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REVIEW ARTICLE

Precision in harsh environments

Paddy French1, Gijs Krijnen2 and Fred Roozeboom3,4

Microsystems are increasingly being applied in harsh and/or inaccessible environments, but many markets expect the same level of functionality for long periods of time. Harsh environments cover areas that can be subjected to high temperature, (bio)-chemical and mechanical disturbances, electromagnetic noise, radiation, or high vacuum. In the field of actuators, the devices must maintain stringent accuracy specifications for displacement, force, and response times, among others. These new requirements present additional challenges in the compensation for or elimination of cross-sensitivities. Many state-of-the-art precision devices lose their precision and reliability when exposed to harsh environments. It is also important that advanced sensor and actuator systems maintain maximum autonomy such that the devices can operate independently with low maintenance. The next-generation microsystems will be deployed in remote and/or inaccessible and harsh environments that present many challenges to sensor design, materials, device functionality, and packaging. All of these aspects of integrated sensors and actuator microsystems require a multidisciplinary approach to overcome these challenges. The main areas of importance are in the fields of materials science, micro/nano-fabrication technology, device design, circuitry and systems, (first-level) packaging, and measurement strategy. This study examines the challenges presented by harsh environments and investigates the required approaches. Examples of successful devices are also given.

Keywords: atomic layer deposition; harsh environments; micro/nano-fabrication technology; packaging; sensors

INTRODUCTION

The earliest known weights and measures systems date to approximately the 4th or 3rd millennium BC and was developed among the ancient peoples of Egypt, Mesopotamia, the Indus Valley, and perhaps Elam (Iran). Over the centuries, different weights and measures systems have emerged. Sensors were designed that could use these systems to measure and define a wide range of parameters. With the industrial revolution, the need for measurements increased greatly, and measurement devices were increasingly used in harsh environments. In the early days, sensors were quite simple and relied on the operator to control the machinery. With the advent of automation, it became increasingly necessary to use sophisticated sensors as components of a control system. These sensors were designed to simply control the machinery. In the automotive industry, this approach was used to improve performance. In recent years, an increasing need has arisen for sensors for environmental control, for example, regulation of the exhaust from automobiles or from the process industry. The source of the harshness might not always be the measurand itself, for example, in the case of measuring pressure at high temperature.

This study defines a harsh environment as any environment that can impede the operation of the device. Harshness can originate from various sources, and examples include the following:

- High pressure
- High temperature
- Shock/high vibration
- Radiation
- Harsh chemicals
- Humidity
- Biological (including inside the body for medical implants).

Many industries must address these environments, and selected examples are given in Table 1. The extent of the harshness and the limitations on design differ from application to application. The approach chosen depends on the domain of the harshness and the application. Some examples are given in Table 2.

Table 2 shows a matrix of the harsh conditions (columns) and hierarchical levels at which the specific harsh conditions can be counteracted (rows). The number of + signs indicates the appropriateness of the given level for improved resistance against harshness. For example, chemical harsh environments can best be counteracted by proper material choices and packaging as well as the choice of fabrication technology. Typical approaches to improving resistance to harsh environments are listed below:

- Materials
  - Chemically inert
  - High glass or melting temperature
  - Dense materials to reduce device exposure to radiation
  - Material combinations and alloying


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● Technology
  ○ Fabrication method, conditions, annealing
  ○ Additional layers (for example, to prevent delamination and increase resilience), additives

● Device design
  ○ Special zones to absorb mechanical/chemical loading or thermal cycling
  ○ Choice of measurand (for example, a derivative quantity)

● Packaging
  ○ Special zones to absorb mechanical/chemical loading or thermal cycling
  ○ Materials used in packaging (for example, chemically inert)

● System
  ○ Isolation of the electronics from the harsh environment (for example, high temperature)
  ○ Modes of operation (for example, intermittent to prevent self-heating or low power)

As an example, in certain cases, the best approach might be optical (that is, often non-invasive) sensing. This method can allow remote sensing in applications where the sensing system is not required to be exposed to the harsh environment, for example, excitation by a laser and measurement of the optical absorption or scattering in the area of interest or use of fiber materials that can withstand high temperatures, such as sapphire. Optical signals in fibers are also not affected by electrical noise. Coating layers, such as those used with atomic layer deposition (ALD) or plasma-enhanced CVD (PECVD), may protect the device from harsh chemical environments as well as the use of chemically inert materials such as SiC. For high-temperature applications, wide band gap materials such as SiC, GaN, AlN or diamond may be used. More recently, interest in the use of graphene has increased for high temperature applications.

The following sections examine the sources of harshness and the approaches required to address them and allow accurate measurement.

