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:
Sensors in Cars

- Cam/crankshaft position, engine speed
- Throttle, EGR valve position
- Compass, HVAC position, sunroof, wipers
- Trunk / door lock switches, electric windows
- Engine oil and brake fluid level
- Throttle by wire
- Brushless DC motors, cooling fan, coolant level
- Starter / Alternator, stop/start systems
- Accelerator pedal position
- Transmission gear position, speed
- Current sensors for HEV battery management, wing mirror position, steering wheel angle, torque

Source: http://www.memsindustrygroup.org
The Industrial Internet of Things

Image Credit: General Electric
Meeting of the Minds and Machines
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

- 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
In-situ Combustion Monitoring

**Goal:** Clean and efficient industrial gas turbines

- SiC/AlN Harsh Environment Sensors
- SiC Integrated Circuits & AlN RF Components
- SiC/AlN Energy Scavenging Power Sources

*Clean Emissions*

Wireless, Multi-Chip Sensing Module

Efficient, Clean & Smart Harsh Environment Energy Systems
Current Technology

Interval-based maintenance
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)

<table>
<thead>
<tr>
<th>Property</th>
<th>6H-SiC</th>
<th>GaN</th>
<th>AlN</th>
<th>Diamond</th>
<th>Silicon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting Point (°C)</td>
<td>2830 sublimes</td>
<td>2500</td>
<td>2470</td>
<td>4000 phase change</td>
<td>1420</td>
</tr>
<tr>
<td>Energy Gap (eV)</td>
<td>3.0</td>
<td>3.4</td>
<td>6.2</td>
<td>5.6</td>
<td>1.12</td>
</tr>
<tr>
<td>Critical Field (x10^6 V/cm)</td>
<td>2.5</td>
<td>5.0</td>
<td>10</td>
<td>5.0</td>
<td>0.25</td>
</tr>
<tr>
<td>Thermal Conductivity (W/cm-K)</td>
<td>5.0</td>
<td>1.3</td>
<td>1.6</td>
<td>20</td>
<td>1.5</td>
</tr>
<tr>
<td>Young’s Modulus (GPa)</td>
<td>450</td>
<td>390</td>
<td>340</td>
<td>1035</td>
<td>190</td>
</tr>
<tr>
<td>Acoustic Velocity (x10^3 m/s)</td>
<td>11.9</td>
<td>8.0</td>
<td>11.4</td>
<td>17.2</td>
<td>9.1</td>
</tr>
<tr>
<td>Yield Strength (GPa)</td>
<td>21</td>
<td>-</td>
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<td>53</td>
<td>7</td>
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<tr>
<td>Coeff. of Thermal Expansion (°C x10^{-6})</td>
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<td>3.7</td>
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Material properties of SiC, AlN, GaN, diamond and Si.
SiC Resonant Strain Gauge

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

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

The polycrystalline 3C-SiC sensor resonates in air and can operate at 600°C in dry steam.

The strain sensor has a sensitivity of $66 \text{ Hz/\mu\varepsilon}$ and resolution of $0.045 \text{ \mu\varepsilon}$ in a 10 kHz bandwidth.

This poly-SiC sensor utilizes a fabrication process that can be utilized to 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.

SiC/AlN Energy Harvesting

Output Power for Various Pressure Pulsations at 1 kHz

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

Material Properties (Gallium Nitride)

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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°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.

AlGaN/GaN Device Integration

- Development of multiple devices (HEMT circuits, energy harvesters, sensors and RF resonators) on a single chip using the multifunctional properties of the AlGaN/GaN heterostructure.
Monitoring of Hot Structures & Hot Climates

Hypersonic Aircrafts

Photo credit: DARPA

Venus Climate

Photo credit: www.the8planets.com

Hydrothermal Vents

(c) 2004 MBARI

“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”
- Stanford University, “Characterization of Gallium Nitride Heterostructures for Strain Sensing at Elevated Temperatures”
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