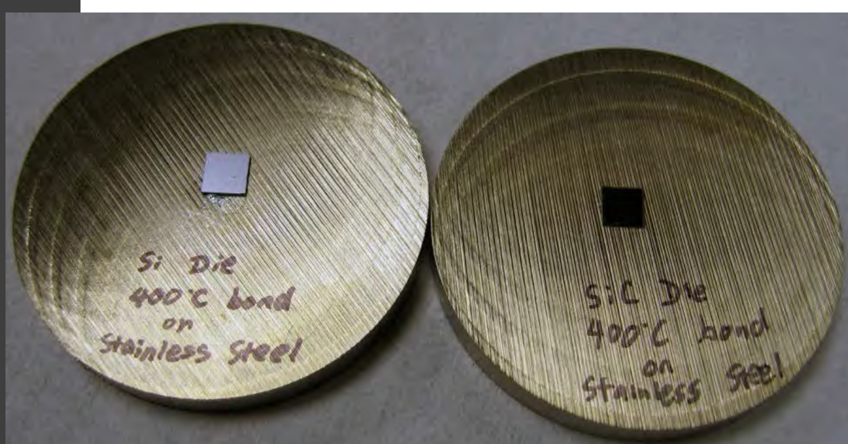
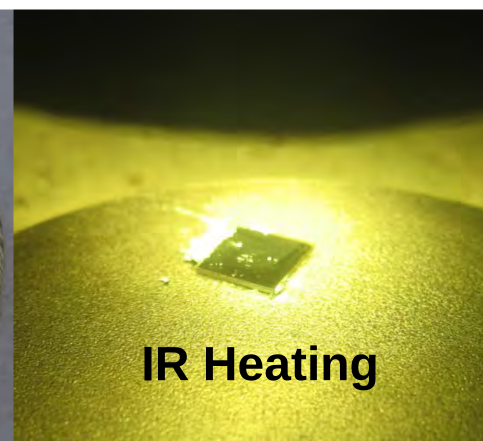
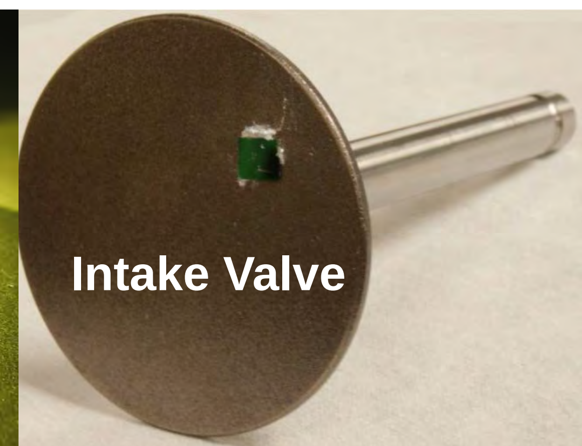


IR heating and S-Bond to adhere SiC ships to engine components







Exposure Testing

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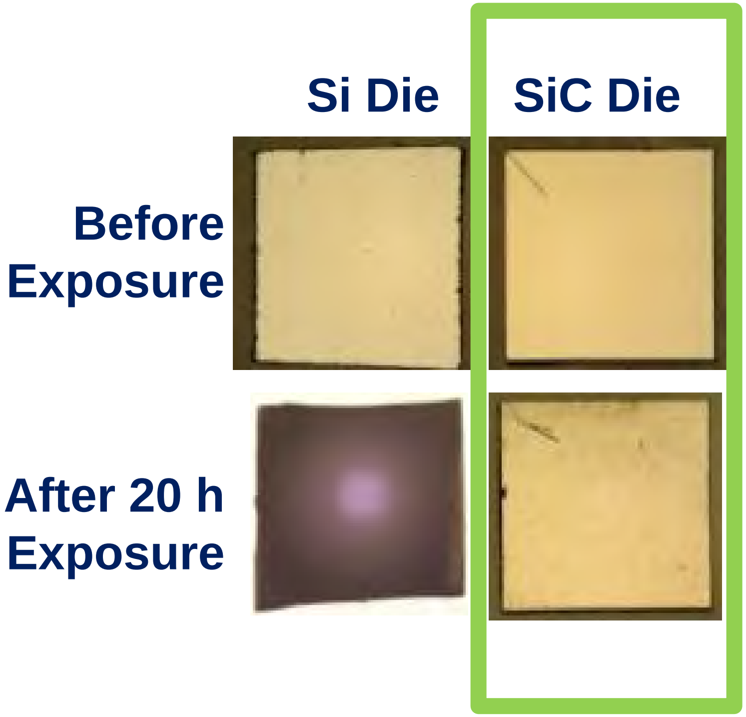
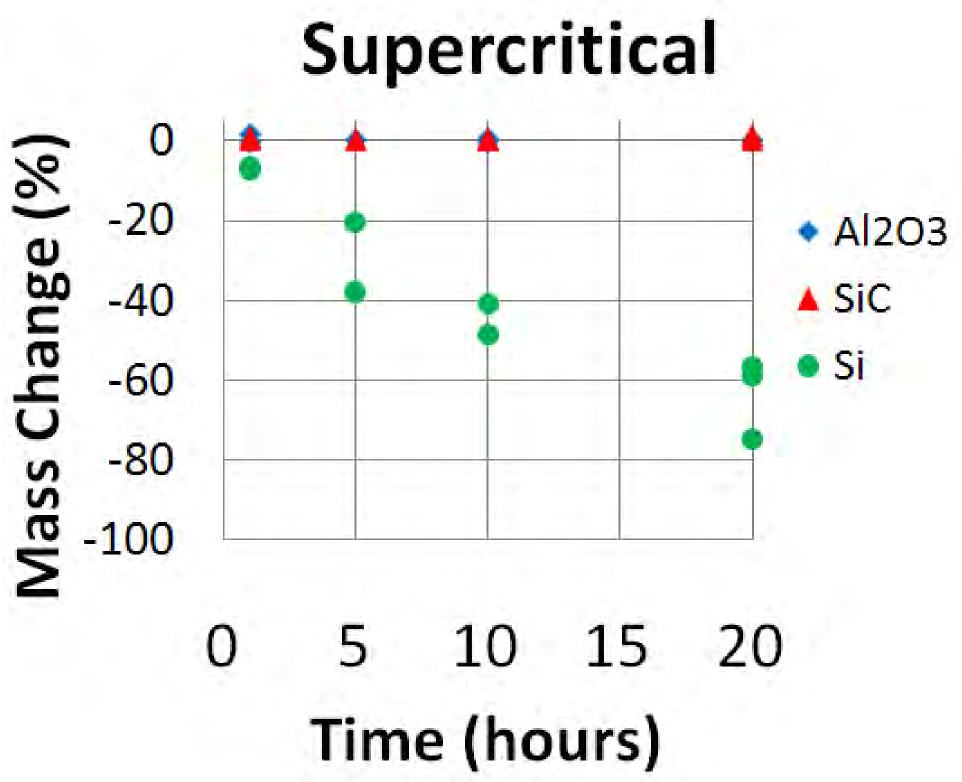


Sample size = ~ 5 mm x 5 mm



Exposure testing of sensor materials in supercritical H_2O (with Ni ions) environments (P = 100 MPa, Temperature = 427˚C) with Tuttle pressure vessel.

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Exposure Testing

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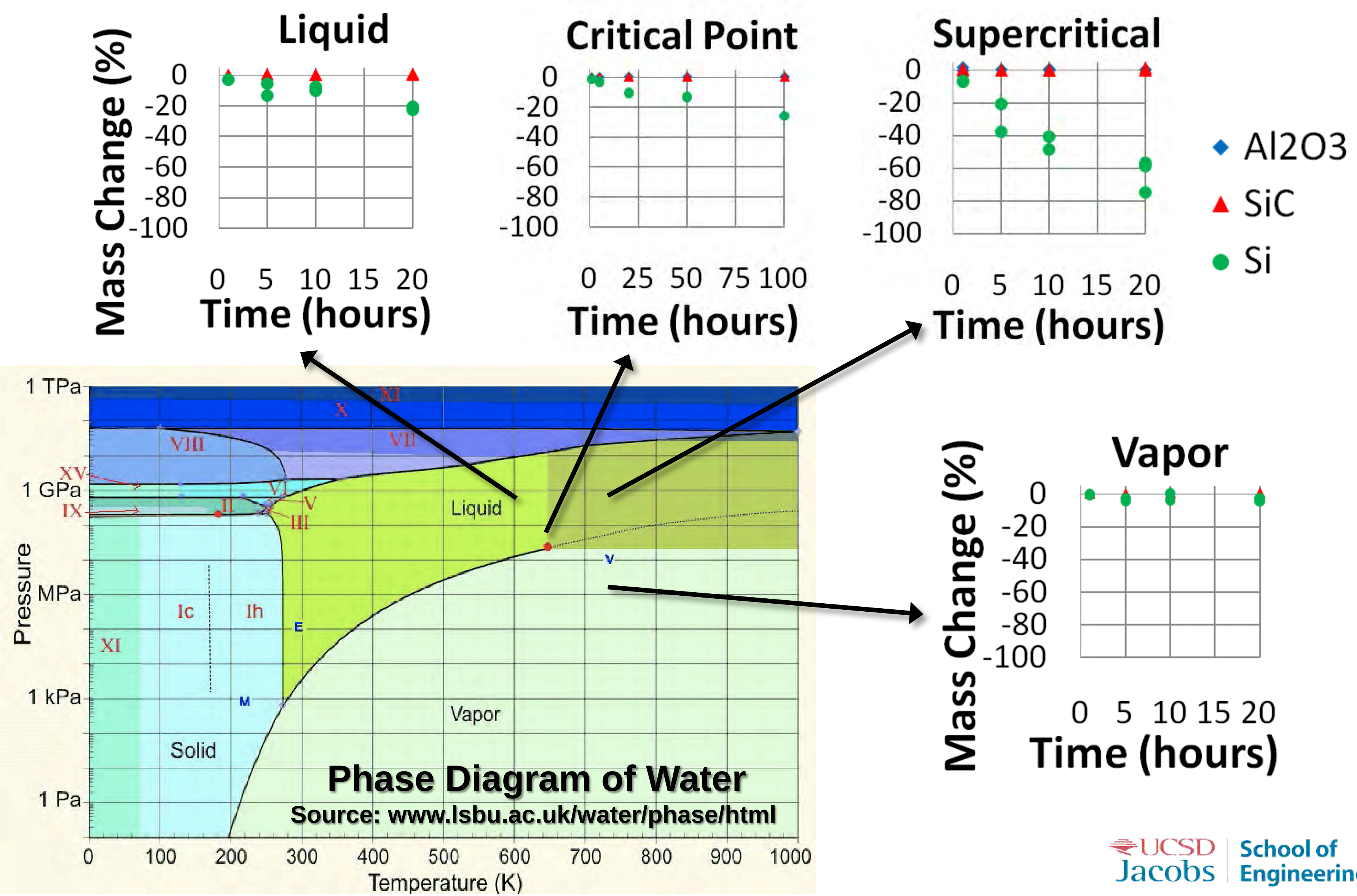

Energy Flow for USA (circa 2006)