Table 1 Harsh environments in different industries

<table>
<thead>
<tr>
<th>Industry</th>
<th>Harsh environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil/process Automotive</td>
<td>Temperature, chemical, pressure</td>
</tr>
<tr>
<td>Space</td>
<td>Temperature swings, radiation, high vacuum</td>
</tr>
<tr>
<td>Aircraft</td>
<td>Temperature, pressure, vibration, electric fields</td>
</tr>
<tr>
<td>Farming</td>
<td>Pesticides, chemical, biological</td>
</tr>
<tr>
<td>Medical implants</td>
<td>Biological (for example, stomach, colon, blood)</td>
</tr>
</tbody>
</table>

Table 2 Examples of harsh environments and domains that offer the most effective approaches

<table>
<thead>
<tr>
<th>Materials</th>
<th>Chemical</th>
<th>Thermal</th>
<th>Mechanical</th>
<th>EM loading</th>
<th>Radiation</th>
</tr>
</thead>
<tbody>
<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>

*EM loading occurs when electromagnetic disturbances are present. EM: electromagnetic.

PROCESSING AND MATERIALS

Substrate materials

Standard electronics are fabricated using single-crystalline silicon, which is an excellent material from both electrical and mechanical perspectives. However, silicon encounters limitations with respect to temperature range. Silicon-based electronic devices are not usually operated above 150 °C owing to junction leakage. Above ~ 200 °C, the material becomes intrinsic owing to thermal generation of electron–hole pairs. This effect can be offset locally using the exclusion principle. An alternative approach is to use a semiconductor with a wider band gap, such as SiC, GaN, and AlN. However, the Integrated Circuit (IC) technology for these materials is less well developed, and the substrates are more expensive.

Thin-film deposition

Modern semiconductor thin-film deposition techniques are treated in detail in textbooks. A non-exhaustive list of current thin-film deposition methods is shown in Table 3 together with short descriptions.

General selection criteria for thin-film deposition are given in Table 4.

Brief comparison of the most popular thin-film technologies

For over 50 years, the most popular thin-film deposition methods in industry have been physical vapour deposition (PVD) and chemical vapour deposition (CVD), with atomic layer deposition (ALD) emerging in applications where nanometer-size layer thicknesses or pinhole free layers are crucial. In particular, spatial ALD has potential as an interesting newcomer. On the basis of the selection criteria listed above, one can compare the different deposition methods compiled in Table 5.

CVD This method is widely used in the deposition of thin films and is available in three forms: atmospheric-pressure CVD (APCVD), low-pressure CVD (LPCVD), and plasma-enhanced CVD (PECVD). The main layers deposited are silicon oxide, silicon nitride, silicon and silicon carbide (SiC). For harsh environments, SiC is of particular interest because it is chemically inert and can operate at high temperatures. Using PECVD, SiC can be deposited at temperatures < 400 °C, thus making it suitable as a coating layer for an IC intended for use in harsh chemical environments. This layer has been observed to be pinhole-free for thicknesses greater than ~ 200 nm and can be used as the mechanical material for pressure sensors. LPCVD SiC can also be used, but this material has a deposition temperature above 700 °C and thus cannot be used as a coating layer for standard circuitry (unless an alternative metal layer is used). Other wide band gap semiconductors such as GaN and AlN are also useful materials for high temperature applications.

ALD This technique is used to deposit films in an atomic layer-by-layer manner, which enables the deposition of notably thin pinhole-free layers of high quality. ALD was first published under the name molecular layering in the early 1960s by Professor
Kol’tsov from Leningrad Technological Institute, although the basic concept was proposed by Professor Aleskovski in his PhD thesis in 1952. The characteristic feature that distinguishes ALD from other deposition technologies such as CVD, PVD, sol–gel synthesis, and spray pyrolysis is the self-limiting chemisorption of precursors in each half-cycle. This feature makes ALD unique in sub-nanometer film thickness and conformity control, offering next to (nearly) equal growth-per-cycle values for identical precursors in different equipment. The remaining drawback of conventional ALD that prevents it from cost-effective commercial use is the low deposition rate, but this shortcoming has been largely overcome by the launch of spatial atmospheric ALD.

Table 3 Concise survey of mainstay thin-film deposition methods and characteristics

