Robust Sensors for Structural Health Monitoring in Extreme Harsh Environments

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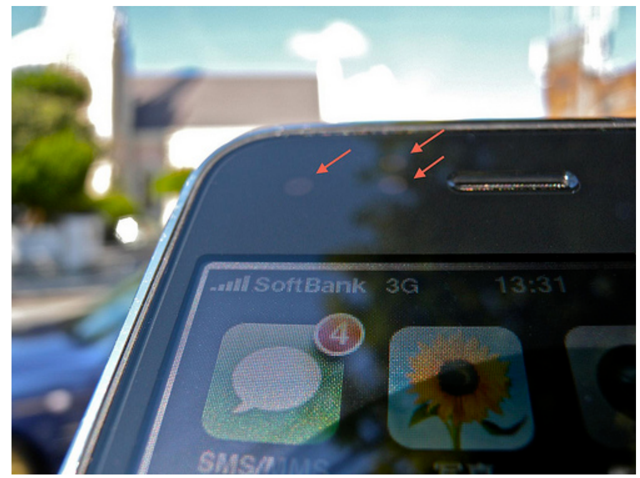
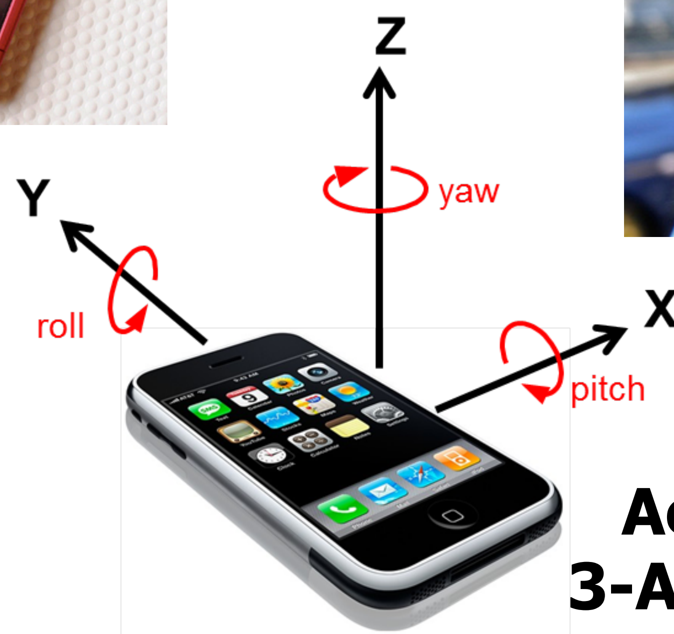
International Workshop on Structural Health Monitoring
12 September 2013

Sensors in iPhones

Digital Compass [1]

Proximity & Ambient Light Sensors [2]

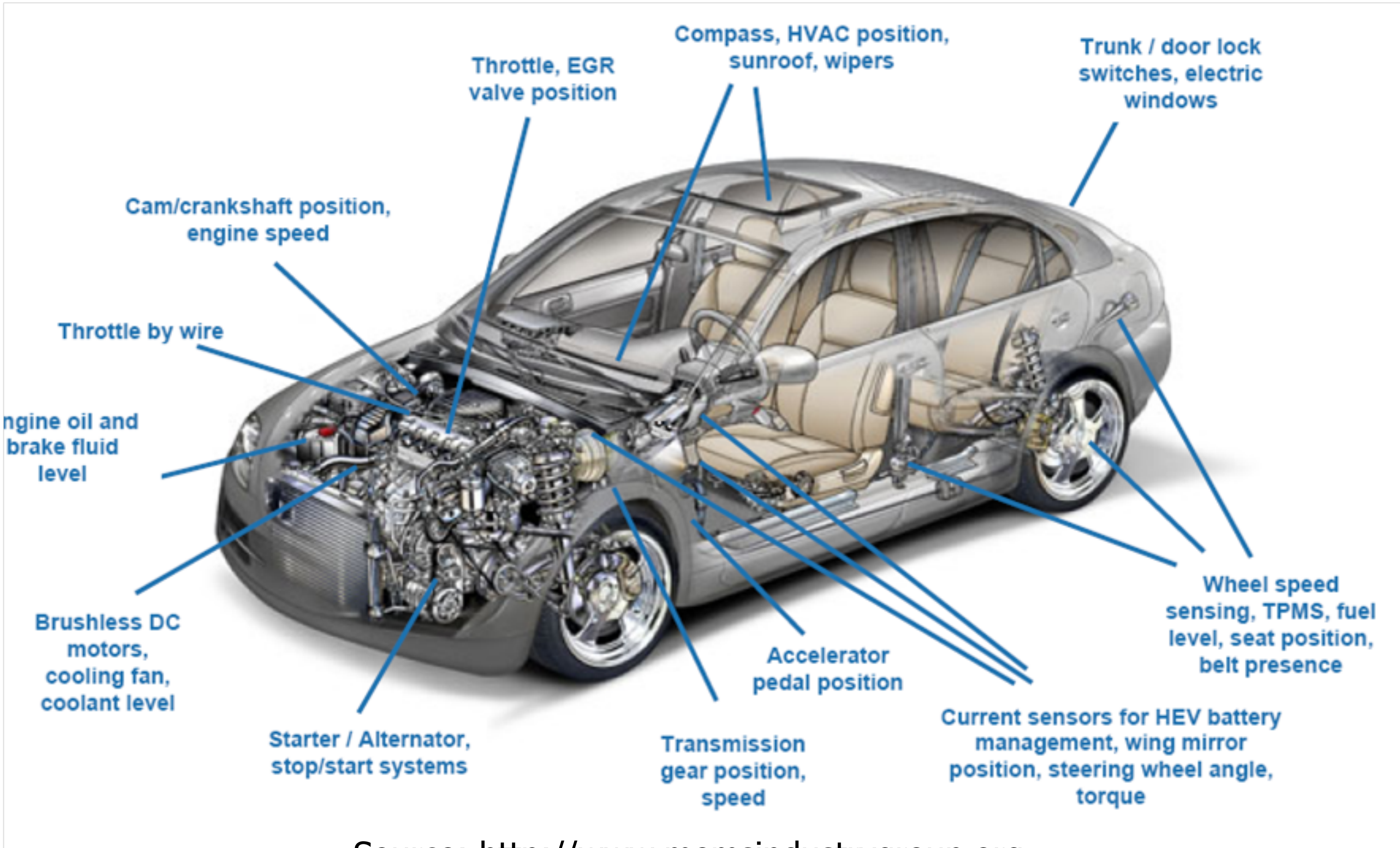




Accelerometers & 3-Axis Gyroscope [3]