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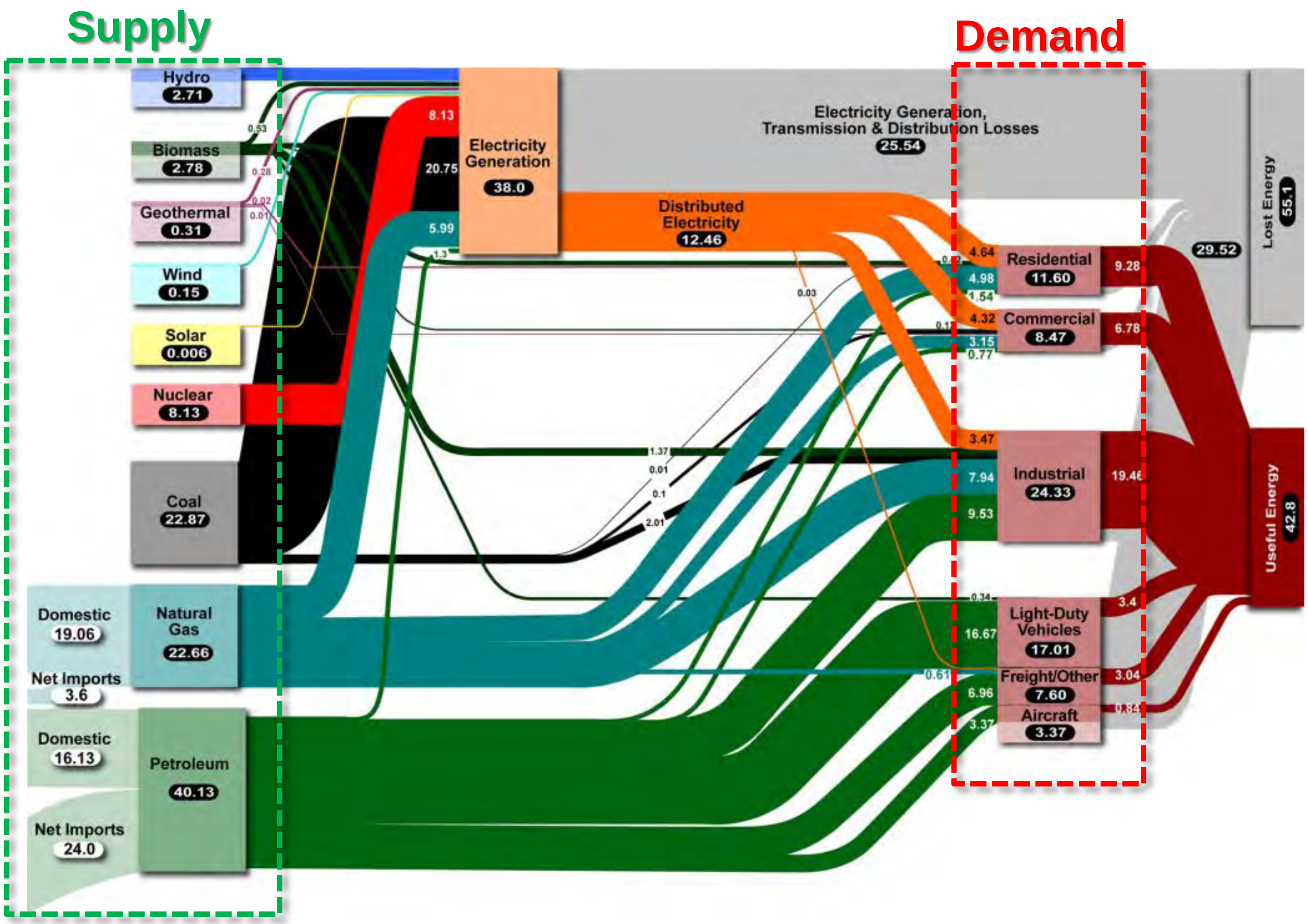

Source: Energy Flow Charts, LLNL, 2006 - https://eed.llnl.gov/flow

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Geothermal Energy

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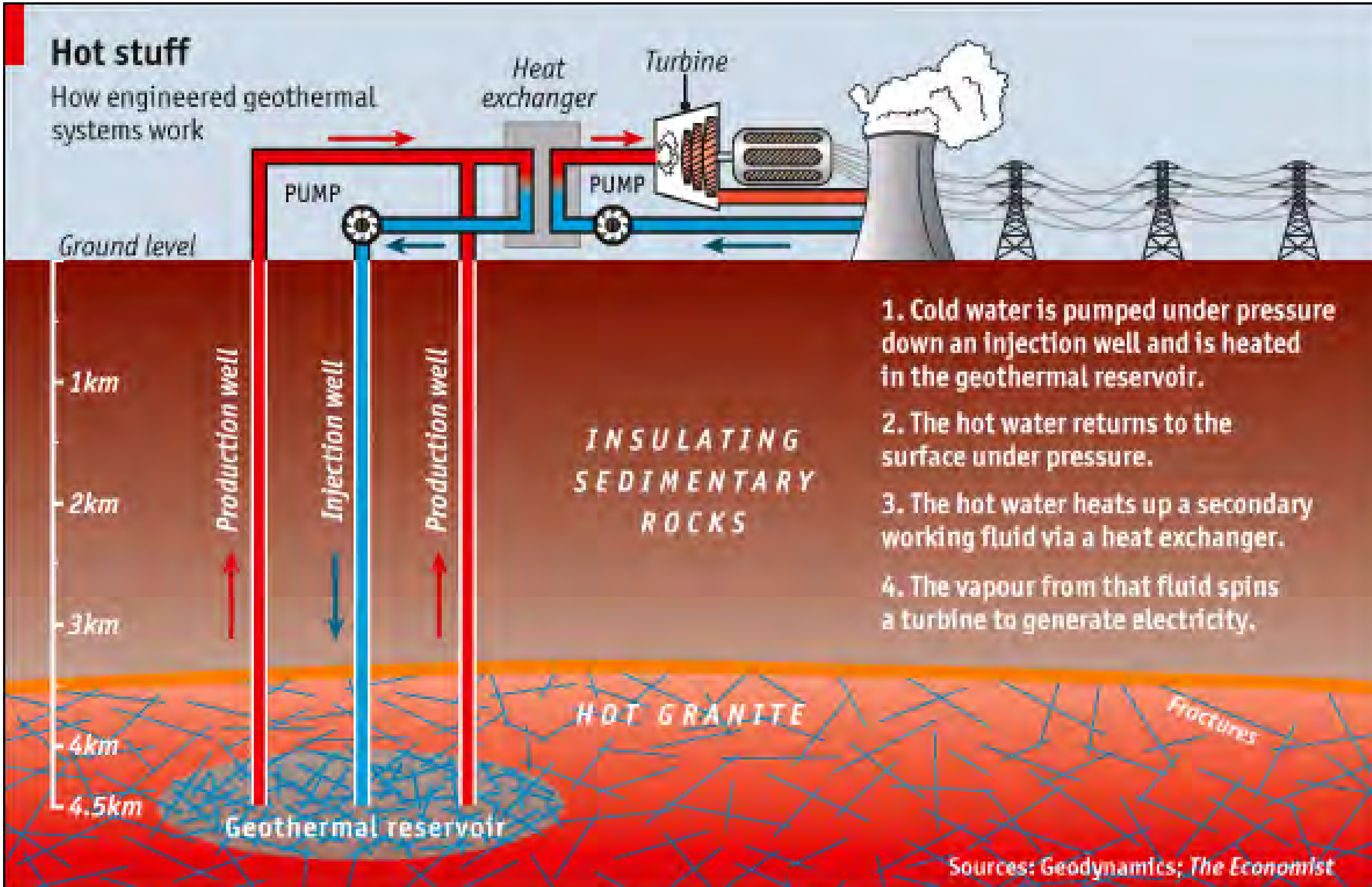

U.S. Geothermal Resources

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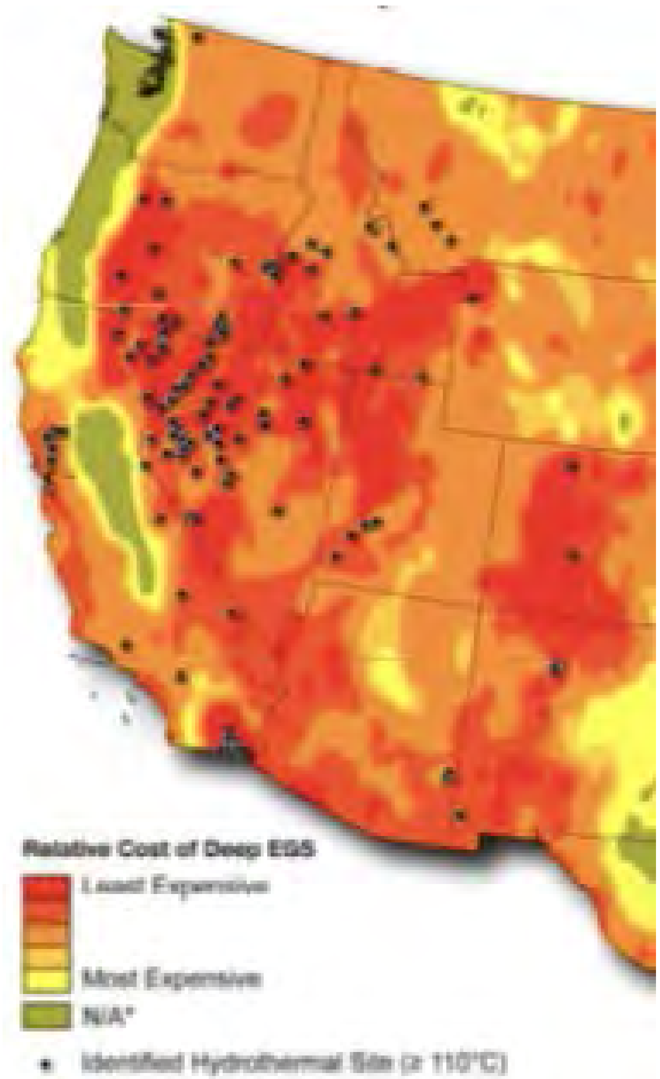

Western United States Geothermal Energy Resources:

- **Hydrothermal = 30,000 MW**
- **Enhanced Geothermal Systems (EGS) = 500,000 MW**

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European Geothermal Resources