<table>
<thead>
<tr>
<th>Method</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electroplating</td>
<td>Film formation from chemicals in dissolved electrolytic solution placed onto substrate surface with a seed layer on top that is electrically biased.</td>
</tr>
<tr>
<td>Spin coating</td>
<td>Film formation from chemical reaction between liquid-phase sources (often sol–gel) that have been applied onto the rotating substrate and subsequently heated.</td>
</tr>
<tr>
<td>Thermal oxidation</td>
<td>Film formation by chemical oxidation of the substrate surface.</td>
</tr>
<tr>
<td>Physical vapor deposition (PVD)</td>
<td>Film formation by condensation of gasified source material directly transported from source to substrate through the gas phase via Evaporation (thermal, E-beam), Molecular beam epitaxy (MBE), Pulsed laser deposition (PLD), Reactive PVD, Sputtering (DC, DC magnetron, RF)</td>
</tr>
<tr>
<td>Chemical vapor deposition (CVD)</td>
<td>Film formation by chemical reaction between mixed gaseous source materials on a substrate surface using: Atmospheric-pressure CVD (APCVD), Low-pressure CVD (LPCVD), Plasma-enhanced CVD (PECVD), Metal-organic CVD (MOCVD)</td>
</tr>
<tr>
<td>Atomic layer deposition (ALD)</td>
<td>A sub-class of CVD with film formation via sequential cycling of self-limiting chemical half-reactions on the substrate surface. Each reaction cycle accounts for the deposition of a (sub)monolayer. The reaction can be activated by thermal energy or plasma enhancement or can be performed in the spatially divided regime. Thermal ALD, Plasma-enhanced ALD (PEALD), Spatial ALD (S-ALD)</td>
</tr>
</tbody>
</table>

Table 4 Criteria for selection of thin-film techniques

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deposition rate</td>
<td></td>
</tr>
</tbody>
</table>
| Deposition directionality             | Directional: suitable for lift-off, 3D feature filling  
                                      Non-directional: suitable for step coverage |
| Film thickness and composition uniformity | Within-wafer  
                                      Wafer-to-wafer (single-wafer deposition) and run-to-run (batch deposition) |
| Film quality (physical and chemical properties) | Adhesion  
                                      Breakdown voltage  
                                      Film density, pinhole density  
                                      Grain size, grain boundary features, and grain orientation  
                                      Impurity level  
                                      Stoichiometry  
                                      Stress and yield strength  
                                      Hermeticity |
| Functional materials to be deposited  | Metals/conductors  
                                      Dielectrics, magnetics, piezoelectrics, etc.  
                                      Polymers |
| Cost-of-ownership and operation cost  |                                                                            |

Abbreviation: 3D, three dimensional.
## Table 5  Comparison of thin-film deposition methods

<table>
<thead>
<tr>
<th>Process</th>
<th>Material</th>
<th>Substrate temperature (°C)</th>
<th>Deposition rate (Å s⁻¹)</th>
<th>Directionality</th>
<th>Uniformity</th>
<th>Film density</th>
<th>Grain size (nm)</th>
<th>Impurity level</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal evaporation</td>
<td>Metal or low-melting</td>
<td>50–100</td>
<td>1–20</td>
<td>Yes</td>
<td>Poor</td>
<td>Poor</td>
<td>10–100</td>
<td>High</td>
<td>Very low</td>
</tr>
<tr>
<td>E-beam evaporation</td>
<td>Both metal and dielectric</td>
<td>50–100</td>
<td>10–100</td>
<td>Yes</td>
<td>Poor</td>
<td>Poor</td>
<td>10–100</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Sputtering</td>
<td>Both metal and dielectric</td>
<td>–200</td>
<td>Metal –200</td>
<td>Dielectrics 1–10</td>
<td>Some degree</td>
<td>Good</td>
<td>20</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>PECVD</td>
<td>Mainly dielectrics</td>
<td>200–300</td>
<td>Metal –100</td>
<td>Dielectrics 1–10</td>
<td>Some degree</td>
<td>Good</td>
<td>10–100</td>
<td>Very low</td>
<td>Very high</td>
</tr>
<tr>
<td>LPCVD</td>
<td>Mainly dielectrics</td>
<td>600–1200</td>
<td>Metal –100</td>
<td>Dielectrics 1–10</td>
<td>Some degree</td>
<td>Good</td>
<td>1–10</td>
<td>Very low</td>
<td>Very high</td>
</tr>
<tr>
<td>ALD (thermal)</td>
<td>Mainly dielectrics</td>
<td>50–300</td>
<td>0.1–1</td>
<td>Isotropic step</td>
<td>Superior</td>
<td>Superior</td>
<td>1–10</td>
<td>Very low</td>
<td>Very high</td>
</tr>
<tr>
<td>ALD (plasma)</td>
<td>Mainly dielectrics</td>
<td>20–200</td>
<td>0.1–1</td>
<td>Isotropic step</td>
<td>Superior</td>
<td>Superior</td>
<td>1–10</td>
<td>Very low</td>
<td>Very high</td>
</tr>
<tr>
<td>ALD (spatial)</td>
<td>Mainly dielectric</td>
<td>20–200</td>
<td>1–10</td>
<td>Isotropic step</td>
<td>Superior</td>
<td>Superior</td>
<td>1–10</td>
<td>Very low</td>
<td>Very high</td>
</tr>
</tbody>
</table>

