Sensors based on Semi-Conductor Strain Gages for Automated Structural Health Monitoring and Medical Applications

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Abstract

Semi-conductor strain gauges are used to measure stress and temperature and possess all key characteristics required by sensitive elements for structural health monitoring of long-life, safety critical items and medical applications. Their key characteristics are:

- high gain, which generates a very high signal-to-noise ratio in applications;
- long-term stability and repeatability, which makes them suitable for long-life items;
- miniature size, allowing flexible sensor design and direct gauging of parts at peak-stress or peak thermal load zones;
- high resistance, minimizing power consumption and allowing automatic, embedded wireless monitoring application (passive RFID without battery, autonomous wireless mesh networks, etc.).

Proven applications range from industrial, robotics, defence, piping infrastructure and civil structures to critical medical applications in cardiology, orthopedics and neurology.

Key benefits are increased safety and minimization of life-cycle costs: as such they are an ideal support for structural health monitoring of long-life systems.

This paper illustrates the technology and shows some proven applications.

Keywords: Semi-conductor strain gauges, Smart structures, Experimental validation, Industrial applications, IoT

1. INTRODUCTION

Semiconductor strain gages make use of the piezo-resistive effect exhibited by certain semiconductor materials such as silicon and germanium in order to obtain greater sensitivity and higher-level output. Semiconductor gages can be produced to have either positive or negative resistance changes when strained. They can be made physically small while still maintaining a high nominal resistance. Semiconductor strain gage bridges may have 100 times the sensitivity of bridges employing metal films, but are temperature-sensitive and therefore require temperature compensation.
Micron Instruments' Semiconductor Strain Gages are micro-machined from a solid single grown crystal of "P" doped Silicon. This results in a two terminal resistive device that has a minimum of molecular slippages or dislocations permitting repeatable use to high strain levels. Gage shape is application sensitive and presently available in bar, U and M shapes. Industry standard gages are normally bar shaped; the length and resistivity varies but the width is nominally 0.005 inches\(^1\) and the thickness 0.0005 inches for a bar gage. Normally, a gold lead is bonded to ends of the gage for electrical connection. For miniature sensors, it can be important that the gold electrical leads come out the same end, requiring U shaped gages. The U shaped gage also has twice the resistance over the same length, making it desirable for small areas of high strain or for wireless applications where higher resistances are important. There are also M shaped gages, which provide four times the resistance of the same length bar gage when even higher resistance is required.

2. HIGH FREQUENCY, HIGH TEMPERATURE GAGES

There are many applications where high frequency pressure at high temperatures is required.

One application would be testing and tuning jet aircraft engines to optimize performance and quickly detect any deleterious harmonics that could cause rapid engine failure.

Another application would be down-hole oil measurement detecting sudden high pressure or excessive pressure oscillation. Such sensors would provide unattended, early failure warning, and could be designed into a system to automatically detect anomalies and gracefully shut down the sub-system at risk before it destroys itself or blows out the well. When integrated as a wireless sensor, it could also autonomically provide alert and alarm notifications.

High frequency, high pressure, high temperature strain gages could also be used as wind tunnel skin friction sensors. Exploiting the high gage factor in semiconductor strain gages\(^2\) makes it easier to design for higher frequencies, and the high temperature gages makes the sensor especially useful for wind tunnel ultrasonic and hypersonic wind skin friction measurements. Data from such a sensor leads to designs that minimize friction and optimize performance.

There are many other applications requiring flush mounting and high temperature sensors, but some would not require high frequency. One would be high temperature injection molding.

2.1 Using Micron Instruments’ High Temperature Semiconductor Strain Gages to Build a 500°F High Frequency Pressure Sensor

The sensor design starts with the semiconductor strain gage. Sensor performance can be no

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\(^1\) All dimensions herein shall be in inches, unless specified otherwise.

better than the gage performance, so there is no better choice than a semiconductor gage. In addressing technical considerations such as electrical conductivity and oxidation, it is preferable to use gold pads at the ends of the silicon strain gages. Gold begins to slowly amalgamate with silicon at about 500°F. At higher temperatures, the amalgamation accelerates.