Image credits:
[1] www.upaa.org
[2] www.readwrite.com
[3] www.hillcrestlabs.com

Sensors in Cars



Source: http://www.memsindustrygroup.org

The Industrial Internet of Things

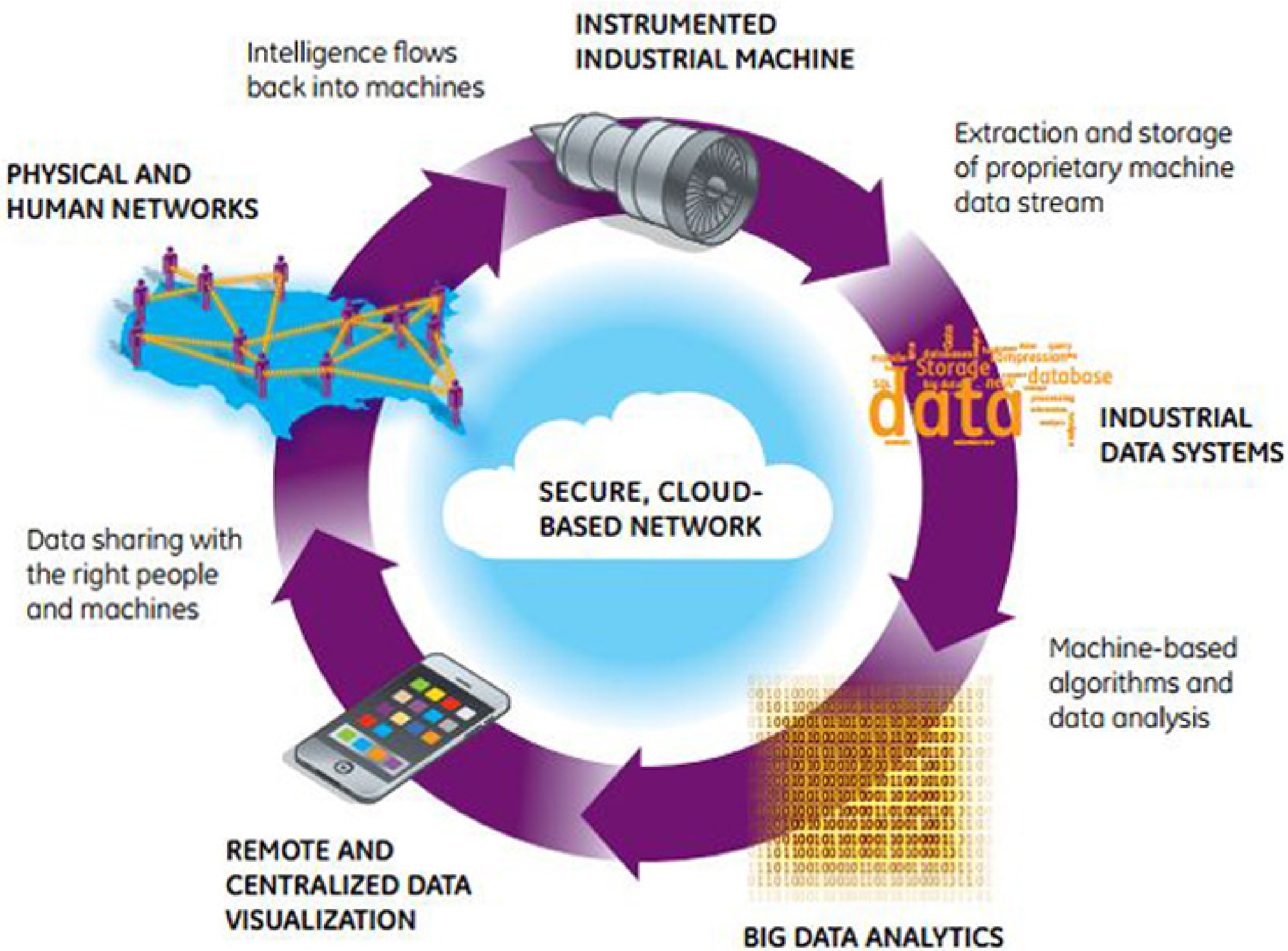
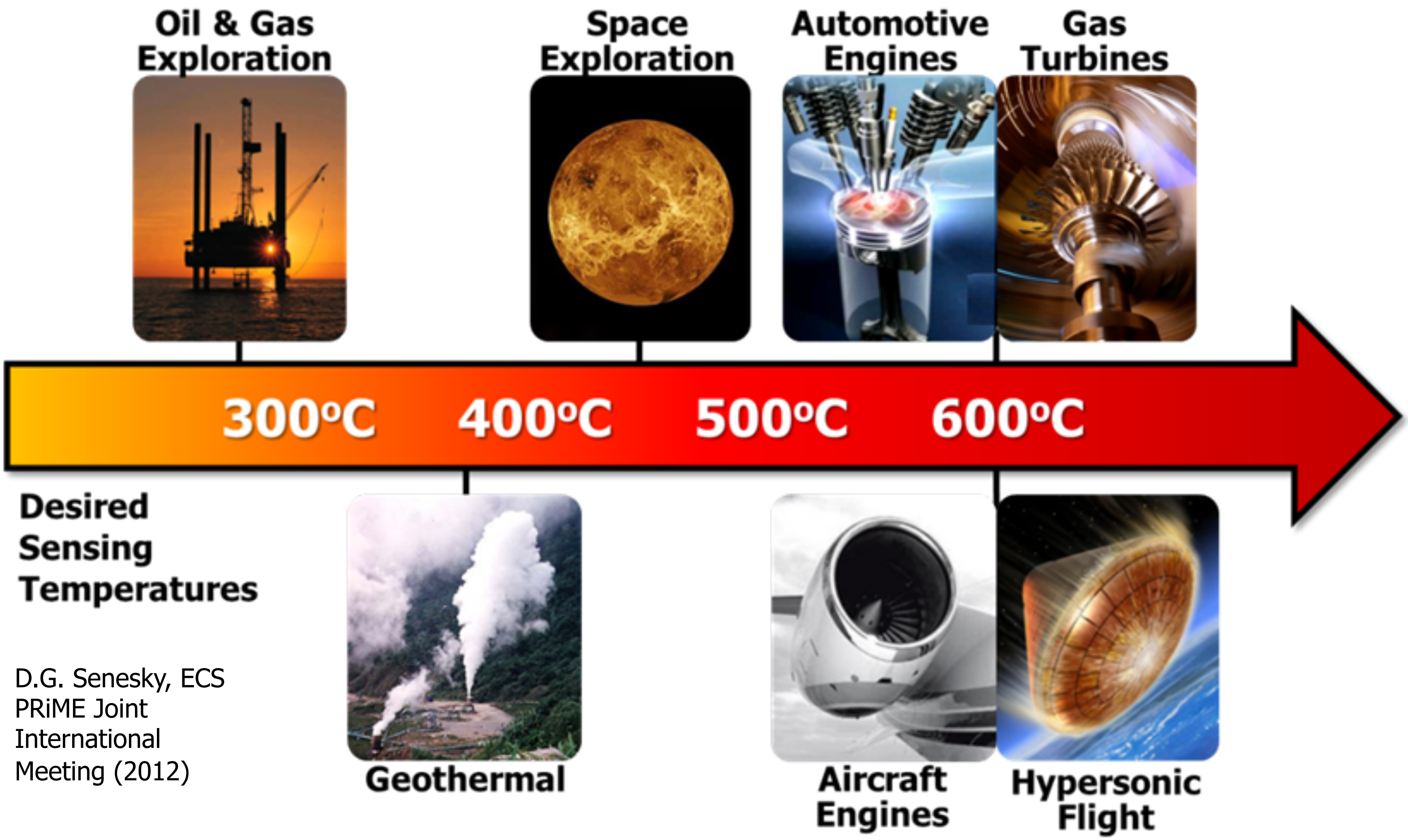


Image Credit: General Electric
Meeting of the Minds and Machines

Extreme Harsh Environment

- **A "extreme harsh environment" includes extremes of temperature, pressure, shock, radiation and chemical attack.**

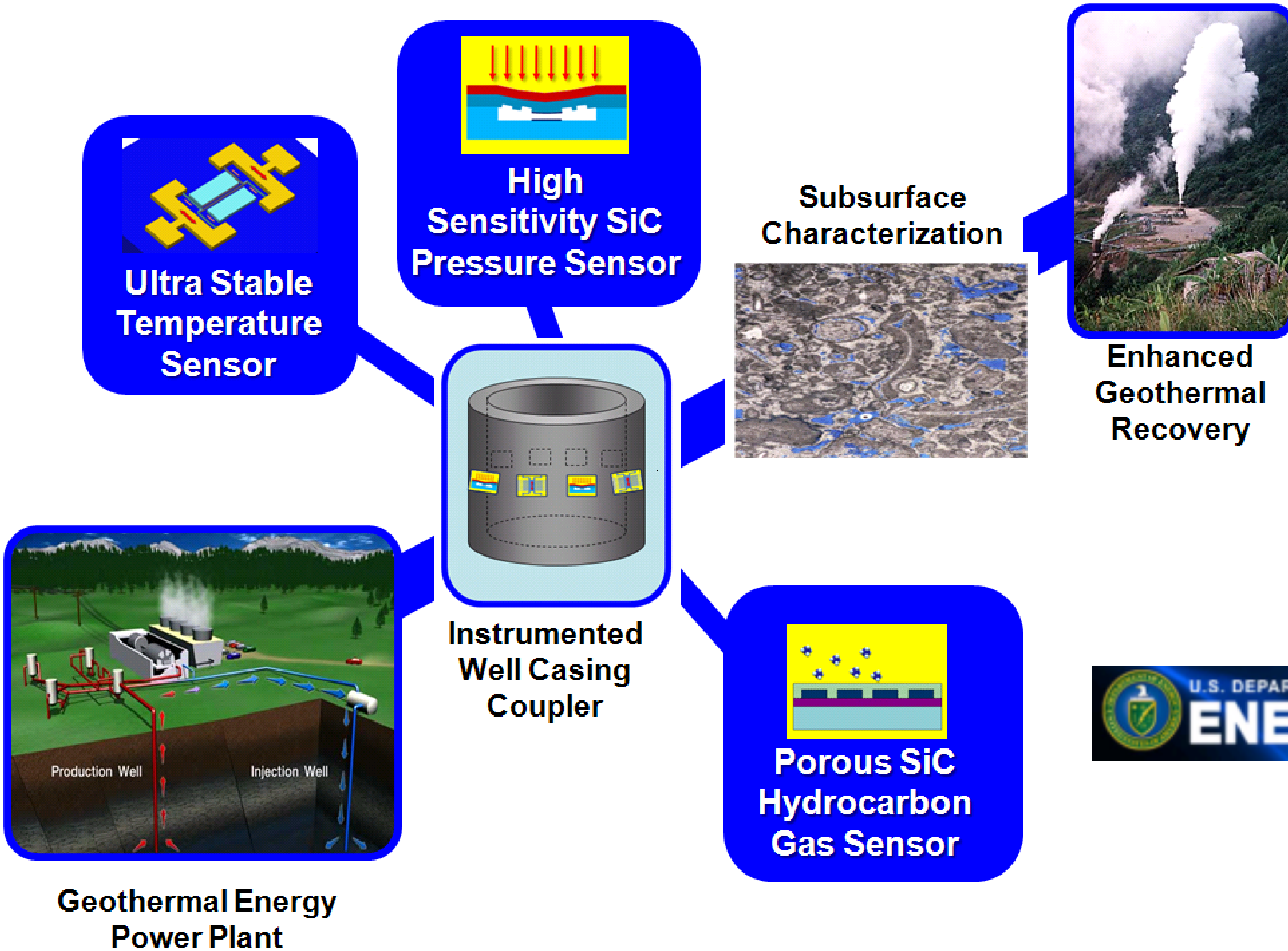


D.G. Senesky, ECS PRiME Joint International Meeting (2012)