---

## Table 6  Examples of reaction mechanisms and applications for ALD layers

<table>
<thead>
<tr>
<th>Type of ALD</th>
<th>Temperature range</th>
<th>Viable layers</th>
<th>Precursors/reactants</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catalytic ALD</td>
<td>&gt; 32 °C with Lewis base catalyst³</td>
<td>Metal oxides (that is, TiO₂, ZrO₂)⁴</td>
<td>TiCl₄, ZrCl₄, H₂O (Ref. 4)</td>
<td>High k-dielectric layers, protective layers, anti-reflective layers, and so on⁴</td>
</tr>
<tr>
<td>Al₂O₃ ALD</td>
<td>30–300 °C</td>
<td>Al₂O₃, metal oxides²⁹</td>
<td>Trimethyl aluminum, TiCl₄, H₂O, Ti(OiPr)₄ (Metal)(Et)₂ (Ref. 4)</td>
<td>Dielectric layers, insulating layers, and so on, solar cell surface passivation²⁴</td>
</tr>
<tr>
<td>Metal ALD using thermal chemistry</td>
<td>175–400 °C (Ref. 19)</td>
<td>Metal fluorides, organometallics, catalytic metals²⁹</td>
<td>M(C₂H₅)₂, (CH₃C₅H₄)M(CH₃)₃, Pd(hfac)₂, Ni(acac)₂, H₂ (Ref. 20)</td>
<td>Conductive pathways, catalytic surfaces, MOS devices²⁹</td>
</tr>
<tr>
<td>ALD on polymers</td>
<td>25–100 °C (Ref. 4)</td>
<td>Al₂O₃, ZnO, TiO₂, and metal oxides on for example, PET, PEN polyimide for flexible solar cells and displays¹⁴ and on textile¹⁵</td>
<td>Al(CH₃)₃, Ti(OiPr)₄, (C₂H₅)₂Zn, H₂O (Ref. 18)</td>
<td>Polymer surface functionalization and modification, creation of composites, diffusion barriers, and so on⁴</td>
</tr>
<tr>
<td>ALD on particles</td>
<td>25–100 °C for polymer particles, 100–400 °C for metal/ alloy particles³⁶</td>
<td>BN, ZrO₂, CNTs, polymer particles</td>
<td>Various gases: use of rotary fluid bed reactor is highly important to ensure fluidization of particles⁶⁻²³</td>
<td>Deposition of protective and insulating coatings, optical and mechanical property modification, formation of composite structures, conductive media³⁶⁻²³</td>
</tr>
<tr>
<td>Plasma- or radical-enhanced ALD for single- and multiple-element ALD conductors</td>
<td>450–800 °C (Ref. 4)</td>
<td>Pure metals (that is, Ta, Ti, Si, Ge, Ru, Pt)²⁰ and metal nitrides (that is, TiN, TaN, and so on)⁶⁻²³</td>
<td>Organometallics, MH₂Cl₂, terbutylimidotris (diethylamido)tantalum (TBTDET), bis (ethylcyclopentadienyl)ruthenium, NH₃ (Ref. 4)</td>
<td>DRAM structures, MOSFET and semiconductor devices, capacitors¹⁹ and Cu- and Li-diffusion barrier layers¹⁵,²¹</td>
</tr>
</tbody>
</table>

---

**Abbreviations:** ALD, atomic layer deposition; CVD, chemical vapor deposition; LPCVD, low-pressure CVD; PECVD, plasma-enhanced CVD.

---

**Abbreviation:** ALD, atomic layer deposition; MOS, metal–oxide–semiconductor. PET, Polyethylene terephthalate; PEN, Polyethylene naphthalate.
Selected examples of ALD processes and applications are given in Table 6, which is based on Refs. 4,5,15,18–23.

The high quality of the layer makes it highly suitable for biomedical applications4 and for the use in harsh chemical environments in which the underlying layers must be protected 24,25.

**Graphene** This material is an sp²-hybridized allotrope of carbon in the form of a two-dimensional, atomic-scale, hexagonal lattice in which one atom forms each vertex. The material is 200 times stronger than steel by weight and has high thermal and electrical conductance. Graphene has a tensile strength of 130 GPa and a Young’s modulus of 1 TPa, is able to operate at high temperature, is suitable for harsh chemical environments and is acceptable as a coating layer in medical implants26.

