Smart Precision in Harsh Environments

Paddy French+, Gijs Krijnen* & Fred Roozeboom#

+ TU Delft, *U Twente, #TU Eindhoven
Overview

• Introduction/definitions
• Application areas
• Approaches
• Solutions
• Conclusions
What is harsh?
Any environment which impedes the normal operation.
Any environment which impedes the normal operation.

- Temperature: High T / Low T / Large $\Delta T$
Any environment which impedes the normal operation.

- Temperature: High $T$ / Low $T$ / Large $\Delta T$
- Pressure: High $P$ / Low $P$ / Large $\Delta P$
Any environment which impedes the normal operation.

- Temperature: High T / Low T / Large $\Delta T$
- Pressure: High P / Low P / Large $\Delta P$
- Mechanical loading
Any environment which impedes the normal operation.

- Temperature: High T / Low T / Large $\Delta T$
- Pressure: High P / Low P / Large $\Delta P$
- Mechanical loading
- High vacuum
Any environment which impedes the normal operation.

- Temperature: High T / Low T / Large ΔT
- Pressure: High P / Low P / Large ΔP
- Mechanical loading
- High vacuum
- Radiation (X)-UV, X-ray
Any environment which impedes the normal operation.

- Temperature: High T / Low T / Large $\Delta T$
- Pressure: High P / Low P / Large $\Delta P$
- Mechanical loading
- High vacuum
- Radiation (X)-UV, X-ray
- Harsh chemical environment
Any environment which impedes the normal operation.

- Temperature: High T / Low T / Large ΔT
- Pressure: High P / Low P / Large ΔP
- Mechanical loading
- High vacuum
- Radiation (X)-UV, X-ray
- Harsh chemical environment
- Biological environments/Medical implants
Any environment which impedes the normal operation.

- Temperature: High T / Low T / Large $\Delta T$
- Pressure: High P / Low P / Large $\Delta P$
- Mechanical loading
- High vacuum
- Radiation (X)-UV, X-ray
- Harsh chemical environment
- Biological environments/Medical implants
- Often: poor accessibility
Any environment which impedes the normal operation.

- Temperature: High T / Low T / Large ΔT
- Pressure: High P / Low P / Large ΔP
- Mechanical loading
- High vacuum
- Radiation (X)-UV, X-ray
- Harsh chemical environment
- Biological environments/Medical implants
- Often: poor accessibility
- etc.
SPIHE
Harsh environmental applications
Applications I

Sensor Systems in Space

Sensor Systems in Wafer Stepper
Applications II

Oil industry

Farming
Applications III

Neurostimulation: Feed-Through
Morgan Advanced Ceramics' Alumina products assist in the development of bio-electronics that can provide treatment for medical conditions, involving pain relief, depression, migraines and obesity.

Drug Delivery: Feed-Through
Morgan Advanced Ceramics' Alumina products assist in the development of drug-delivery systems that can be used to deliver medication in a controlled manner.

Ky Joints: HIP Valve
Morgan Advanced Ceramics' HIP valve, made of alumina, is designed to replace natural joint cartilage and provide long-term relief from joint pain.

Pacemakers & Defibrillators: Feed-Through
Morgan Advanced Ceramics' Alumina products ensure high reliability and performance in medical devices, which are critical for patient safety and effectiveness.

Implantable Joints: Biomimetic Cables
Morgan Advanced Ceramics' Biomimetic Cables are made of alumina and provide flexibility and strength for medical applications.

Body Contact Lids
- Low V, N-channel diodes
- L, L, V, 2N3904 transistors
- MOSFETs
- 1% wire-wound resistors

Kneeling Control
- Low V, N-channel diodes
- L, L, V, 2N3904 transistors
- Control circuit transistors
- Ainseng diodes

Door Modules
- Low V, N-channel diodes
- Linear, laser cut transistors
- Internal power transistors
- Fuse protection devices

Automotive Networking
- EDC protection devices
- 12V and 5V CAN-bus devices

Automotive Power
- LED cable
- Low V, N-channel diodes
- L, L, V, 2N3904 transistors
- Wide range of alternative grade power MOSFETs
- Memory
- Logic
- Multiplexing
- Body control
- Engine management
- Case control
- Transmission
- Water-pump
Hierarchy in compatibility with harsh environments

<table>
<thead>
<tr>
<th>Some known harsh conditions</th>
<th>Chemical</th>
<th>Thermal</th>
<th>Mechanical</th>
<th>EM loading</th>
<th>Radiation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials</td>
<td>++</td>
<td>++</td>
<td>+</td>
<td></td>
<td>+</td>
</tr>
<tr>
<td>Technology</td>
<td>+</td>
<td>++</td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Device Design</td>
<td></td>
<td>+</td>
<td>++</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Packaging</td>
<td>++</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td>System</td>
<td></td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

Levels at which conditions can be counteracted
Compatibility with harsh environments: Examples

- **Materials**
  - Chemically inert
  - High glass or melting temperature
  - High fracture, yield strength and/or hardness
  - Dense materials to reduce device to exposure to radiation
- **Technology**
  - Fabrication method, conditions, annealing
  - Additional layers (e.g. to prevent delamination, increase resilience), additives
- **Device design**
  - Special zones to absorb mechanical/chemical loading or thermal cycling.
  - Choice of measurand (e.g. a derivative quantity)
- **Packaging**
  - Special zones to absorb mechanical/chemical loading or thermal cycling
  - Materials of package (e.g. chemically inert)
- **System**
  - Limited on-time
  - Judicious choice as to where to put the sensors.
Materials