Real-time Sensing in Harsh Environments

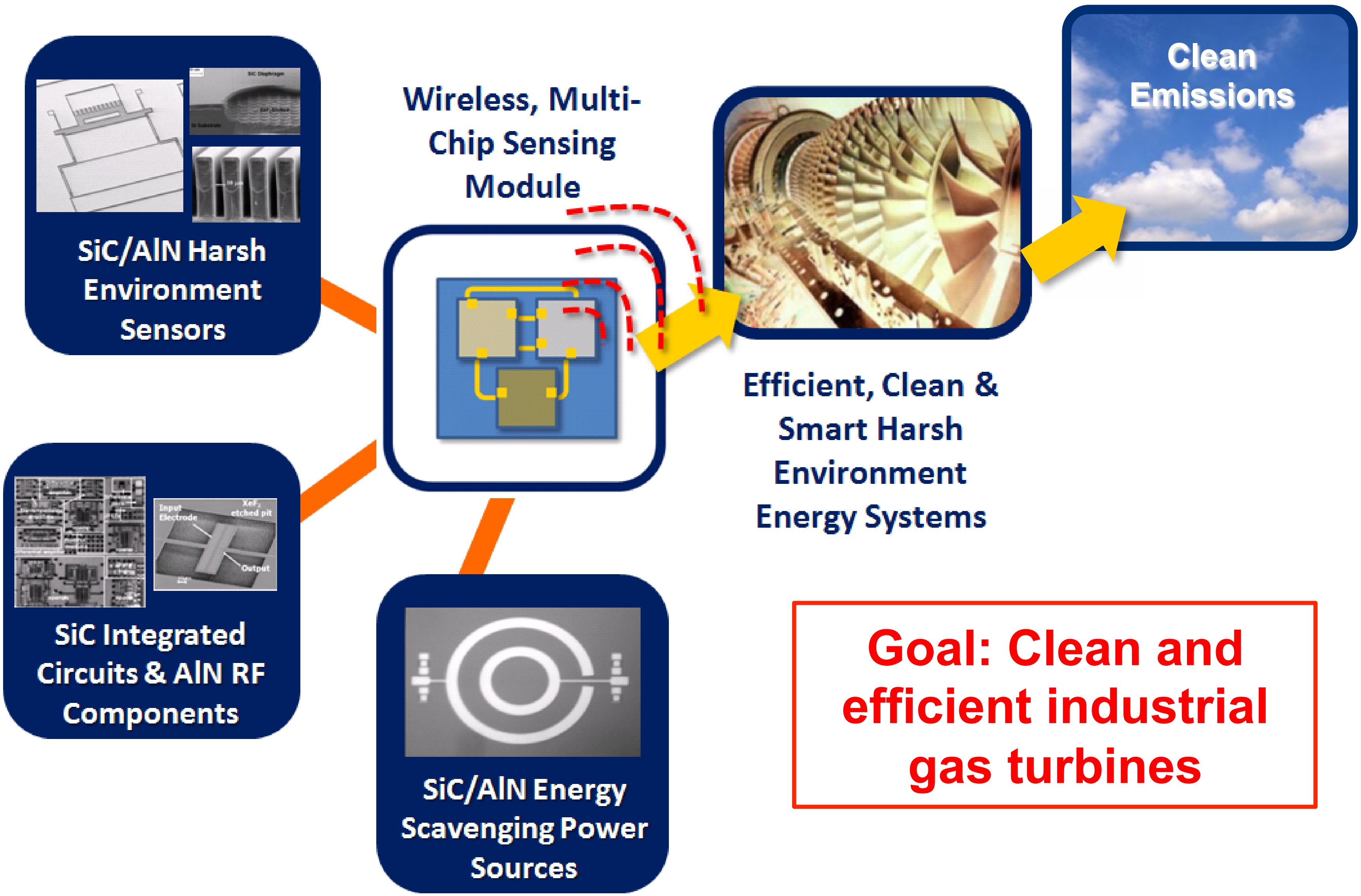
- **Sensing within harsh environments enables real-time monitoring of combustion processes, subsurface properties, critical components, and space environments.**
  - Subsurface: *pressure, temperature, flow, tilt and chemical conc.*
  - Combustion: *pressure, temperature and flame speed*
  - Space: *pressure, radiation, strain and magnetic fields*
- **Commercial-off-the-shelf sensors and electronics are limited to temperatures below 200°C and short operation periods.**
- **Technical challenges:**
  - A new materials platform must be utilized to extend the operation limits (**up to 600°C**).
  - New sensing methodologies (e.g. packaging, temperature compensation, communication and power) must be developed.