**Polymers** Polymers are composed of a large, chain-like molecular structure made of monomers, which are covalently linked in three-dimensional networks. There are many examples of both natural and synthetic polymers and polymers have found numerous applications in the sensor field. One of these applications is in medicine where a number of polymers have been found to be suitable for both in vitro and in vivo devices. These polymers do not generate any bodily reactions and are also able to withstand the biological environment. Examples of these polymers include the following:

- **Natural**
  - Plants: cellulose, natural rubber
  - Animals: collagen, heparin, DNA

- **Synthetic**
  - Parylene
  - Silicone rubber
  - Polyethylene
  - Polypropylene
  - Polymethyl methacrylate (PMMA)
  - Polyvinyl chloride
  - Polyether ether ketone (PEEK)

Parylene is a trade name for a variety of chemical vapor-deposited poly(p-xylylene) polymers used as moisture and dielectric barriers. The most common of these materials is parylene-C, which was first discovered by Szwarc in 1947 and is suitable for a range of applications, including medical implants27–32. Parylene is deposited by selecting a raw dimer of the material and heating it to nearly 150 °C. The vapor is pulled out under vacuum and heated to high temperature, which allows for sublimation and splitting of the molecule into a monomer. This monomer is subsequently further drawn by vacuum for deposition onto the required substrate.

Silicone rubber is well known for its elastic behavior with a maximum elongation that can range from 90 to 900% depending on the composition33. This material can form watertight seals and is water-repellent, although rather permeable to gas, which is an interesting combination for medical applications. Combination with liquid metals allows for use in strain sensing with up to 50% change in resistance and application, for example, in smart gloves34,35 and soft artificial skin36.

PMMA is probably better known under the name ‘plexiglas’ and is a low-cost, optically transparent material that has numerous applications in sensing. PMMA is often used in the formation of microfluidic chips37, for example, in the form of molded structures.

PEEK is a semi-crystalline plastic used abundantly in engineering components owing to its mechanical strength, high wear resistance, chemical inertness in organic, and aqueous environments, high maximum operating temperature (up to 250 °C) and low thermal degradation. Although PEEK has relatively high glass transition and melting temperatures, it can be processed by molding and extrusion, computer numeric controlled machining38, and recently even through additive manufacturing by either fused deposition modeling (FDM)39 or selective laser sintering40. The properties of PEEK make it a biocompatible material that is used in the reconstruction of large cranial osseous defects41, among other applications.

**Ceramics** Ceramics span a wide range of inorganic materials that can be highly ordered or amorphous (for example, glass). Ceramics such as sintered alumina are thermally and chemically resistant and can withstand temperatures as high as >2000 °C (Ref. 42) and aggressive applications in, for example, oven linings and plasma-etching equipment43. Some ceramics are also piezoelectrics and can therefore be applied in both sensors and microactuators. A review of the development of piezoelectric ceramics can be found in Ref. 44. In terms of medical applications, ceramics have been used in dental and orthopedic implants. For these applications, ceramics are robust and biocompatible (that is, they do not generate any reactions from the body). Ceramics have replaced many metal devices for implants45 and examples exist of biodegradable ceramics for bone implants46. Glass is used in the encapsulation of implants.

**HARSH ENVIRONMENTS**

This section discusses the different types of harsh environments. In certain cases, attempts are made to measure parameters such as high temperature or alternative parameters at high temperature. There are many such examples within different signal domains.

**High temperature**

Silicon is an excellent material for sensors but has certain limitations in terms of its process temperature window (the temperature tolerance range in which device fabrication can take place) and device-operating temperature range.

If the device uses a p-n junction, the temperature is limited to ~125 °C. Above this temperature, the junction suffers from leakage. Near 200 °C, extrinsic silicon is reverted to intrinsic silicon owing to the high generation of electron–hole pairs. This transition can be extended to higher temperatures for small volumes of silicon (which might contain the device) using the exclusion principle12. The device is designed and biased such that a small contact must supply a large number of minority carriers, which means that if the semiconductor begins to generate large numbers of electron-hole pairs, the minority carriers are immediately absorbed and the volume remains an extrinsic semiconductor. If we are able to fabricate devices within this region, they can continue to operate normally at temperatures above the transition. In this work12, Hall devices were fabricated to operate at up to 500 °C. The basic principle is shown in Figure 1.

For direct temperature measurements, platinum resistors can be a good option. Platinum is stable up to ~1000 °C (Ref. 47), and platinum-based thermocouples are widely used in temperature measurement. The materials used in the construction determine the device sensitivity and also the temperature range. Certain thermocouples are able to measure temperatures up to 3000 °C (Ref. 48). These high-temperature measurements require refractory (that is, high melting point) materials such as tungsten and rhenium.

In applications such as pressure sensing at high temperature, the sensor must be exposed to the environment. One option is to use wide band gap semiconductor materials that maintain their electrical properties up to higher temperatures. For example, SiC
power devices have been operated successfully at temperatures of ~600 °C. Diamond devices have been found to operate at even higher temperatures (>1000 °C). These alternative materials can be combined with device/package designs that protect the sensing element from the high environmental temperatures. This approach is illustrated in Figure 2. The use of a silicon membrane in direct contact with the environment limits the working temperature for measuring pressure. If p–n junctions are used, the temperature is limited to below 150 °C. Above 500 °C, the good mechanical properties are lost, and the materials become plastically deformable. The temperature range can be extended using a metal membrane with a mechanical connection to the chip. In this case, the pressure can be transduced to a pressure sensor via an incompressible fluid or through a hard contact to a stress sensor. Using the same basic principle, the sensor chip can be further isolated from the environment by adding a longer mechanical element that allows for further thermal isolation, as shown in the top right option, which greatly improves the temperature range, although it also increases the costs.