• SiC
  • High temperature
  • Chemically inert
• ALD (atomic layer deposition)
  • Pinhole free
• Polymers/parylene
  • Biocompatibility
• SOI
• Graphene
  • High temperature, medical implants
• Etc.
Oil industry

Temperature & pressure sensors
Automotive engine
High Temperature

TU Berlin

SiCOI pressure sensor
Pressure sensors for high temperature

<table>
<thead>
<tr>
<th>Packaging</th>
<th>Chip Direct Exposure</th>
<th>Steel Membrane</th>
<th>Steel Membrane with Transmisionelement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chip-technology</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Si</td>
<td>150°C</td>
<td>200°C - 250°C</td>
<td>450°C - 500°C</td>
</tr>
<tr>
<td>SOI</td>
<td>350°C</td>
<td>400°C - 450°C</td>
<td>650°C - 700°C</td>
</tr>
<tr>
<td>SiCO1N</td>
<td>500°C</td>
<td>550°C - 600°C</td>
<td>800°C - 850°C</td>
</tr>
</tbody>
</table>

GH Kroetz, MH Eickhoff & H Moeller - Daimler Benz
## High temperature materials

<table>
<thead>
<tr>
<th>Semiconductor</th>
<th>Bandgap (eV)</th>
<th>Maximum operating temperature (<em>°C</em>)</th>
<th>Process maturity</th>
<th>Key technical issues and limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>1.1</td>
<td>150</td>
<td>Very high</td>
<td>• Not suitable for aggressive environments</td>
</tr>
<tr>
<td>SOI</td>
<td>1.1</td>
<td>300</td>
<td>High</td>
<td>• Not suitable for aggressive environments</td>
</tr>
<tr>
<td>GaAs</td>
<td>1.43</td>
<td>350</td>
<td>High</td>
<td>• Contact stability at high temperatures • Not suitable for aggressive environments</td>
</tr>
<tr>
<td>3C-SiC</td>
<td>2.39</td>
<td>600</td>
<td>Low</td>
<td>• Not available as bulk material</td>
</tr>
<tr>
<td>6H-SiC</td>
<td>3.02</td>
<td>700</td>
<td>Medium</td>
<td>• Bulk material quality • Ohmic contacts to p-type material</td>
</tr>
<tr>
<td>4H-SiC</td>
<td>3.26</td>
<td>750</td>
<td>Medium</td>
<td>• Bulk material quality • Ohmic contacts to p-type material</td>
</tr>
<tr>
<td>Groupnitrides</td>
<td>1.89 - 6.20</td>
<td>&gt;700</td>
<td>Very low</td>
<td>• Material quality, reproducibility • Ohmic contacts</td>
</tr>
<tr>
<td>Diamond</td>
<td>5.48</td>
<td>1100</td>
<td>Very low</td>
<td>• n-type doping • Material quality (only polycrystalline material available)</td>
</tr>
</tbody>
</table>

*GaN  **AlN

Matthias Ralf Werner and Wolfgang R. Fahrner, 2001
Platinum resistor
Optical approach
Design solution: On-Chip Crumple Zone

- PhD. Work of Vincent Spiering, 1994
- Package ⇒ mechanical loading ⇒ reduced sensor performance
- ID: make corrugated membranes to absorb mechanical stress
High pressure
High radiation
Examples of ALD layers in harsh environment

- ALD-layers of Mo/Si mirrors for XUV reticules, etc.
- Ru-coated X-UV mirrors, etc.

Including diffusion barriers

Source: Fred Bijkerk

Both 2D and 3D layers with ideal step coverage, pinhole-free, etc.
UV-diode

ChangYong Lee et. al. Toyohashi University of Technology
X-ray Radiation on MOSFETs

- No post-radiation threshold shift (due to thin gate oxide),
- Parasitic transistor formation induced leakage current increase around the layout edges,
- Post-irradiation interface trap generation induced leakage current increase.

TU Delft
Harsh chemical
Ammonia sensor
WIRELESS IMPLANTABLE MEDICAL DEVICES

Deep Brain Neurostimulators

Cochlear Implants

Gastric Stimulators

Cardiac Defibrillators/Pacemakers

Foot Drop Implants

Insulin Pumps
In-vivo

TU Delft and EMC
Oxygen measurements

Tissue

Blood
Cochlear implants (CIs)

Electrode for the Cochlear Implant. TUD & LUMC

Source: A 32-Site 4-Channel High-Density Electrode Array for a Cochlear Prosthesis, Pamela T. Bhatti, Kensall D. Wise
Cochlear implants (CIs)

Challenges:
- Small
- 230 channels
- > 20V into a 1V IC
- 126dB DR
- Low power

Source: A 32-Site 4-Channel High-Density Electrode Array for a Cochlear Prosthesis, Pamela T. Bhatti, Kensall D. Wise

Electrode for the Cochlear Implant. TUD & LUMC
New generation cochlear implant

Electrode for the Cochlear Implant.
TUD & LUMC
Sputtered platinum after extended exposure to a salt solution
Key research fields and scientific challenges

1. Materials, technology and packaging
2. Sensors and actuators
3. Systems aspects
4. Maintaining precision in harsh environments
Smart Precision in Harsh Environments

- SPIHE
- STW perspectief proposal writing
- 15% cash / 30% total required from industry
- Round 2015, starting 2017 if granted
- We look for interested companies
- Contacts:
  - p.j.french@tudelft.nl
  - gijs.krijnen@utwente.nl
Conclusions

• Expanding applications mean increasing exposure to harsh environments.
• This can be addressed in many ways including materials, packaging and design.
• The challenge is not only to survive and operate in these environments, but also to maintain reliability and precision.