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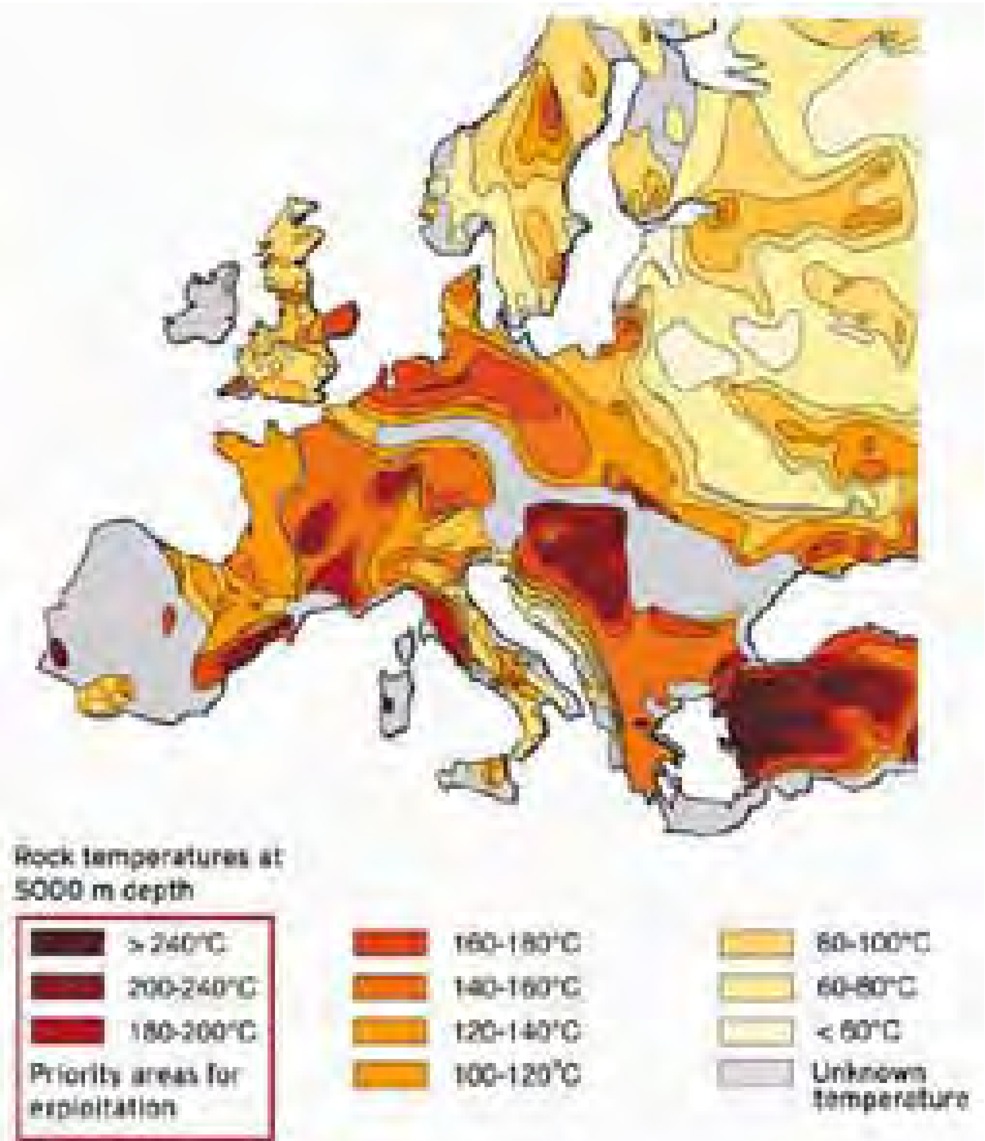

Source:
http://europa.eu.int/comm/research/energy/nn/nn_rt/nn_rt_geo/article_1134_en.htm

Geothermal Resources in Japan

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List of Geothermal Power Plants in Japan

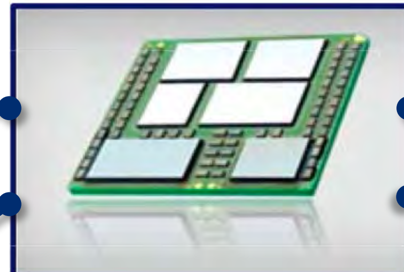
Mori	Ohnuma	Sumikawa
Matsukawa	Kakkonda	Uenotai
Onikobe	Yanaizu-Nishiyama	Hachijo- Jima
Suginoi	Takigami	Ohdake
Hatchobaru	Ohgiri	Kirishima-kokusai Hotel
Yamagawa	Kuju	

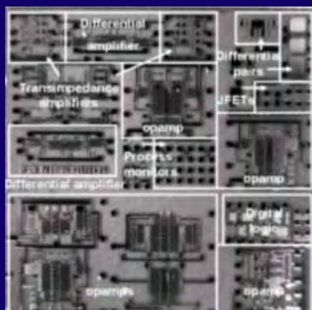
Source:
http://wwwsoc.nii.ac.jp/grsj/geothermalinJ/Res&PP/P_Plant/main121.html

Sensor Cluster in the Ground

Harsh Environment Sensor Cluster

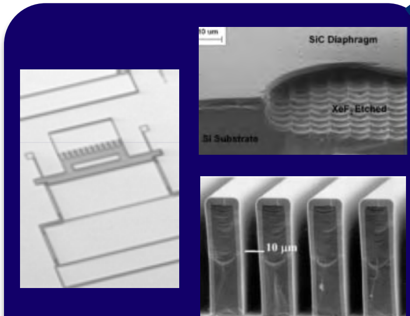
Self-powered, Wireless, Multi-Chip Sensing Module



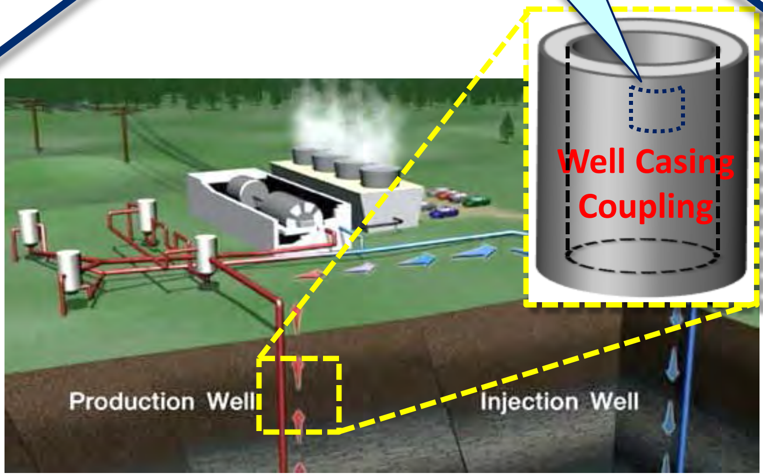


SiC Integrated Circuits

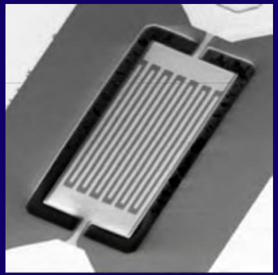
SiC/AlN Scavenging Power Source



SiC/AlN Harsh Environment Sensors



Efficient, Clean & Smart Geothermal Energy Systems



AlN RF Telemetry Components

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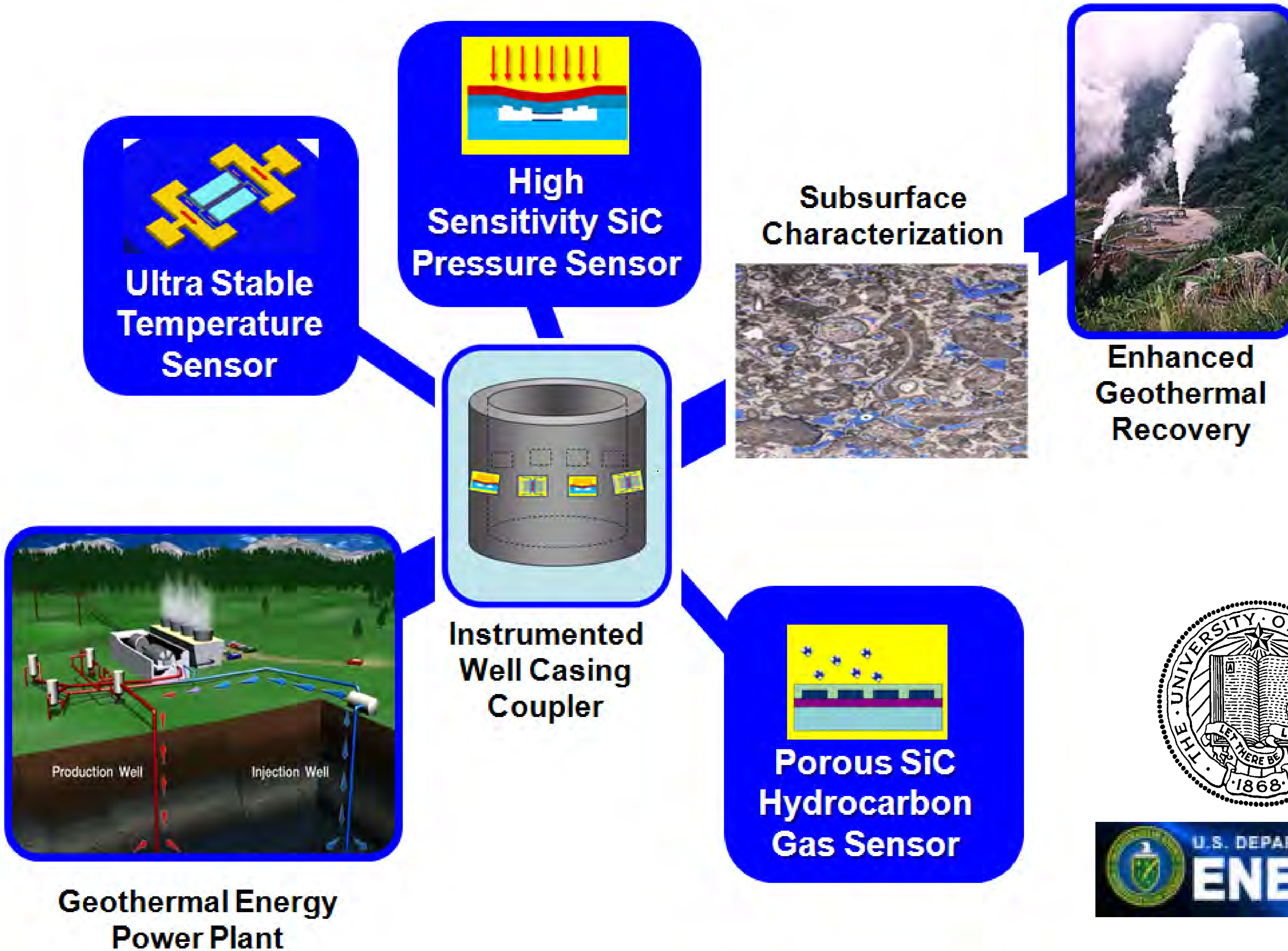
Cluster Sensor in the Ground

Harsh Environment Sensor Cluster



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Cluster Sensor in the Gas Turbine