The use of SOI wafers or polysilicon piezoresistors can also increase the temperature range because these materials do not rely on p–n junctions. Further improvement can be achieved by selecting a wider bandgap material such as SiC or SiC on an insulator. All of these semiconductors have limitations in terms of their temperature range and bursting pressure. If a metal or other material is used as the membrane (Figure 2; Ref. 55), the material and thickness of the membrane can be chosen to meet the pressure and temperature requirements.

An alternative approach to high temperature application is the use of optical fibers. In the oil industry, for example, in the drilling of holes and pipes, long distances often lie between the point of measurement, and the readout in addition to high temperature and high electrical noise in the environment. In this case, optical fibers offer the best option and fibers capable of withstanding high temperatures can be used. Alternatively, free-space optics can be used. In this case, the light source and the receiver are isolated by distance from the harsh environment, and only the light passes through the device.

With fiber-optic devices, the temperature sensitive components of the system can be sheltered from high ambient temperatures. The measurement process can use interference or Fabry–Pérot interferometry. An example of an optical-fiber pressure sensor is given in Figure 2 (Ref. 60).

In extraction and recovery in the oil industry, the point of measurement might be located ~1 km from the instrumentation. Furthermore, the point of measurement and the path to the instrumentation may be at high temperature and also may be subjected to high electrical interference. An optical system can address many of these problems, and one such example is given in Figure 4. The use of optical techniques offers many opportunities for operation at high temperatures.

The operating temperature range of standard CMOS can be increased by careful consideration of the design. Through careful design of the preamplifier, the system was able to operate at temperatures up to 275 °C.

Low temperature

Extremely low temperatures (<100 K) also create challenges for sensors and the electronics. Fibre Bragg gratings have been shown to work effectively at extremely low temperatures, as have a number of other devices. At moderately low temperatures, approximately ~50 °C, problems occur with the packaging and the batteries in devices. As the temperature decreases further to cryogenic temperatures and below, the challenges greatly increase. Silicon continues to operate, but adjustments to the processing and the design are required. An overview of the issues for operation at cryogenic temperatures and below is given in Ref. 67. Enhanced operation at these low temperatures using high-K dielectrics can aid in maintaining correct operation.

### Figure 2

<table>
<thead>
<tr>
<th>Packaging</th>
<th>Direct exposure</th>
<th>Metal membrane</th>
<th>Metal membrane with transmission element</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>200–250 °C</td>
<td>450–500 °C</td>
</tr>
<tr>
<td>SOI</td>
<td>350 °C</td>
<td>400–450 °C</td>
<td>650–700 °C</td>
</tr>
<tr>
<td>SiCOI</td>
<td>500 °C</td>
<td>550–600 °C</td>
<td>800–850 °C</td>
</tr>
</tbody>
</table>

Figure 2 Different approaches to high temperature/pressure sensing. Adapted from Ref. 55.
High pressure
Silicon membrane pressure sensors are excellent for low to medium pressure (0–300 bar)\(^{69}\), but might easily fail when overloaded due to the brittleness of silicon. However, in many industries, such as the automotive and process industries, the pressure to be measured might lie in the range of 2000–3000 bar. For these higher pressures, alternative membrane material can be used. The main approach uses a metal membrane that determines the pressure range and transfers the value to the sensing element via a fluid or fixed connection. This method is similar to the approach used in sensors that operate at high temperature. One example deposits polysilicon onto a stainless steel substrate\(^{70}\), although this method generates additional processing challenges. The best option is to use sputtered oxide as an insulator because it can be formed on a wide range of substrates at relatively low temperature. The type of stainless steel used was suitable for temperatures up to ~500 °C. Polysilicon piezoresistors were deposited at low temperature and laser-annealed to avoid excessive heating of the substrate. High pressure/high temperature measurement systems have also been developed using optical techniques\(^{71}\), and ceramics can be applied for this purpose\(^{22}\).

Shock/high acceleration
In some military applications, measurement devices are expected to survive high acceleration and shock during operation. Accelerometers designed for low acceleration still must withstand the high shock/high acceleration, which can be achieved using stops that prevent the mass from moving too far. Selected accelerometers use oil in the cavity, which prevents the device from oscillating at resonant frequencies and protects it from shock\(^{23}\).