Subsurface Monitoring



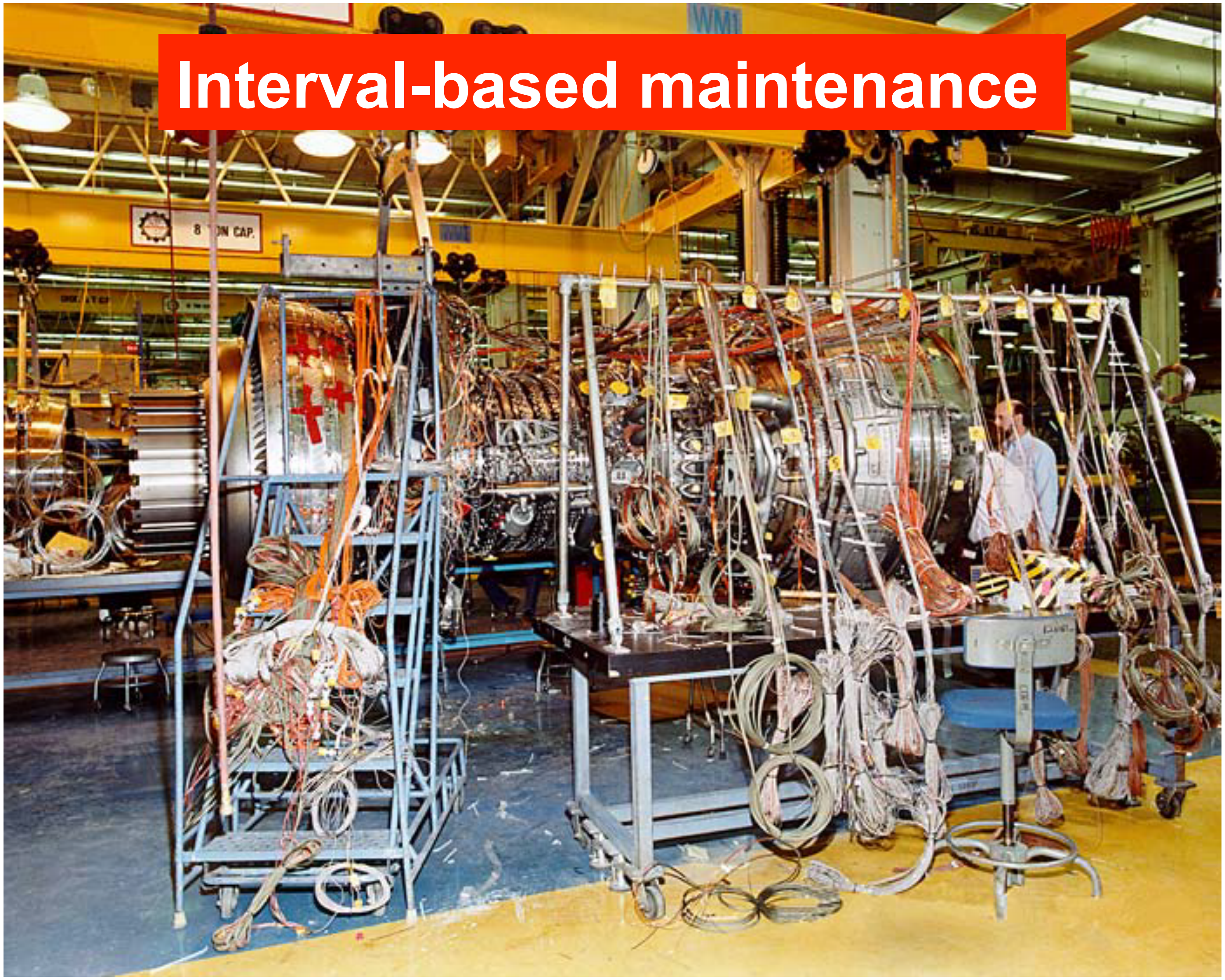
U.S. DEPARTMENT OF ENERGY

In-situ Combustion Monitoring



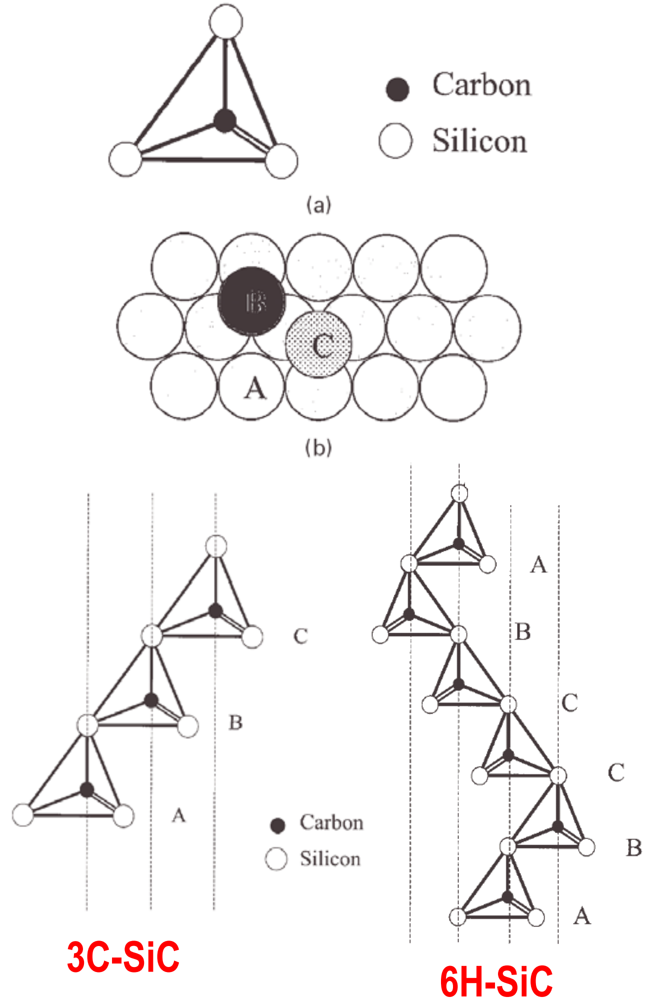
Goal: Clean and efficient industrial gas turbines

Current Technology



Silicon Carbide (SiC)

- **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 and 6H-SiC
  - 4H-SiC is the dominant polytype for the power electronics industry.



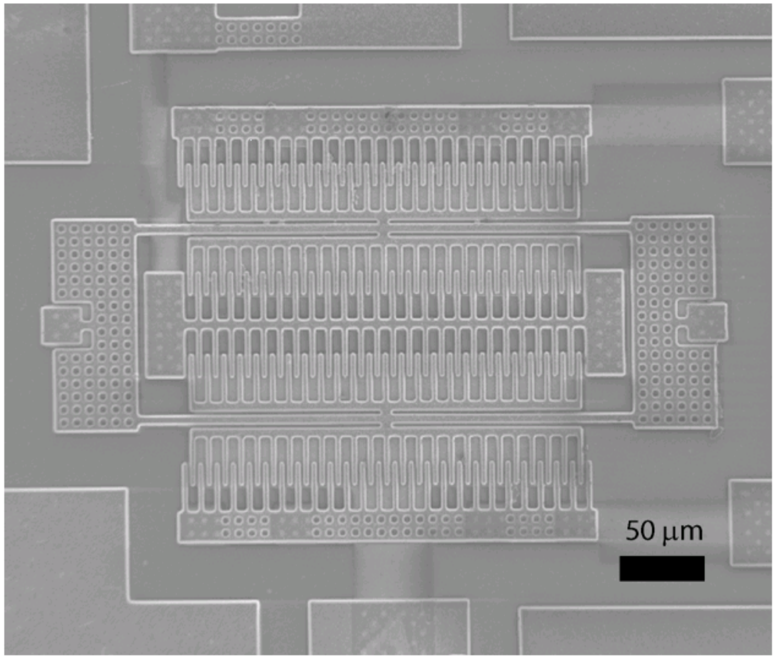
Schematic of atomic arrangement and stacking order of SiC (M. Mehregany et al.).

Material Properties (SiC)

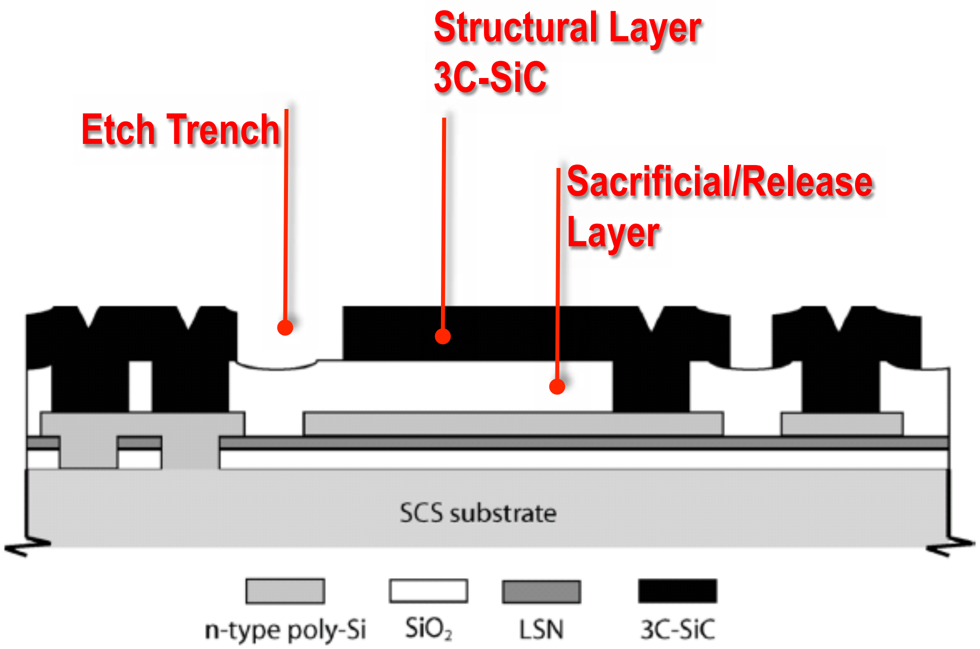
Property	6H-SiC	GaN	AlN	Diamond	Silicon
Melting Point (^oC)	2830 sublimes	2500	2470	4000 phase change	1420
Energy Gap (eV)	3.0	3.4	6.2	5.6	1.12
Critical Field ($\times 10^6$ V/cm)	2.5	5.0	10	5.0	0.25
Thermal Conductivity (W/cm-K)	5.0	1.3	1.6	20	1.5
Young's Modulus (GPa)	450	390	340	1035	190
Acoustic Velocity ($x10^3$ m/s)	11.9	8.0	11.4	17.2	9.1
Yield Strength (GPa)	21	-	-	53	7
Coeff. of Thermal Expansion (^oC $\times 10^{-6}$)	4.5	3.7	4.0	0.8	2.6
Chemical Stability	Excellent	Good	Good	Fair	Fair

Material properties of SiC, AlN, GaN, diamond and Si.