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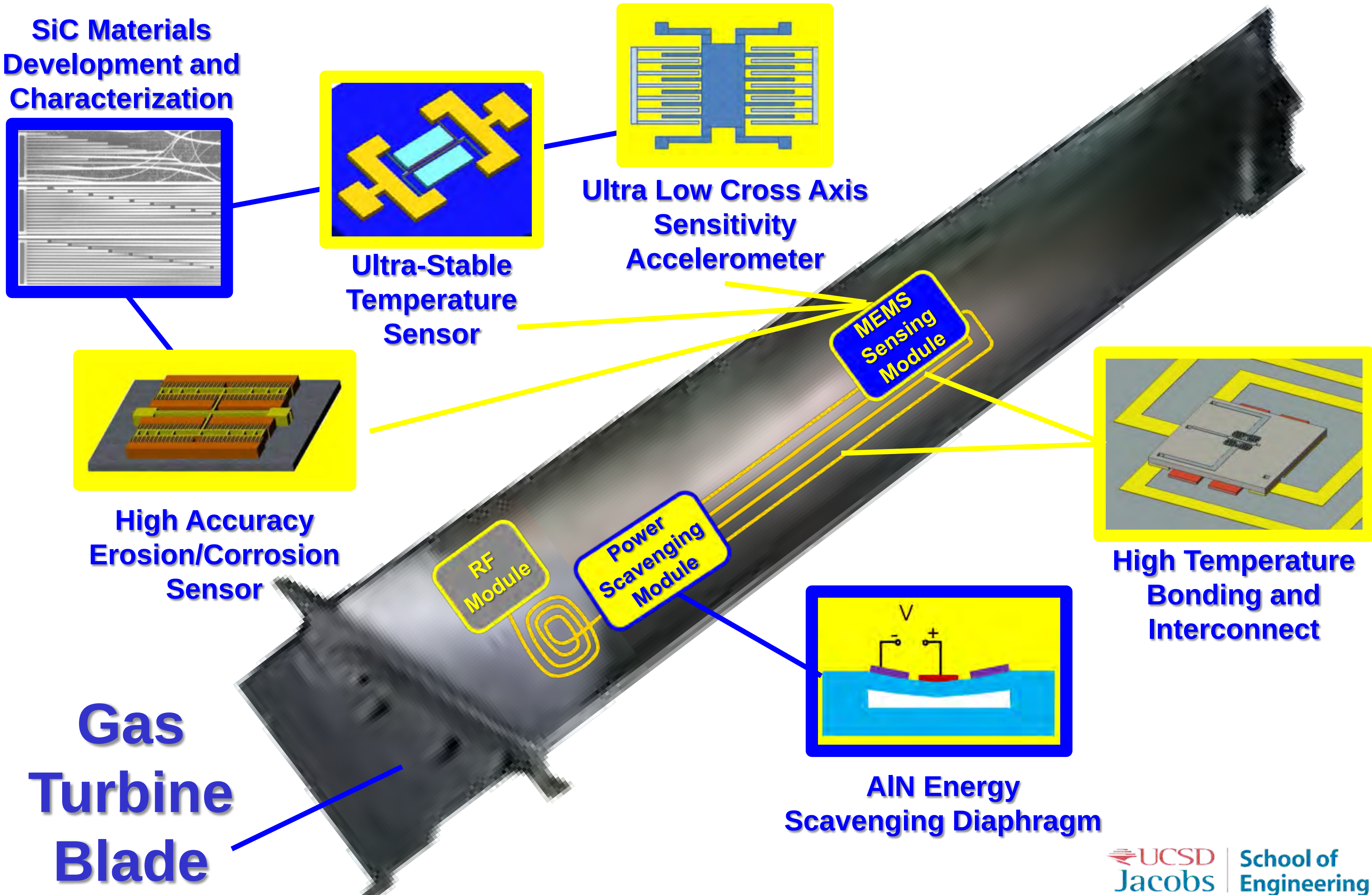


Cluster Sensor in Transportation

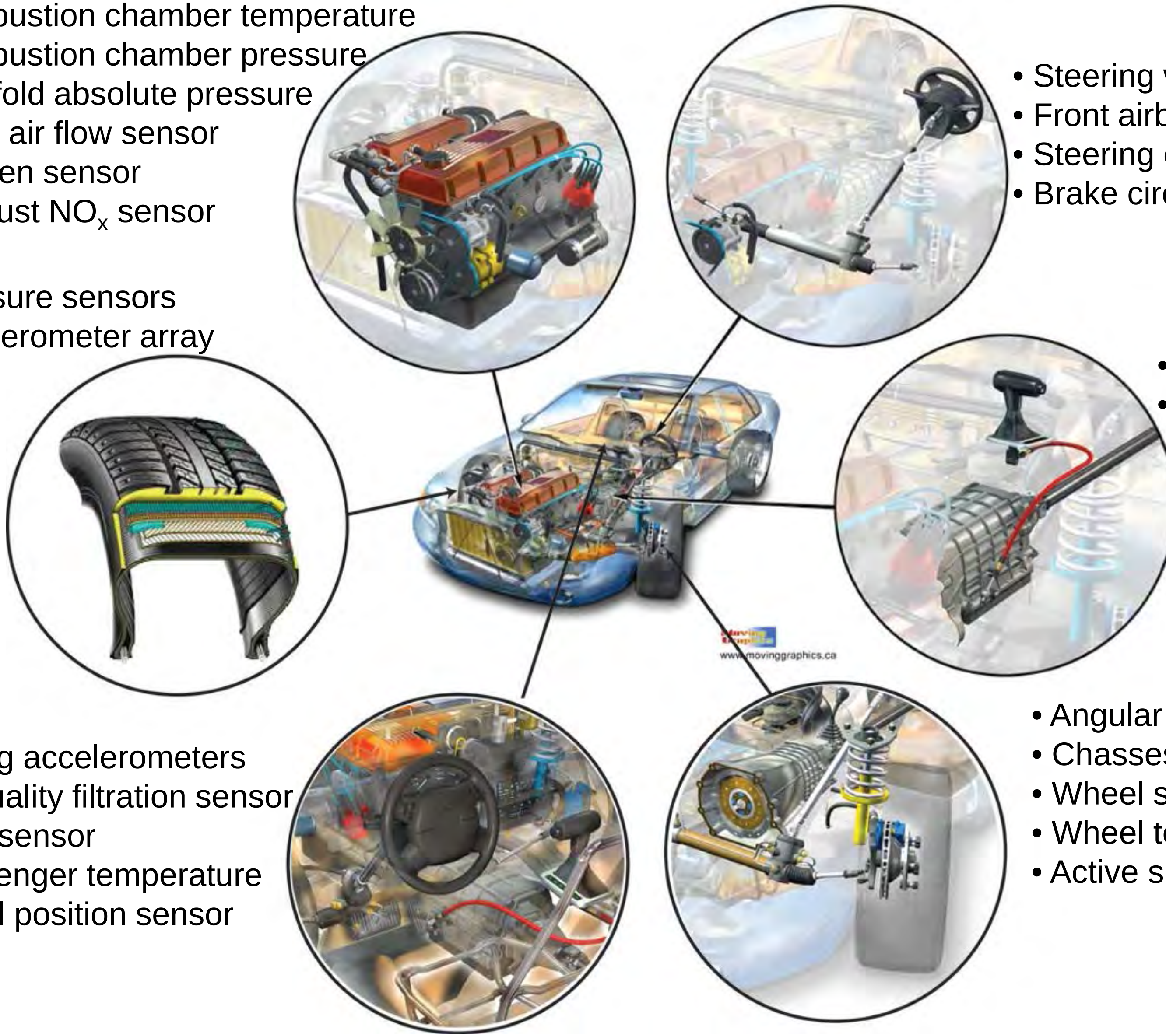
Harsh Environment Sensor Cluster

- Combustion chamber temperature
- Combustion chamber pressure
- Manifold absolute pressure
- Mass air flow sensor
- Oxygen sensor
- Exhaust NO_x sensor

- Pressure sensors
- Accelerometer array

- Steering wheel angle sensor
- Front airbag accelerometer
- Steering circuit oil pressure
- Brake circuit oil pressure

- Transmission torque
- Halfshaft torque



- Airbag accelerometers
- Air quality filtration sensor
- Rain sensor
- Passenger temperature
- Pedal position sensor

- Angular rate (roll over)
- Chasses tilt sensor
- Wheel speed rate (ABS)
- Wheel torque sensor
- Active suspension sensor

Sensor Cluster in the Automobile

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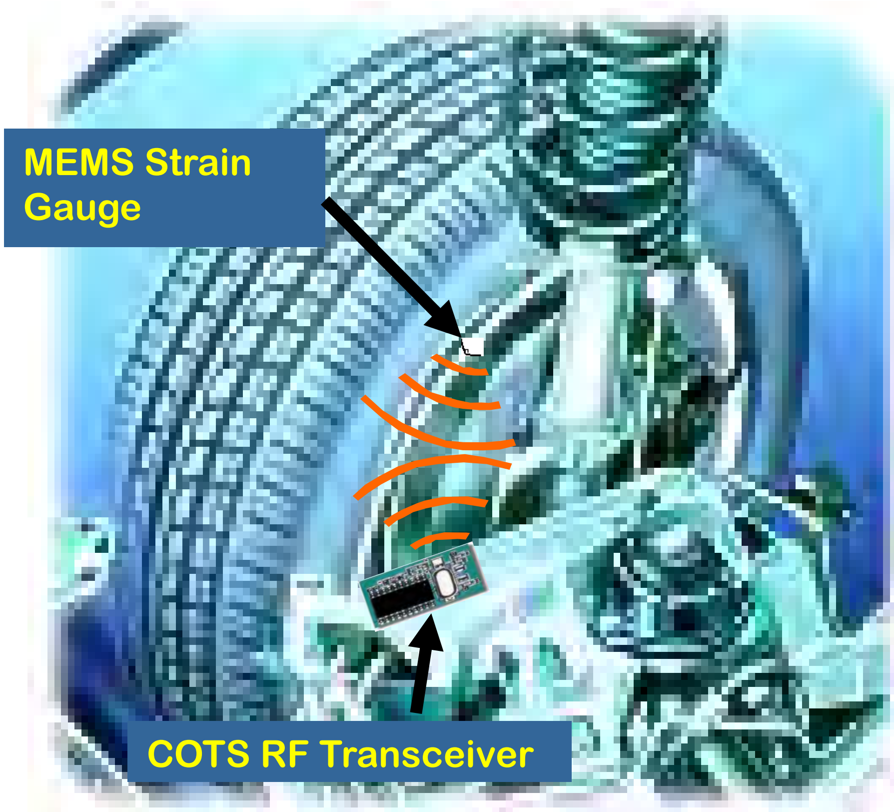
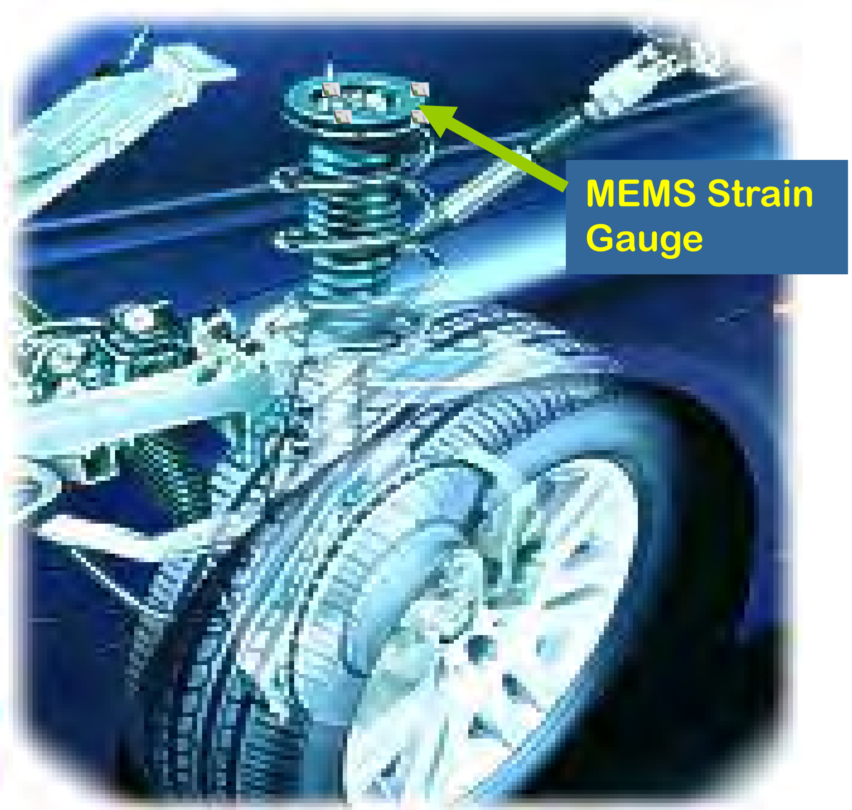