Radiation
Measurement of radiation or operation in an environment with radiation presents many challenges, depending on the type of radiation. In space applications, devices might be exposed to high levels of ultraviolet (UV) radiation from the sun. Certain systems can be protected from this radiation via installation in the satellite or spacecraft, but others must be exposed to be able to measure. In satellite applications, the devices might also be exposed to sharp swings in temperature. In medical applications, the devices could be exposed to X-ray or proton bombardment. Modern lithography uses extreme UV, which is reflected by at least eight Bragg reflector mirrors that compose the reticle stage and the wafer stage in the optics of an EUV system. Still, the current mirror reflectivity record is still only 70.3% of the EUV light. Current state-of-the-art mirrors are produced by e-beam evaporation and ion beam sputter deposition of superlattices (Mo/Si; see Figure 5

![Figure 3](https://example.com/fig3.png)

**Figure 3** Optical fiber pressure sensor. On the basis of Ref. 60.

![Figure 4](https://example.com/fig4.png)

**Figure 4** *In situ* monitoring of a steam-assisted gravity drainage (SAGD) well with unique white light Fabry–Pérot interferometer fiber-optic pressure and temperature sensors constructed from highly durable and corrosion-resistant sapphire material. Courtesy of Opsens Solutions Inc., Quebec, Canada.
with B\textsubscript{4}C interlayer diffusion barriers to improve thermal diffusion resistance\textsuperscript{75,76}. These devices yield >70% EUV reflectivity, although 75% yield is theoretically possible with superior mirror surface protection and new absorber and spacer material layers. In addition to the ultrathin layer deposition techniques that are currently used in EUV mirror manufacturing (for example, e-beam evaporation and ion beam sputter deposition), atomic layer deposition can be developed to further improve the so-called spectral purity of the multilayer stacks. Examples are found in anti-reflection coatings designed to improve DUV contrast for inspection (Al\textsubscript{2}O\textsubscript{3}, SiON), absorber layers to absorb EUV for image formation (for example, Ta(B)N, TaSi(N)), and buffer/capping layers to protect the mirror stack from absorber-etch damage and from unexpected oxidation, and blistering due to hydrogen radical diffusion into the mirror layer stack, for example, Ru, TiO\textsubscript{2}, Nb, and B\textsubscript{4}C (Ref. 77). Efforts have also been put forth to increase the emissivity (currently ~30%) of the layer stack to counteract the heating by IR and DUV radiation from the EUV source.

X-ray radiation can have notably harmful effects on operation of MOS devices, and exposure to X-rays can shift the transistor characteristics\textsuperscript{78}. The shift with increasing exposure is shown in Figure 6 (Ref. 78). This effect can be greatly reduced through layout design using an enclosed layout (Figure 7 (Ref. 78)) with the resulting improvement in radiation hardness shown in Figure 8 (Ref. 79).

Alternative materials can be used to measure radiation signals outside the normal range for silicon. One such approach uses GaN photodiodes formed on top of a standard IC. This approach enables UV measurement, and readout can be accomplished using standard IC technology. A cross-section of this device is shown in Figure 9 (Ref. 79).

Harsh chemical environment

Aggressive chemicals affect not only the measurement layer but also the packaging. It is therefore essential that all aspects of the device are considered during development. In certain cases, a layer is used to react with the target chemical to be measured. Many different types of sensors are available for chemical measurement, including electrochemical, chemFET, and optical types. The chemFET option is one of a group of devices that also include devices for measuring ions (ISFET) and enzymes (ENFET). These devices are based on standard MOS transistors in which the gate has been modified to enable the measurement\textsuperscript{80}. Because this device is based on silicon technology, it has a limited...
Humidity