SiC Resonant Strain Gauge



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

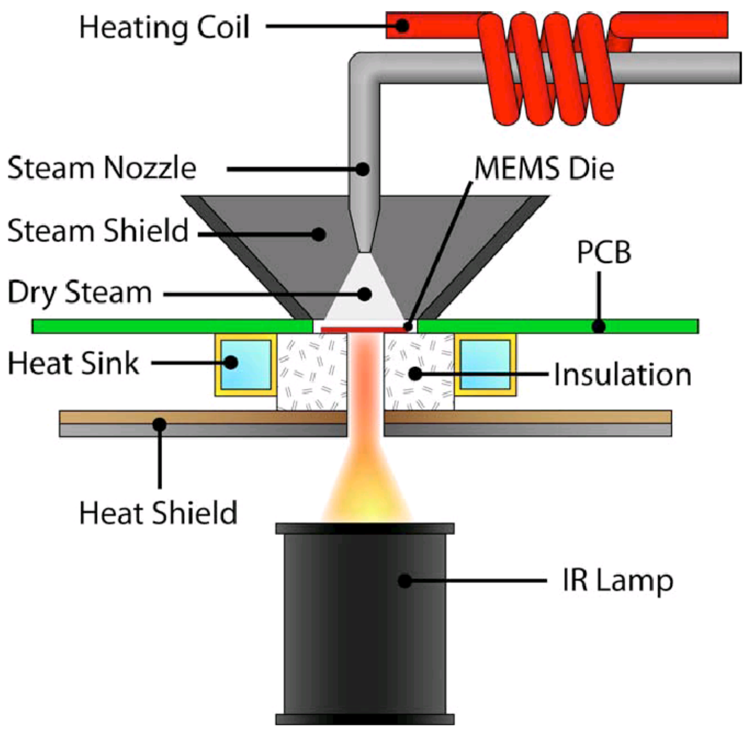


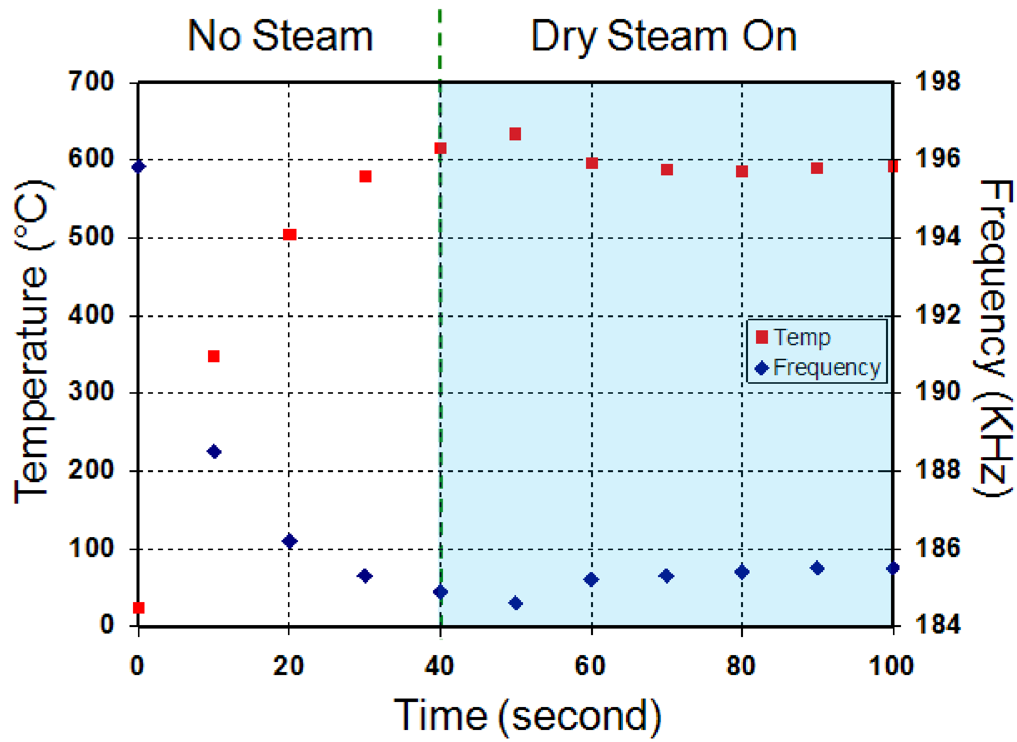
Cross-sectional image of the SiC strain sensor fabrication process.

1. D.G. Senesky, B. Jamshidi, K.B. Cheng, and A.P. Pisano, IEEE Sensors Journal (2009)

2. 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

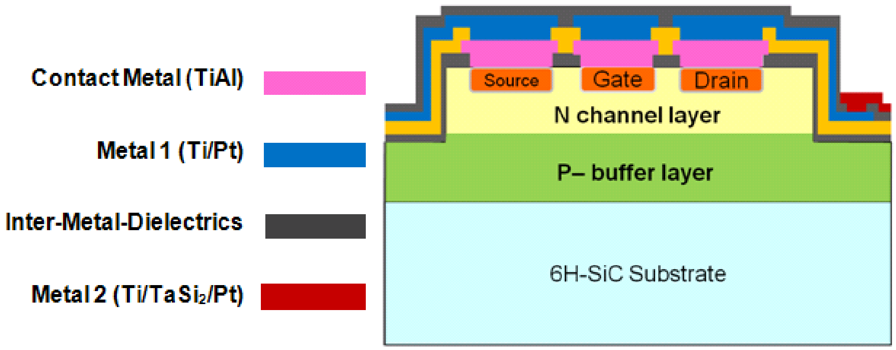


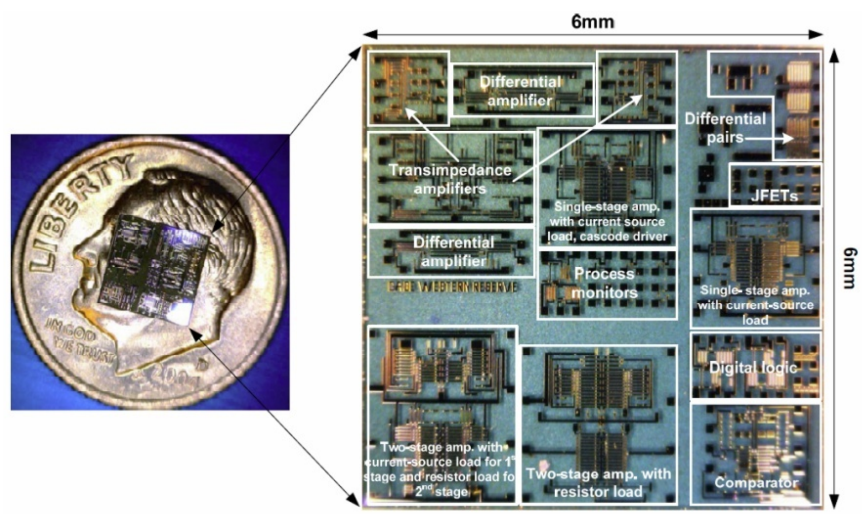


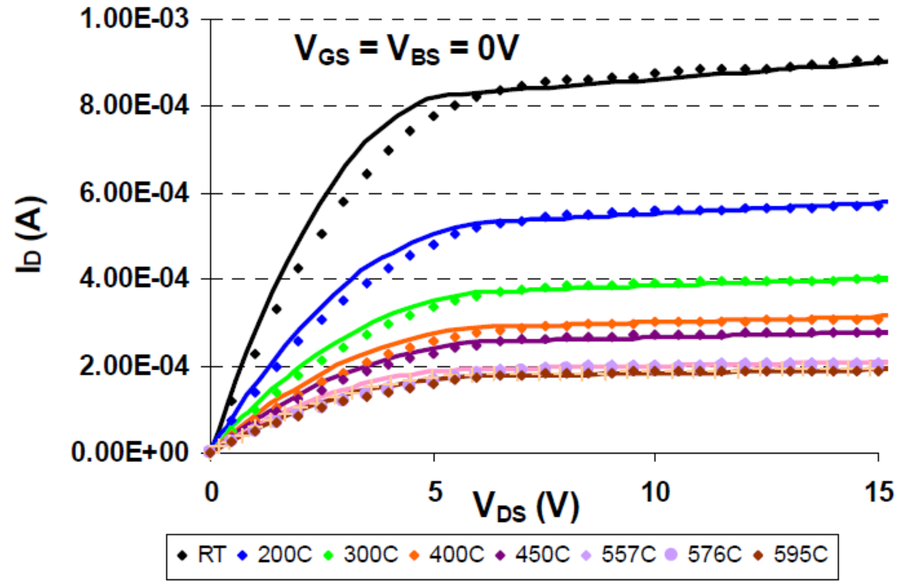
- **The polycrystalline 3C-SiC sensor resonates in air and can operate at 600°C in dry steam**
- **The strain sensor has a sensitivity of 66 Hz/με and resolution of 0.045 με in a 10 kHz bandwidth**
- **This poly-SiC sensor utilizes a fabrication process that can be utilized realize other harsh environment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

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

SiC JFET at 600°C



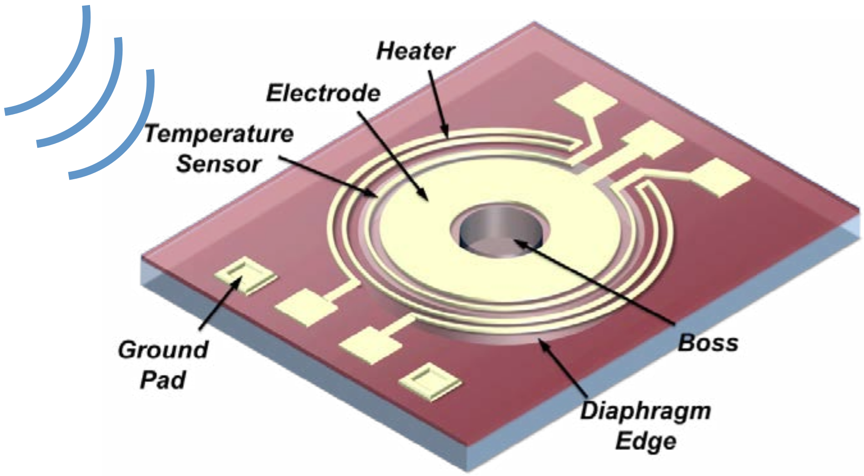


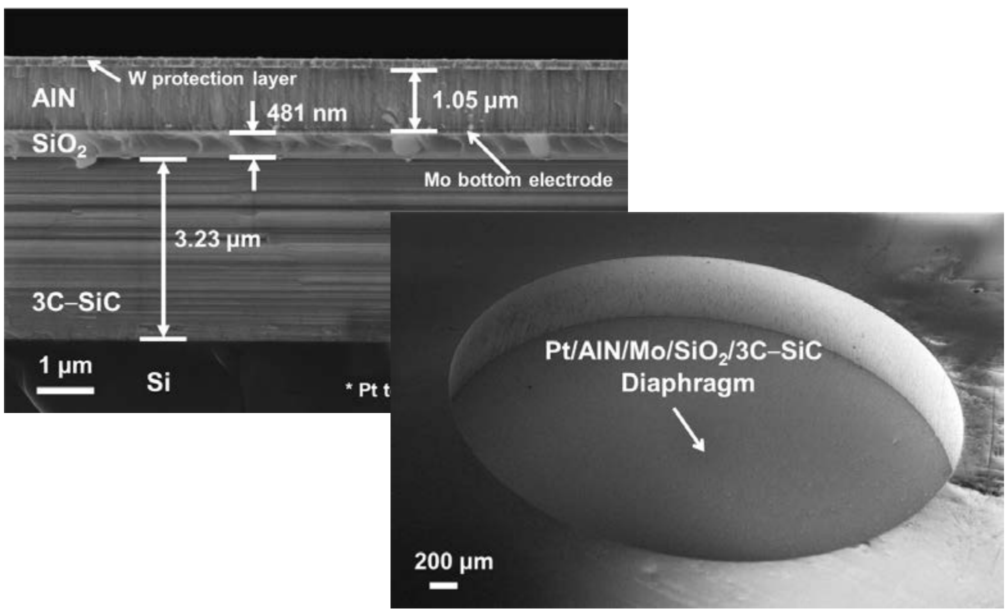


Measured I-V of JFET with W/L = 100 μm/10 μm for temperatures up to 600°C. Symbols mark measured values while solid curves show fit to the 3/2-power model.