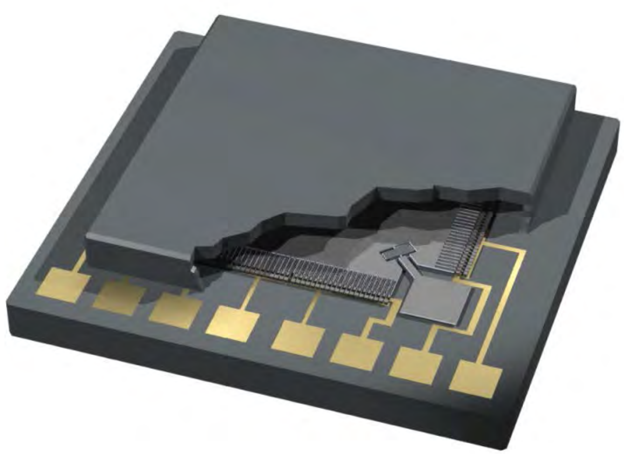
- **MEMS Sensor on Wheel Communicates via RF to Transceiver on Chassis**
- **MEMS Sensor on Shock Tower Measures Vertical Forces On Chassis for DSC Application**

Sensor Cluster in the Tire

Harsh Environment Sensor Cluster

3-Point Array of Sensors

<u>Sensor Types</u>:
Strain Sensors
Pressure Sensors
Accelerometers



Molding & Vulcanization

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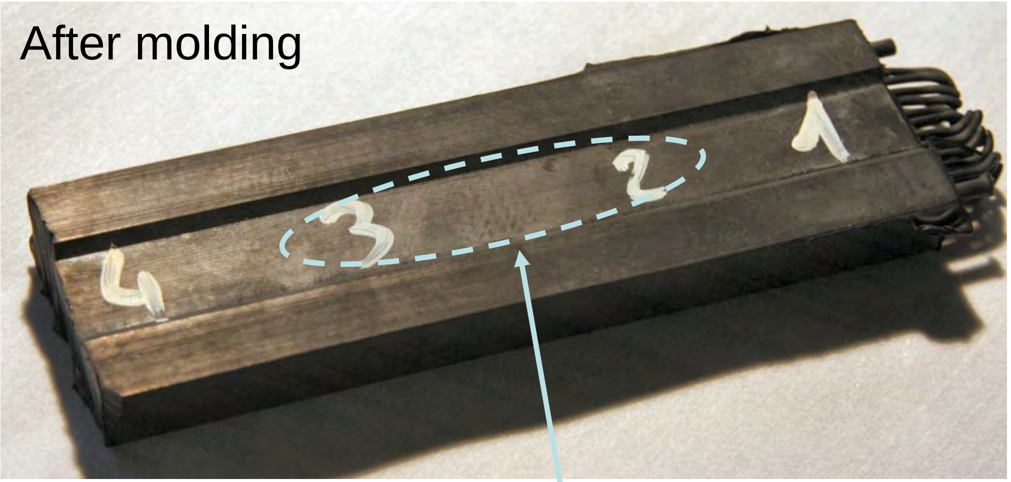
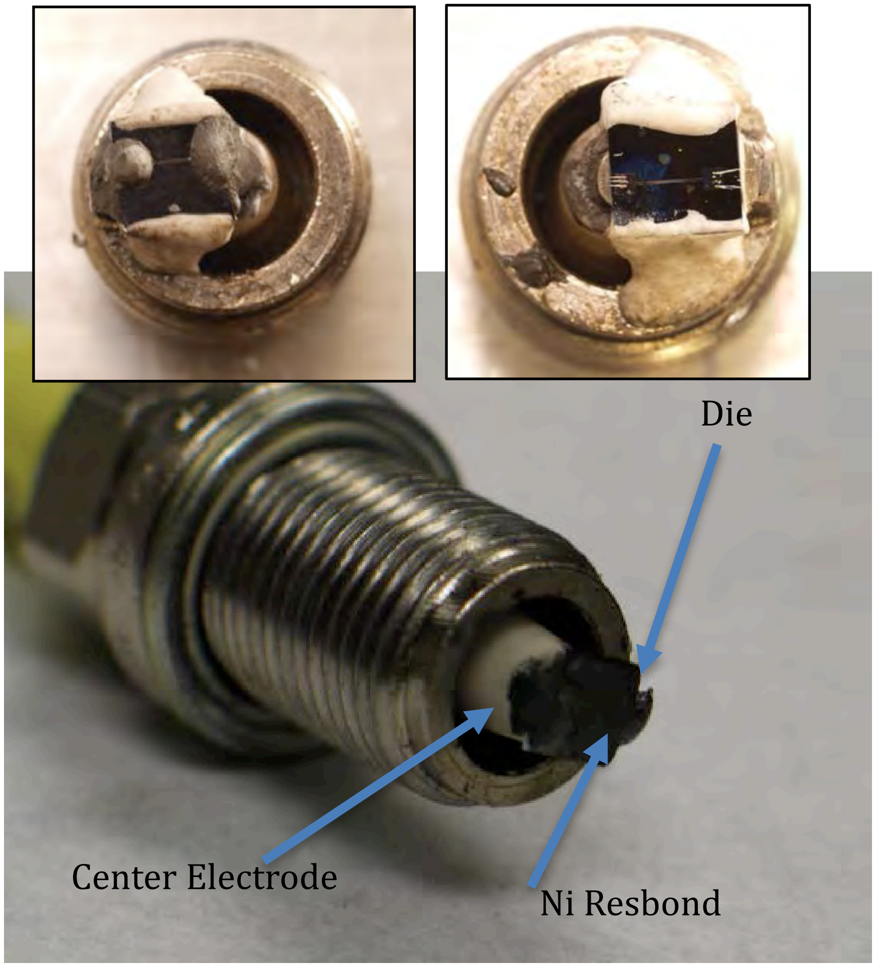


Embedded samples

- **4 embedded samples**
- **5x5mm2 each**
- **Array of SiC Zener diodes**
  - Survivability test
- **Si substrate covered with SiO2/SiC**
  - Delamination test
- **Two Si substrates**
  - Bare Si
  - Si + Ni (2nm)
  - → Sample/rubber adhesion

Cluster Sensor in the Auto Engine

Harsh Environment Sensor Cluster



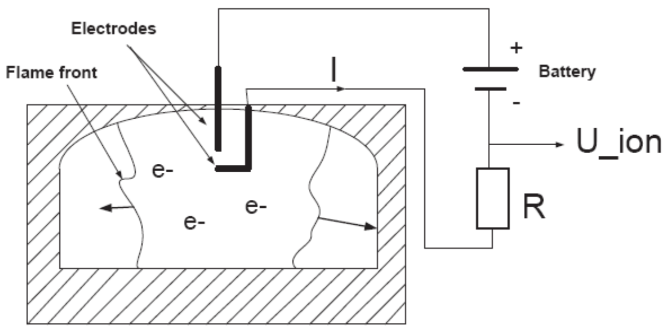
Test Fixture for signal collection. There are two die attachment methods:

1) <u>Simultaneous Electrical and Mechanical Attachment</u> via Ni Resbond with Auxiliary Mechanical Attachment via Ceramic Adhesive

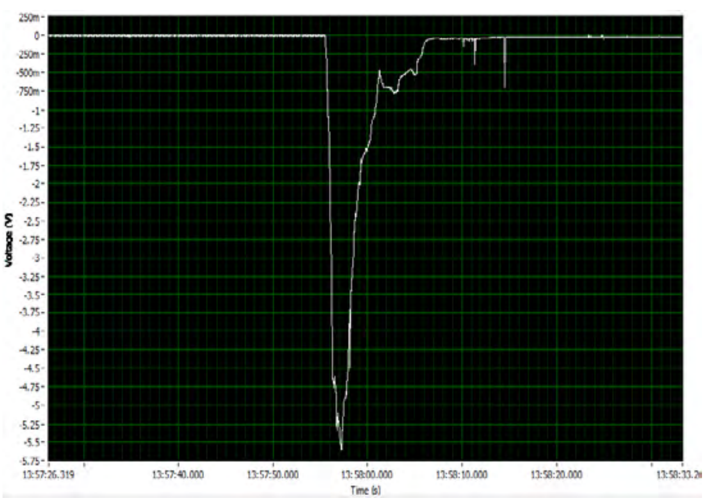
2) Separate Electrical and Mechanical Attachment via Ceramic Adhesive for Mechanical and Aluminum Wire Bonds for Electrical

Cluster Sensor in the Auto Engine

Harsh Environment Sensor Cluster



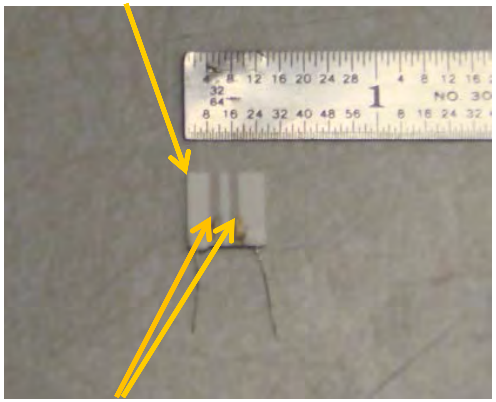
Bias voltage -> leakage current -> ion concentration detection

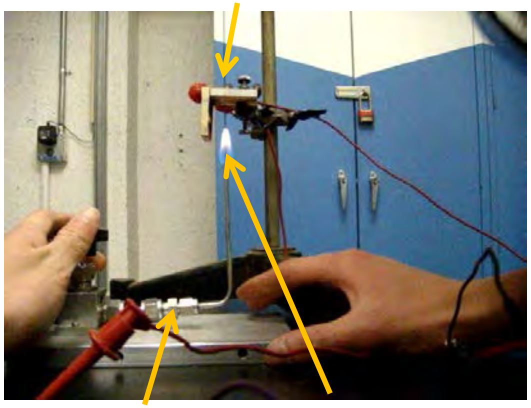


5.5V peak signal (from 120V bias voltage). Expecting **< 0.010V resolution**.

1 cm^2 fired alumina substrate

Ceramic shield to protect wire leads





Sintered Pt electrodes (1mm wide, 1mm gap)

Controlled flame jet

Methane diffusion flame

Prototype fabricated and tested:

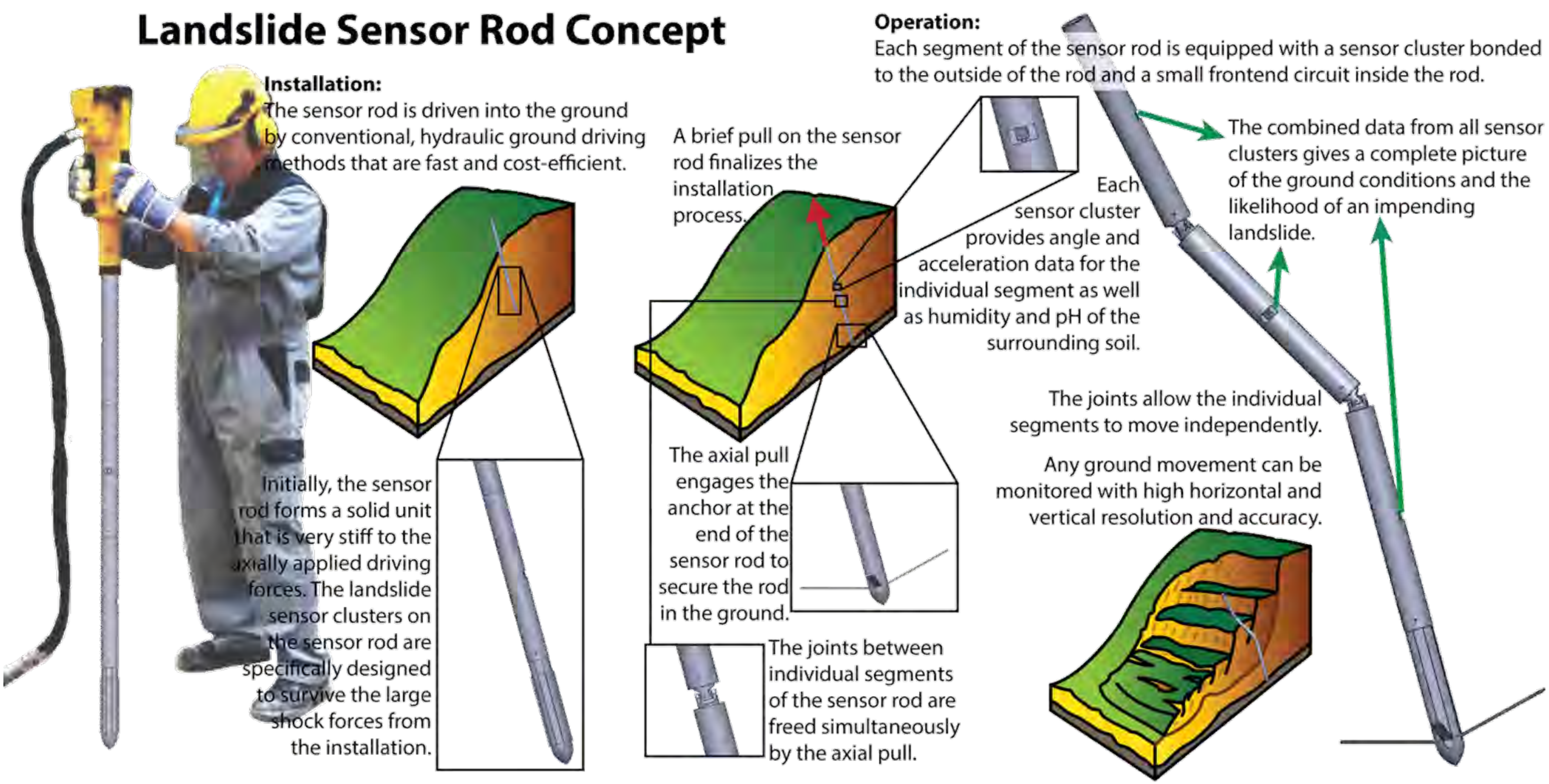
- Platinum ink on alumina substrate
- Preliminary tests show geometry has good sensitivity to flames

Next steps:

- Production via MEMS or microprinting technology
- Design and construction of test chamber

Cluster Sensor Landslide Prediction

Harsh Environment Sensor Cluster



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Cluster Sensor in the Infrastructure

Harsh Environment Sensor Cluster

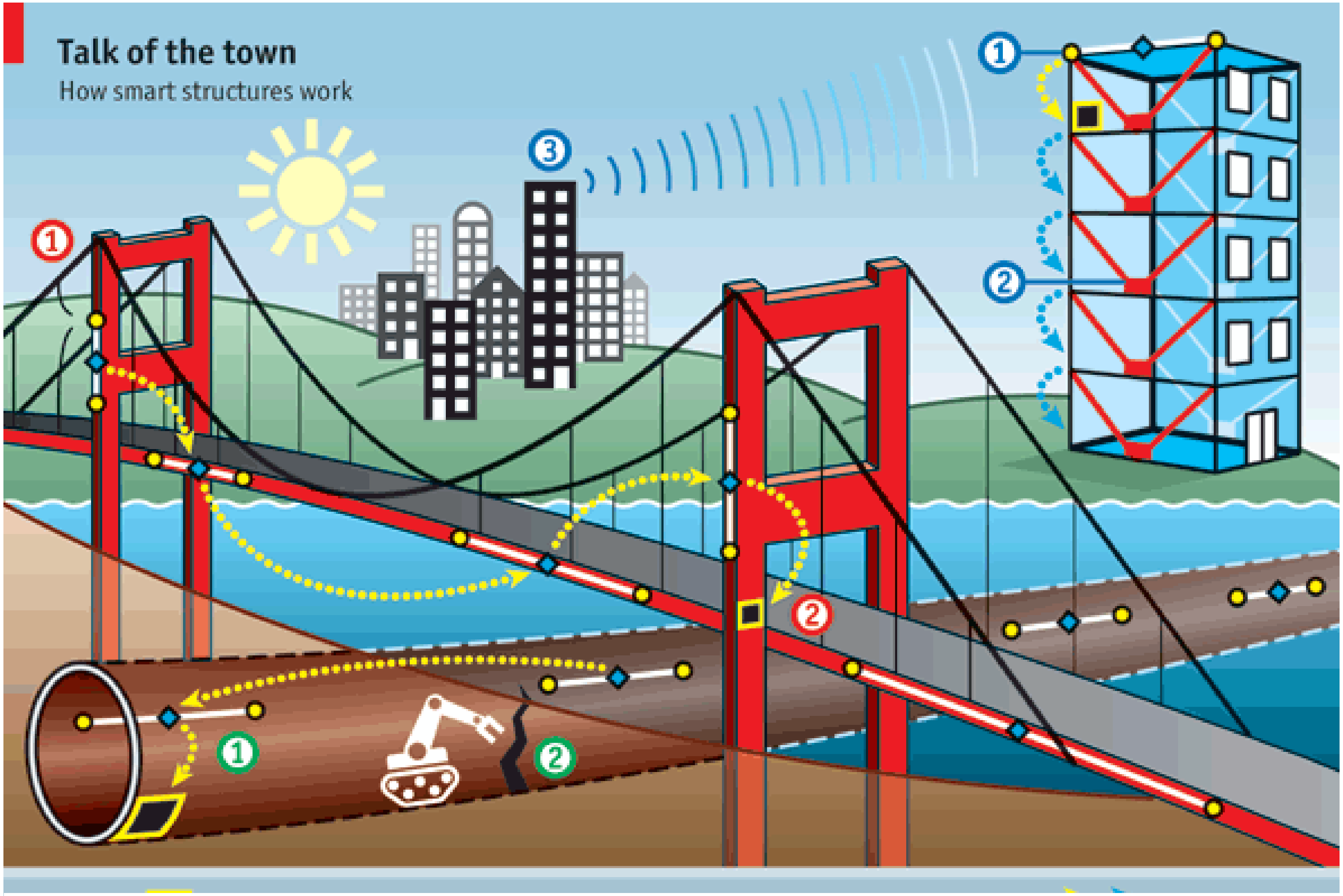
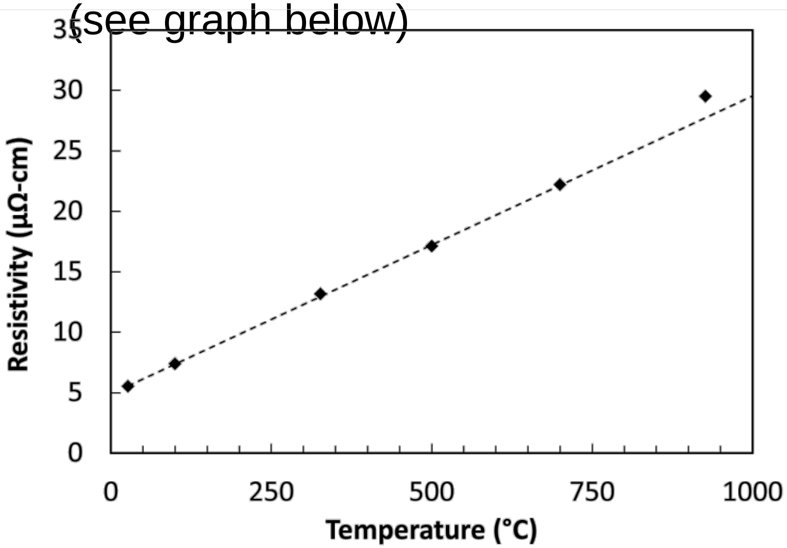


Figure from The Economist Magazine

Advanced Sensor Cluster Prototype

Harsh Environment Sensor Cluster

- Temperature sensor is resistive type (resistance changes linearly with temperature)
- Sensor size can be very small (e.g. 200 µm x 200 µm)
- Many temperature sensors can be placed on the sensor cluster chip
- Linearity is very good for Molybdenum in the required temperature range (see graph below)

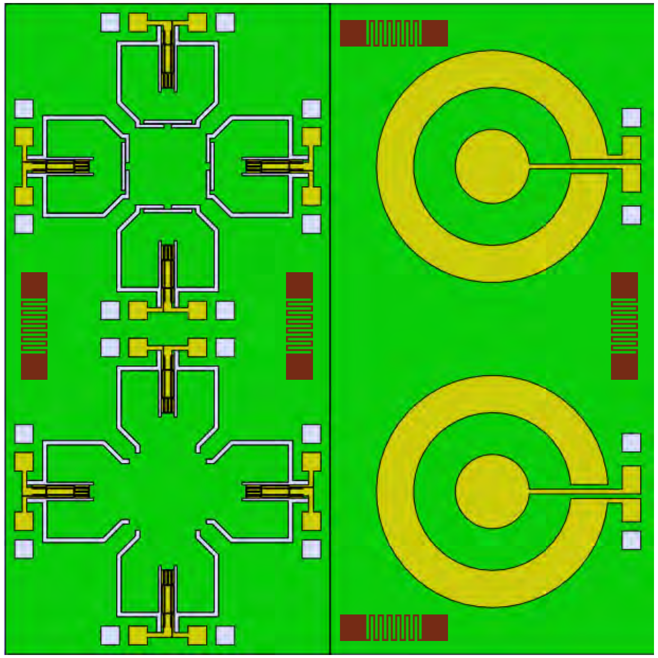


Source: www.elmettechnologies.com

Example of Sensor Design

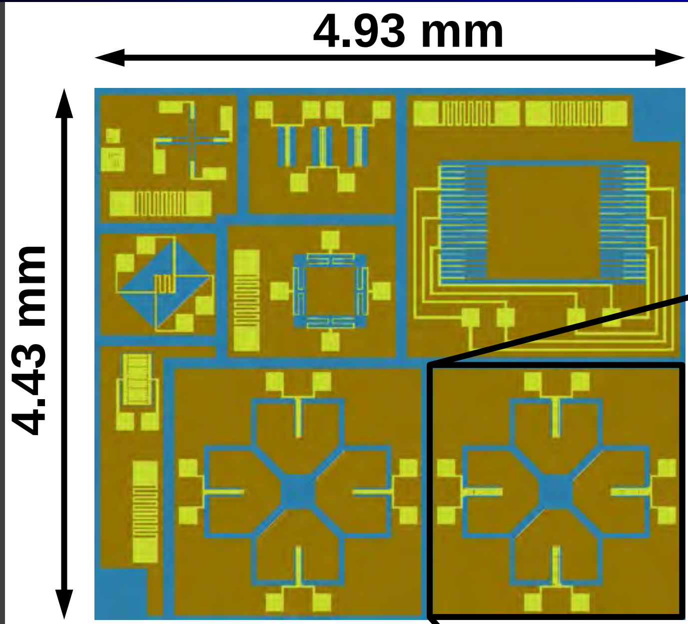
Example of Placement

Note: This is a schematic figure. The actual design of the prototype I chip will be submitted later.