Humidity has always been an issue for ICs. Packaging must be hermetically sealed to prevent moisture from reaching the chip. Humidity results in corrosion of the metallization and even creates short circuits if it reaches under the passivation layer to the silicon itself. Humidity sensors must be exposed to this environment and therefore can suffer from reliability problems. Most humidity sensors are capacitive and use polymers or ceramics to absorb water vapor and therefore change the capacitance. With all of these devices, the remainder of the chip must be hermetically sealed to ensure reliable operation, but a further reliability issue remains with these devices. Both of these materials expand with absorbed moisture, which results in physical expansion.
An overview of biomaterials can be found in Ref. 93, and the role of microsystems is described in Ref. 97. Many implanted devices require a wireless communication system with the outside environment\textsuperscript{99}. In addition to the limitations on materials that can be used, the in vivo environment is highly aggressive, not only because of the chemical environment but also because the body attacks any foreign material. Catheters are generally in place for less than 72 h and maintain direct wired contact to the outside. The first patient treatment with cardiac catheters dates back to the 1950s with the work of Dotter. Silicon sensors were able to meet the space restrictions of this application and, with the correct coating/packaging, were able to withstand the environment and avoid generation of any unwanted reaction from the host. A pressure sensor that uses a membrane was a simple device that met all requirements and has been a successful commercial product for many years\textsuperscript{99}. Companies such as NovaSensors (Buelton, CA, USA), Braun (Frankfurt, Germany), Edwards, Ylisson Medical Technology, and Cook Medical (Bloomington, IN, USA) have pressure-monitoring catheters in the market, and many more companies are currently producing these types of devices. Most of the products are disposables and must therefore be manufactured at low cost. Furthermore, most commercial devices contain only a single sensor. However, use of silicon allows a number of sensors to be included on a single chip\textsuperscript{100,101}. As stated above, catheters are generally used over periods of \textless{} 72 h and maintain direct wired contact to the outside world, but implanted sensors often must remain in the body for longer periods and use wireless communication\textsuperscript{102,103}. In addition, power for the devices must be considered. Batteries are one option, but inductive powering can be a better option\textsuperscript{104}. Polymers are excellent materials for implants owing to the choice of biocompatible polymers because they are generally rather flexible and can also be used as a sensing layer. One such example is measurement of oxygen in tissue using optical techniques and a polymer in direct contact with the tissue\textsuperscript{105}. Long-term implants include pacemakers\textsuperscript{106}, deep brain probes\textsuperscript{107}, prostheses\textsuperscript{108}, cochlear implants\textsuperscript{109}, and retinal implants\textsuperscript{110}. Interest also exists in long-term implants for administration of insulin or other medicines for chronic conditions. In some cases, the sensor can be completely protected from the environment, but in other situations, the sensor must be exposed and therefore must withstand a harsh environment. For example, the cochlear implant operates in a saline solution for a number of years. The electrodes must be maintained as electrically active, which increases corrosion. Modern implants use plate platinum as the electrode. Future cochlear implants might be fabricated using IC technology, and in this case, TiN may be a better option for the electrodes\textsuperscript{111,112}. In the field of medical implants, the challenges are broad and varied. In some applications, the combination of humidity, local pH, and body fluids can combine to erode both the electrode and the packaging.

### Table 7 Brief comparison of metals, ceramics and polymers for implantable applications\textsuperscript{94}

<table>
<thead>
<tr>
<th>Properties</th>
<th>Metal</th>
<th>Ceramic</th>
<th>Polymer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biocompatibility</td>
<td>Good for limited metals</td>
<td>Good for bio-ceramics</td>
<td>Good for many polymers</td>
</tr>
<tr>
<td>Hermeticity</td>
<td>Good</td>
<td>Medium</td>
<td>Mostly poor</td>
</tr>
<tr>
<td>Degree of outgassing</td>
<td>Low</td>
<td>Low</td>
<td>Mostly high</td>
</tr>
<tr>
<td>Mechanical flexibility</td>
<td>Poor</td>
<td>Poor</td>
<td>Good</td>
</tr>
<tr>
<td>Reliability</td>
<td>Good</td>
<td>Good</td>
<td>Mostly poor</td>
</tr>
<tr>
<td>Optical transparency</td>
<td>Poor</td>
<td>Mostly poor</td>
<td>Good (for some)</td>
</tr>
<tr>
<td>RF transparency</td>
<td>Poor</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Ease of processing</td>
<td>Difficult</td>
<td>Difficult</td>
<td>Good</td>
</tr>
<tr>
<td>Cost</td>
<td>High</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Relative weight</td>
<td>Heavy</td>
<td>Medium</td>
<td>Light</td>
</tr>
</tbody>
</table>

### TESTING AND RELIABILITY

If any device is to achieve commercial success, the reliability of the devices must be demonstrated. Where possible, the testing should occur under more extreme conditions than in the intended application. Standard testing methods include high temperature/ high humidity, temperature swings, radiation exposure, high salt solutions, and so on. These tests must be designed to best test the microsystem for the intended environment. At the European Space Agency, a wide range of test facilities is used to ensure that the devices can survive the environment\textsuperscript{113}. In medical implants, biocompatibility tests are complicated and extensive\textsuperscript{\textsuperscript{114}}. In addition, the devices must be tested to maintain good functionality in the environment. Many tests are performed in salt solutions that are more concentrated than those encountered in applications. Reliability testing is an essential component of the development and must be adapted for each application. This requires a good understanding of the environment and the failure mechanisms\textsuperscript{114}.

### CONCLUSIONS

A harsh environment is any environment that impedes the normal operation of a sensing or actuating device. A number of approaches can be used to address these problems, such as alternative materials, coating layers or design as well as protective device packaging. For each application, it is necessary to consider all of these aspects to successfully design and fabricate a reliable system.

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### COMPETING INTERESTS

The authors declare no conflict of interest.

### REFERENCES