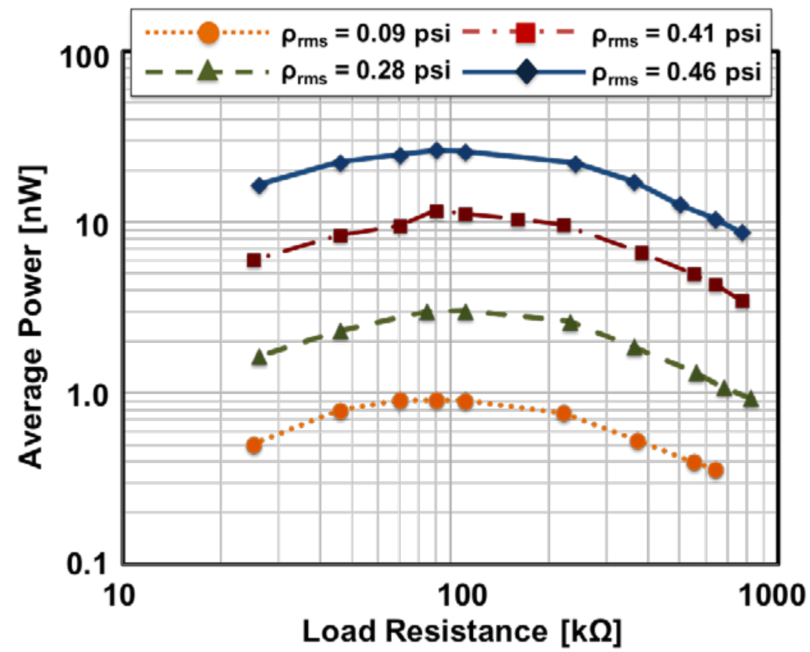
A. Patil, M. Mehregany and S. Garverick, Ph.D. Thesis (2009)

SiC/AlN Energy Harvesting



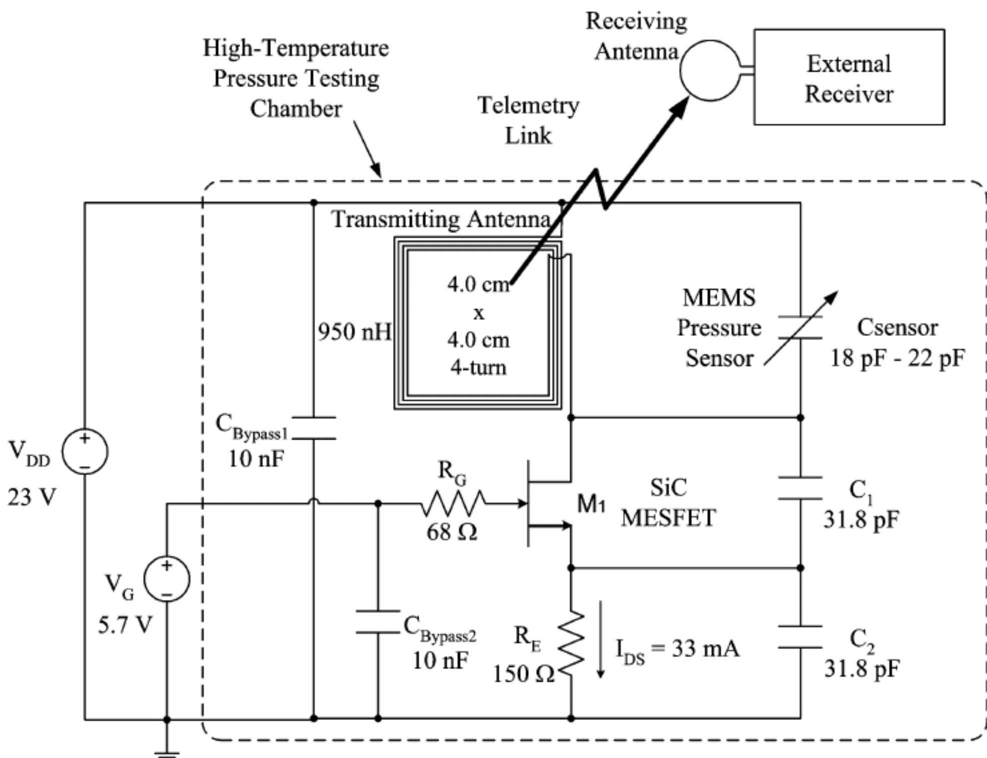


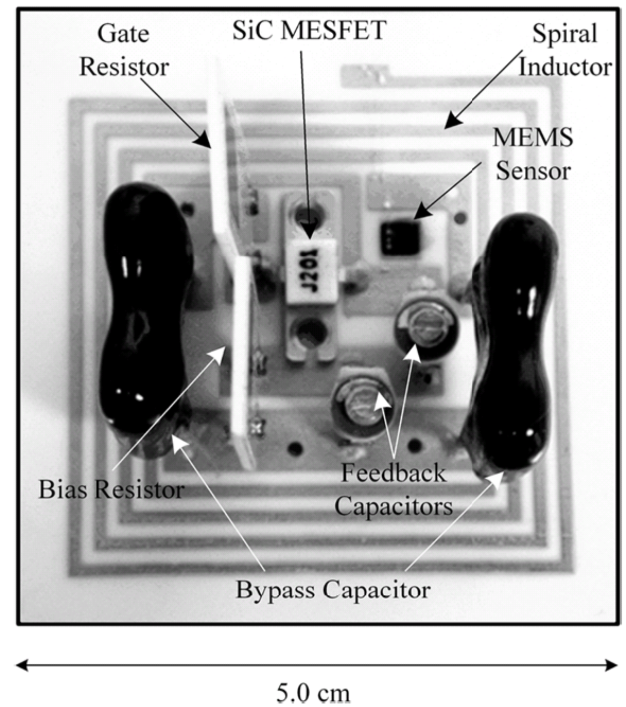
Output Power for Various Pressure Pulsations at 1 kHz



Y.J. Lai et al., Hilton Head Conference (2012).

High-Temperature Wireless





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

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

Material Properties (Gallium Nitride)

Property	6H-SiC	GaN	AlN	Diamond	Silicon
Melting Point (^oC)	2830 sublimes	2500	2470	4000 phase change	1420
Energy Gap (eV)	3.0	3.4	6.2	5.6	1.12
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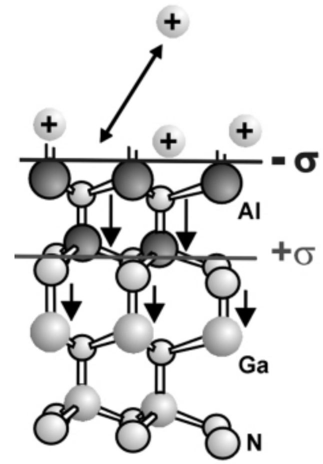
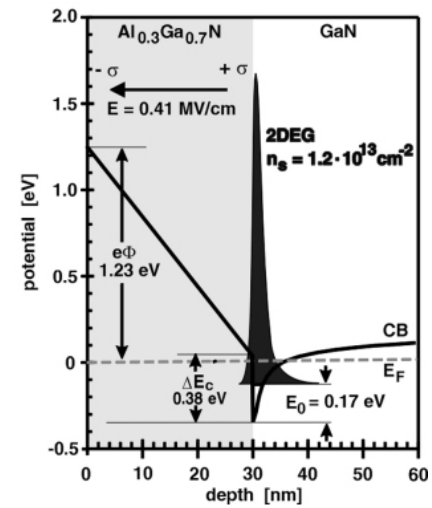
Chemical Stability	Excellent	Good	Good	Fair	Fair

Material properties of SiC, AlN, GaN, diamond and Si.