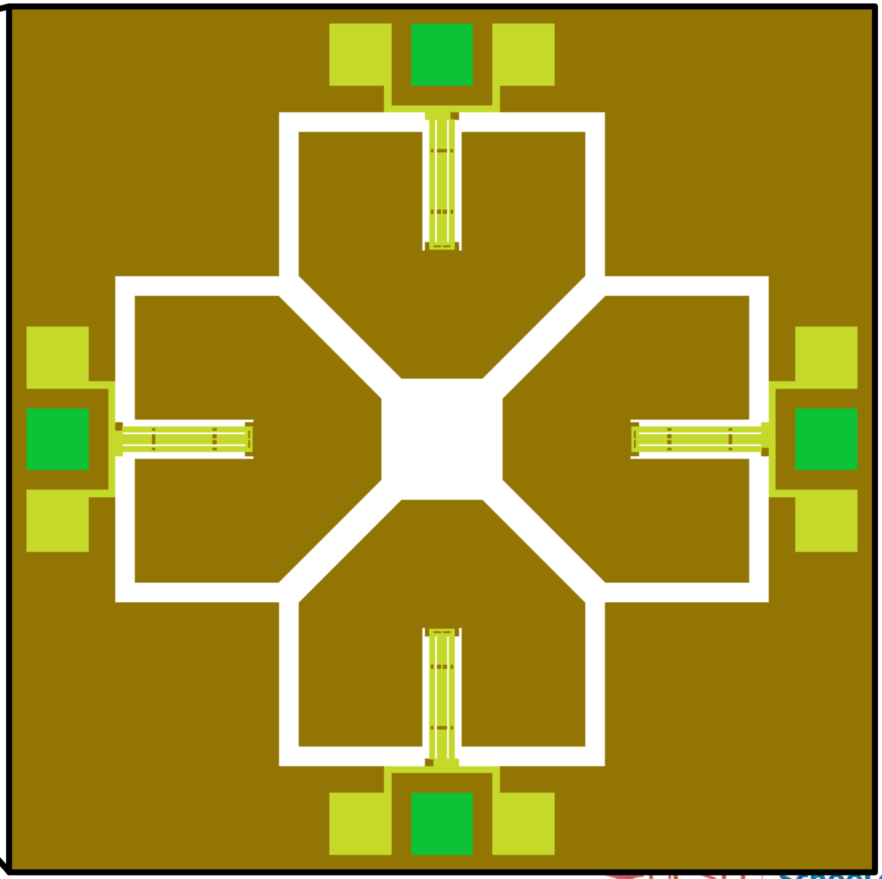


Pre-Prototype Design

Harsh Environment Sensor Cluster



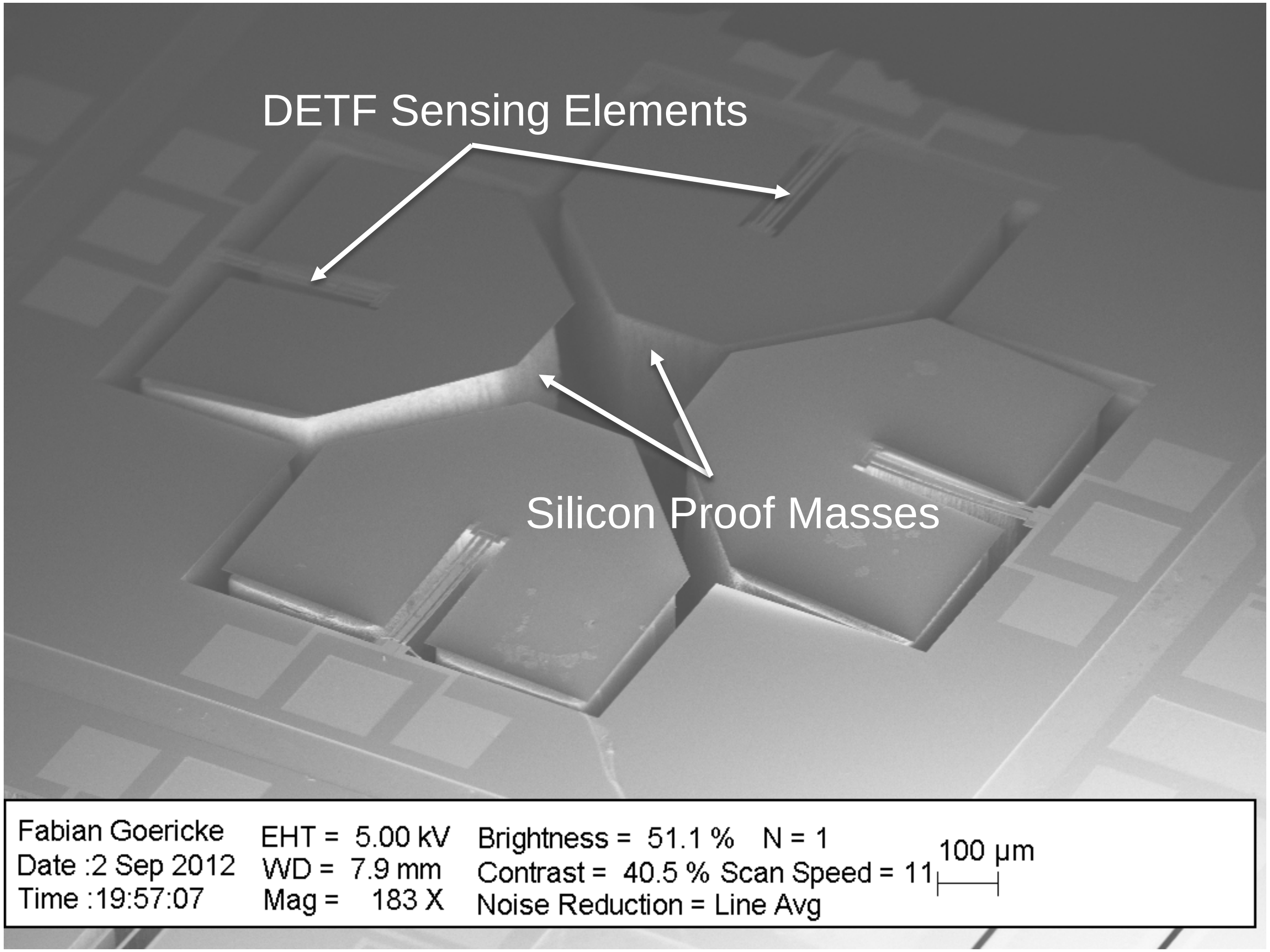
2-Axis Accelerometer



Integrated components:
- 2-axis accelerometer
- Vacuum pressure gauge
- Strain sensor
- Temperature sensor

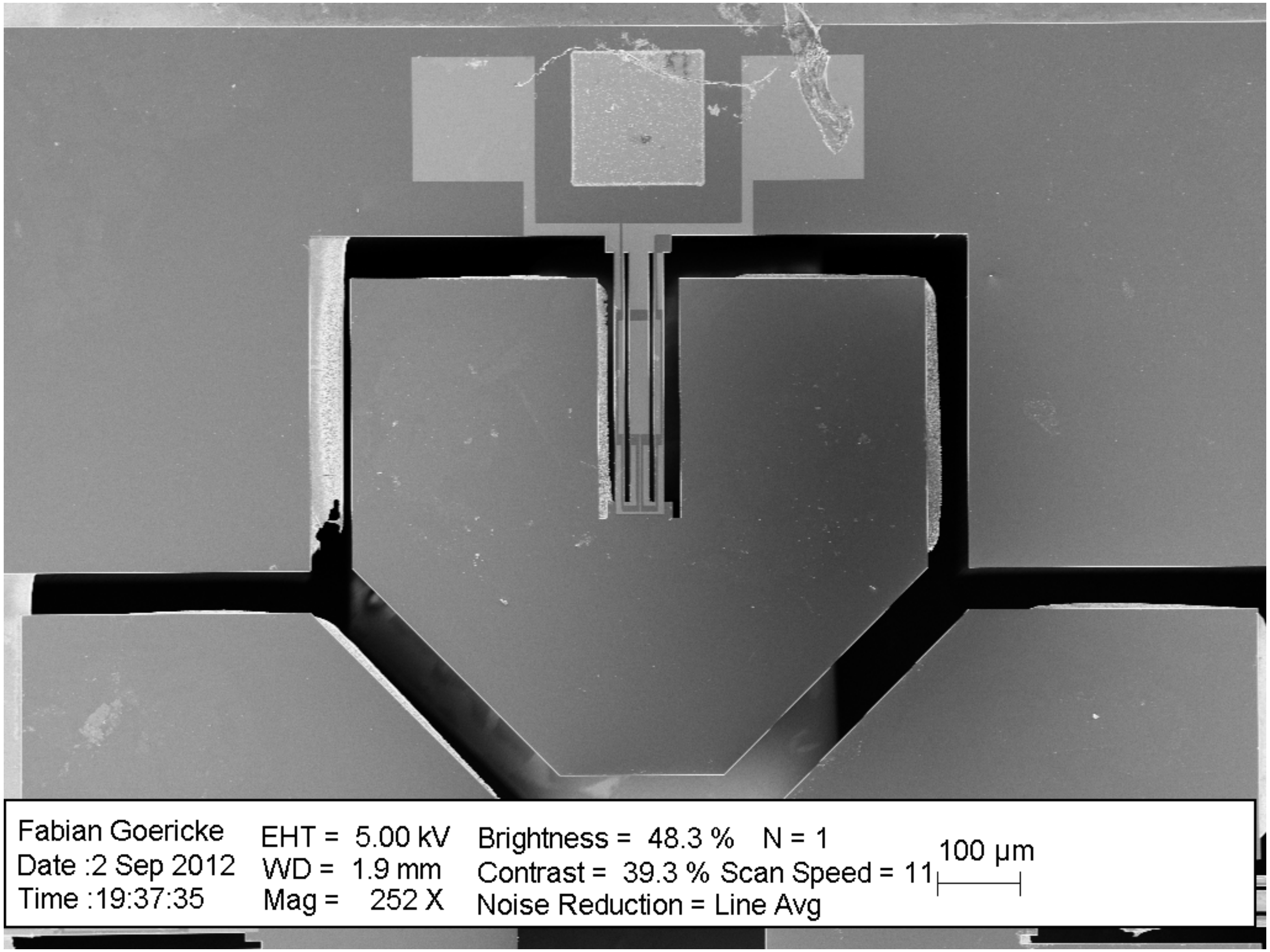
Pre-Prototype Results

Harsh Environment Sensor Cluster



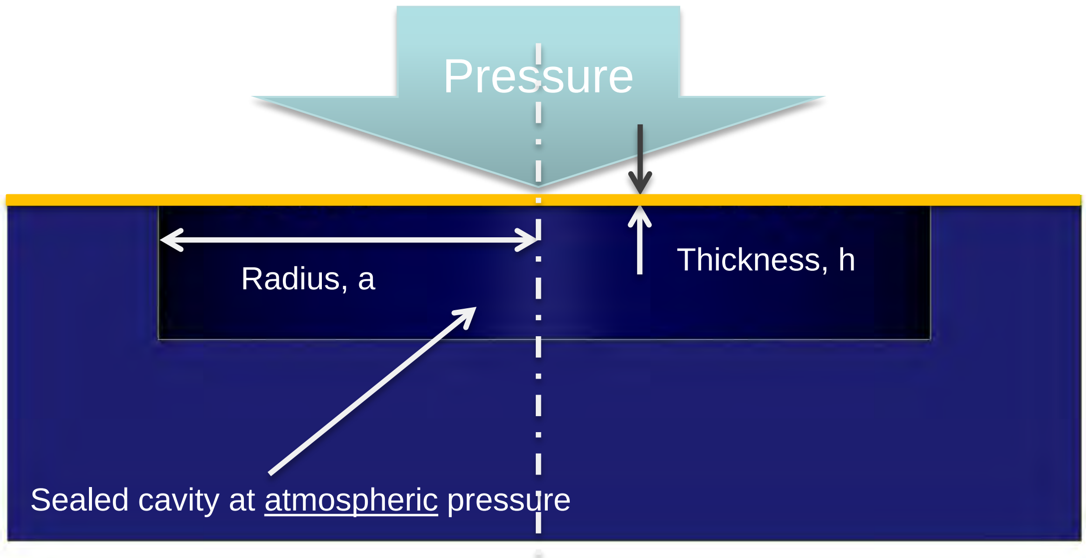
Pre-Prototype Results

Harsh Environment Sensor Cluster



AlN Pressure Sensor Design

Harsh Environment Sensor Cluster



Characteristic Equation for Circular Membrane:

$$\frac{Pa^4}{Eh^4} = 5.86\frac{y}{h} + 3.19\frac{y^3}{h^3}$$

Resonance frequency of membrane:

$$\omega = 9.22\frac{h}{a^2}\sqrt{\left[\frac{E}{\rho(1-\mu^2}\right]}$$

a = radius, h = thickness, y = deflection, E = Young's modulus, Ae = effective area of corrugated diaphragm, D = flesural rigidity, μ = Poisson's ratio, ρ=specific weight of membrane material.