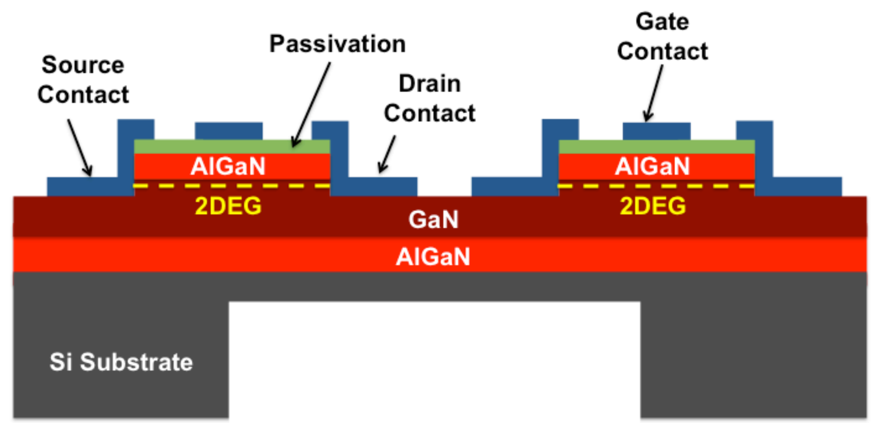
AlGaN/GaN Sensor Development

- The AlGaN/GaN heterostructure is currently being developed to make high electron mobility transistors (HEMTs) for the power electronics industry.
- The piezoelectric, polarization-induced, 2-dimensional electron gas (2DEG) at the AlGaN/GaN interface can improve the sensitivity of sensing devices.
  - Spontaneous polarization-induced charges (at surface and interface)
  - Strain sensitive
  - Ion sensitive





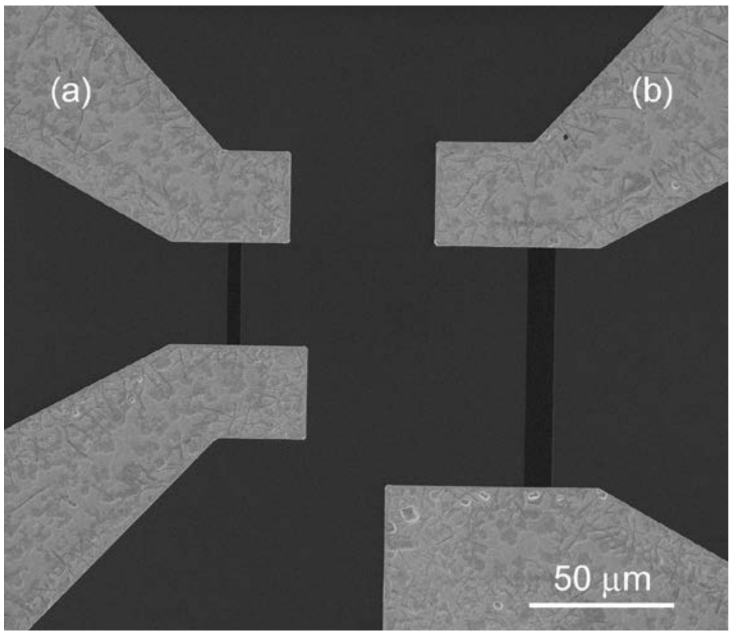
The jump in the macroscopic polarization (discontinuity in dipoles) at the AlGaN/GaN interface causes a positive fixed polarization charge at this interface [M. Stutzmann, et al.].



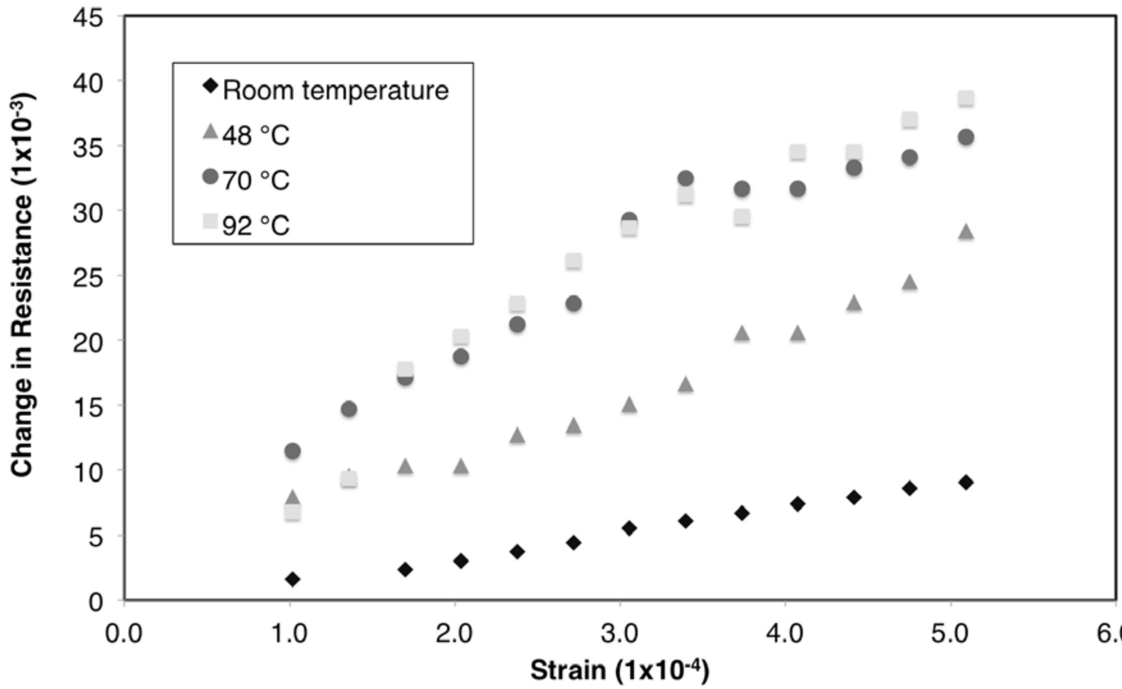
Cross-sectional image of fabrication process for AlGaN/GaN high electron mobility (HEMT) based sensors.

AlGaN/GaN Strain Gauges

Gauge Factor = -81 at 92^{o}C



SEM image of AlGaN/GaN high electron mobility (HEMT) based strain sensors.



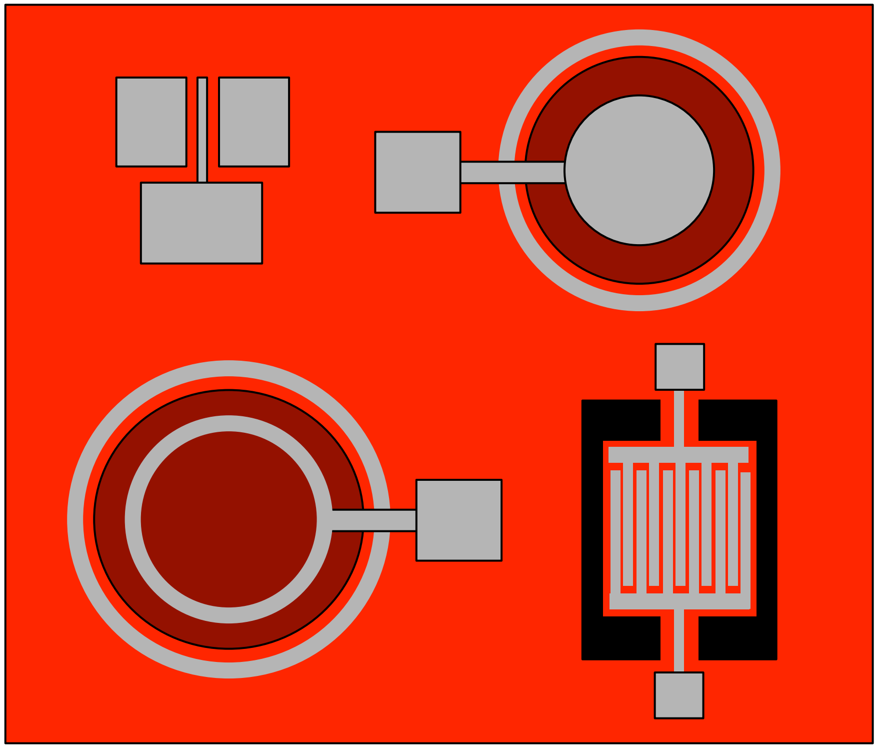
Experimental data obtained from characterization of AlGaN/GaN strain sensors at elevated temperatures.

C.A. Chapin, H. Chiamori, M. Hou & D.G. Senesky, International Workshop on Structural Health Monitoring (2013)

AlGaN/GaN Device Integration

- Development of multiple devices (HEMT circuits, energy harvesters, sensors and RF resonators) on a single chip using the multi-functional properties of the AlGaN/GaN heterostructure.

GaN High Electron Mobility Transistor (HEMT) Circuit

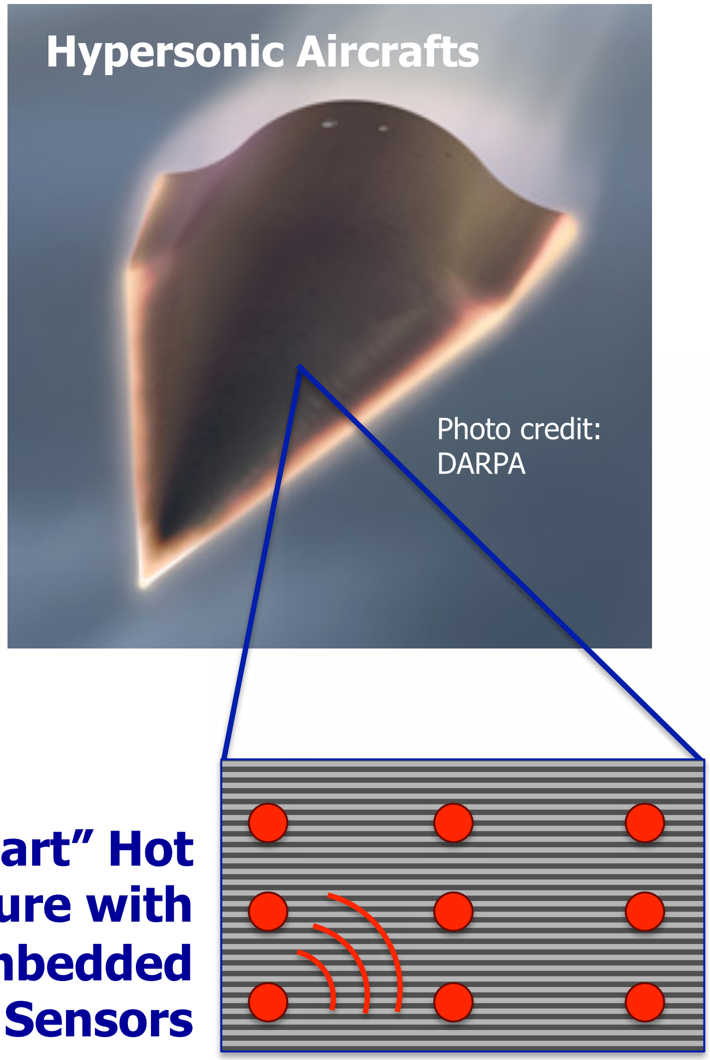


GaN Sensors (e.g. acoustic, acceleration, pressure)