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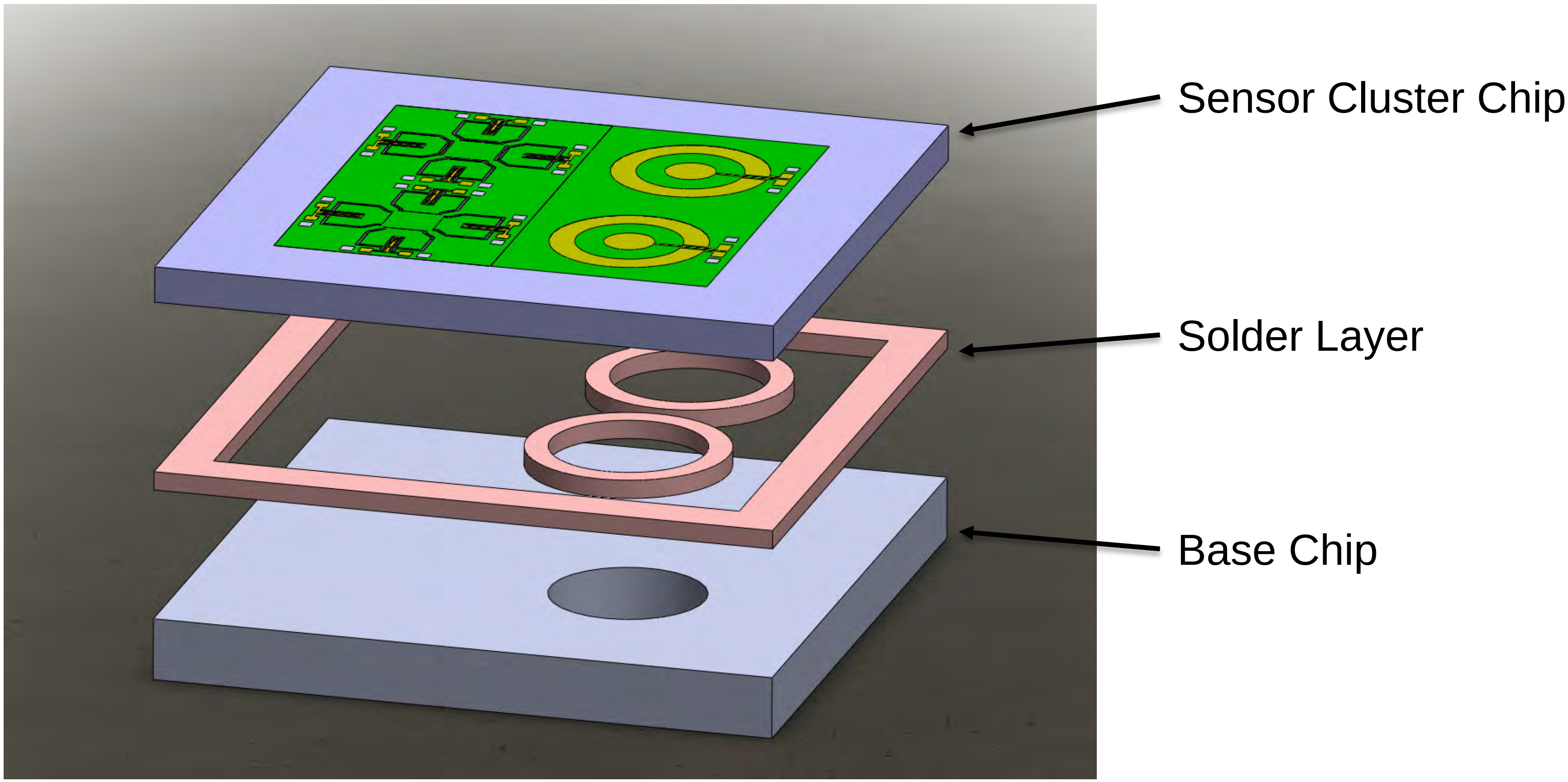
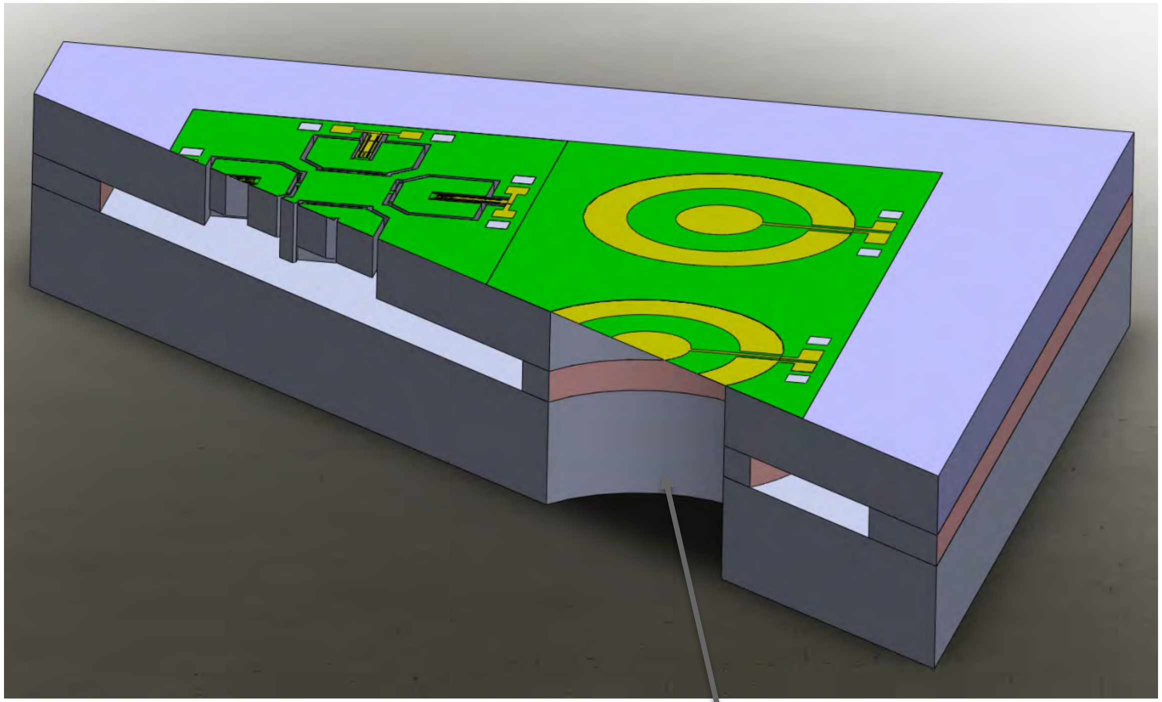
Cluster Prototype Assembly

Harsh Environment Sensor Cluster



Cluster Prototype Assembly

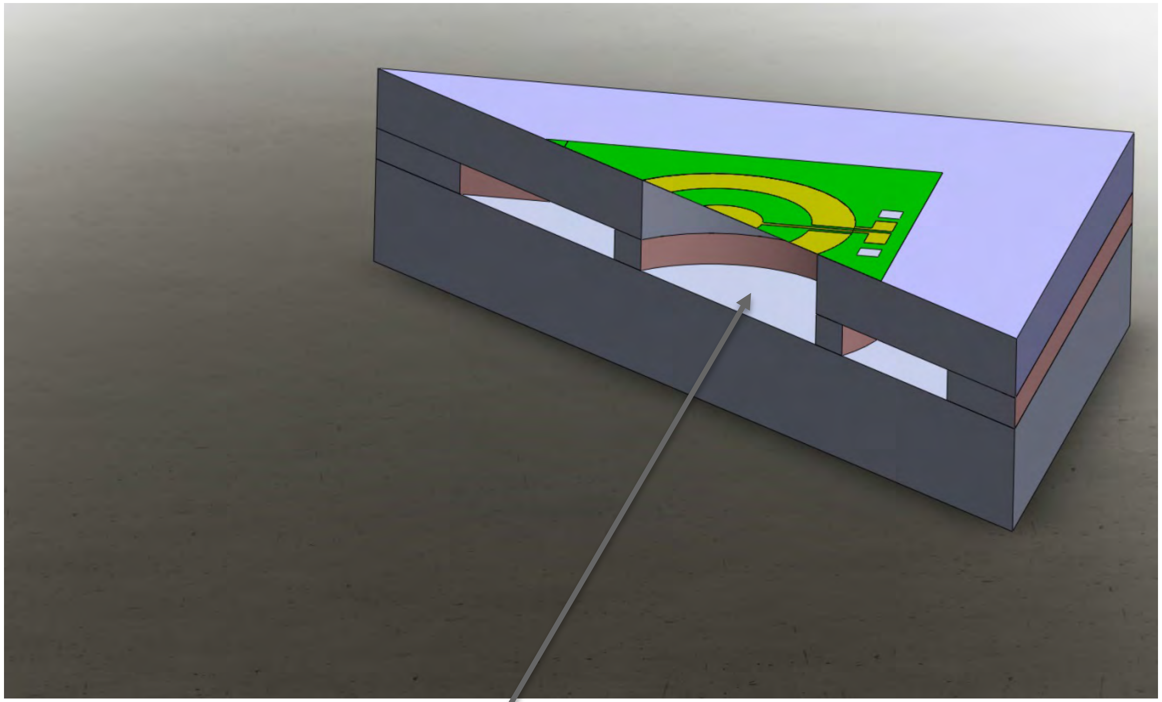
Harsh Environment Sensor Cluster



Reference Device Open to Atmosphere on Top and Bottom

Cluster Prototype Assembly

Harsh Environment Sensor Cluster



Sealed Cavity of Pressure Sensor

Conclusion

Harsh Environment Sensor Cluster

- **Sensor Cluster for**
  - Energy & Environment / Gas Turbine
  - Transportation / Automobile Engine
  - Landslide Prediction / Built Infrastructure
- **Common Fabrication Process**
- **Many Sensors on One Chip**
- **Sensor Signal and Packaging are the Next Challenges**
- **Seeking Industrial Collaboration**

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Harsh Environment Sensor Cluster

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Conclusion

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Thank You!