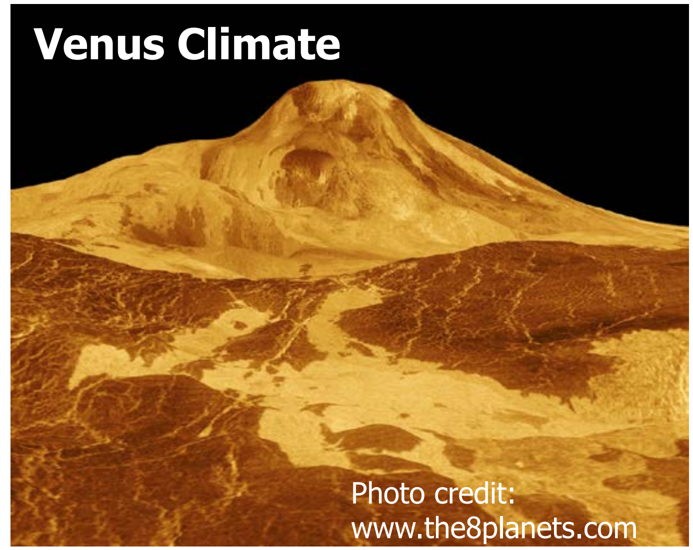
GaN Piezoelectric Energy Harvester

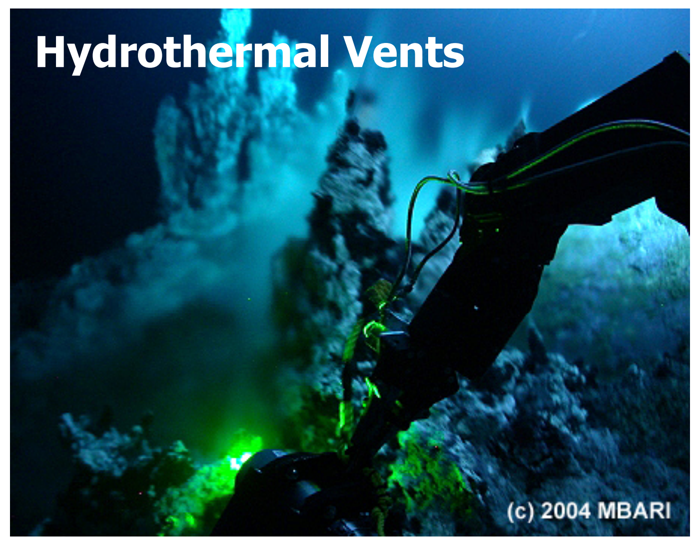
GaN Piezoelectric RF Resonators

Monitoring of Hot Structures & Hot Climates



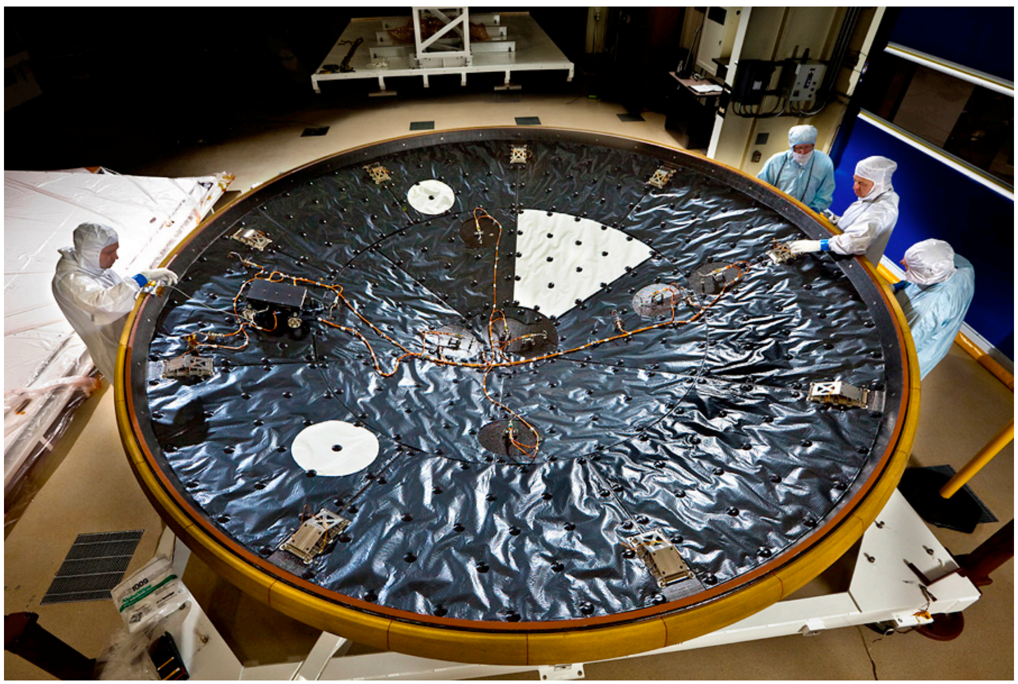
"Smart" Hot Structure with Embedded Sensors





NASA's MEDLI Suite

Mars Science Laboratory Entry, Descent, and Landing Instrument (MEDLI) Suite



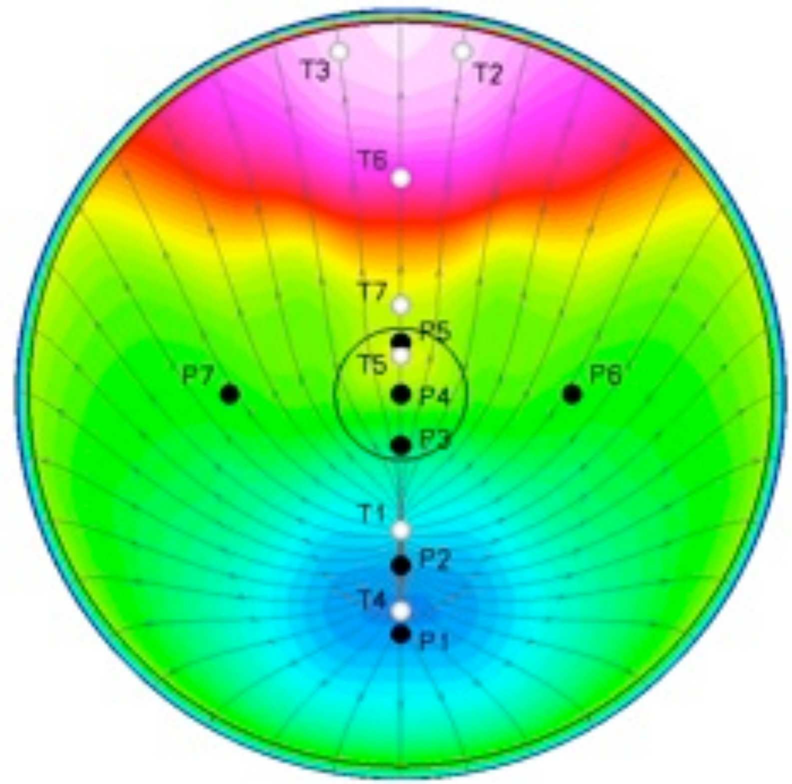


Image Credit: NASA JPL MEDLI Program

Conclusions

- **Ceramic semiconductor materials (SiC, AlN & GaN) can extend the operation environments of sensors and electronics.**
- **Harsh environment sensors can be used to**
  - Illuminate properties (e.g. pressure, temperature, and gas content) of combustion processes & subsurface conditions.
  - Monitor the structural health of critical components.
  - Provide real-time feedback.
- **In addition, these materials can be used to create a multitude of devices (sense, power, processing and communication) on a single chip.**

SPECIAL SESSION: SHM for Harsh Environments

1:30 pm
HC 200-002

- UC Berkeley, "Aluminum Nitride High Temperature Strain Sensors"
- UC Berkeley, "MEMS Piezoelectric Energy Harvesters for Harsh Environment Sensing"
- GE Global Research, "Optical MEMS Pressure Sensors for Geothermal Well Monitoring"
- Stanford University, "Development of High Performance BS-PT Based Piezoelectric Transducer for Structural Health Monitoring of High-Temperature Polymer-Matrix Composite Structures"
- NASA Ames, "Development and Verification of an Aerothermal Thermal Protection System Heat Shield Instrumentation Plug for Flight on Mars Science Laboratory"
- Stanford University, "Characterization of Gallium Nitride Heterostructures for Strain Sensing at Elevated Temperatures"

Acknowledgements

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