Micron Instruments established an initial goal to produce a gage that will sustain 1000°F for short periods and operate reliably for many years at 500°F. This goal was achieved with sophisticated barriers. The gage itself has a minimum of molecular slippages or dislocations, and as such, has a 99-year life and a gage factor of over 150. This gage factor is 50 to 75 times more sensitive than the normally available foil gage. These are some of the characteristics that make the semiconductor strain gage desirable when high performance for a long operational life is required.

Sensor housing material should be selected to optimize the gage performance, but this is also application sensitive. For instance, if in a very corrosion high temperature environment, Titanium 6AL4V should be considered.

2.2 Additional Technical Challenges

2.2.1 Bonding Agents

Bonding strain gages with standard carbon based adhesives such as Epoxylite 6203 or M-Bond 610 is limited to under 250°F. These adhesives will lose bonding power (modulus of elasticity decreases) as temperature increases. Full-scale creep starts to become problematic, with the best of procedures, at about 300°F.

Therefore, bonding the gages at high temperatures with glass fritz or ceramic-based adhesives is preferred. Low temperature melting glass fritz has been used successfully for high temperature work, but it contains lead. Lead-free glass fritz is available and typically requires over 600°F but below 1000°F, which the new Micron Instruments’ high temperature gage can accommodate.

2.2.2 Soldering

The lead free solders contain a large amount of tin. Although this solder junction will not open at 500°F, they can grow tin whiskers, oxidize, and begin to amalgamate with the gold leads. Micron Instruments has a gold base solder which avoids these problems.

2.2.3 Wires and cables

Few exit cables rated at 500°F are commercially available. For those cables that must operate at 500°F, Teflon and other high-temperature overcoats are available. If there is a potential that the temperature may have short excursions to 550°F or more, Teflon can produce Phosgene and will deteriorate, so cable selection is highly application sensitive.
2.2.4 Sensor metal

Matching the metal to the gage optimizes performance. Also, the metal should be one that will not oxidize or corrode at 500°F to the extent it affects performance. This is also application sensitive; e.g., if operated in a highly corrosive environment.

3. MINIATURE IMPLANTED MEDICAL DEVICES (MIMD)

A sensor for implantable medical applications needs to be reliable and have a long life -which also means no battery - and it must be body compatible. The device must be miniature for minimal surgical implant intrusion. This device should be wireless to simplify operation and avoid the complications of tethered wires protruding from the body. To be passive (no batteries) wireless, it requires low activation energy for reasonable transmission distance using the approved radio frequency bands to furnish the wake up energy and respond by sending cogent signals at a reasonable distance.

There may be many basic sensing mechanisms that would meet the above requirements. This paper will deal with one already in production and proven to meet all requirements when properly housed and conditioned. It is the miniature homogeneous single crystal doped Silicon semiconductor. It already exists in two main versions, the strain gage and the temperature sensor. This gage cannot guarantee that the lifetime of the sensor or that performance and reliability of the final product is achieved, since there are other materials and processes in the final product; but the use of these strain gages provides a higher probability of success.

3.1 A Conceptual Design for the MIMD Sensor using Semiconductor Gages

Starting with the miniature sensor requirement, Micron Instrument’s SS-018-011-3000PU is a U shape semiconductor gage 0.018 long (less than 1/2 mm) - the smallest gage presently in stock. The proposed design is for a flush mounted pressure sensor. The most efficient use of the pressure-induced strain on a fixed edge diaphragm with this gage is the pressure-induced radial strain. We would like the gage in radial tensile strain (center of the diaphragm) to be the same in radial compressive strain (at the inner circumference of the diaphragm). This means the shorter compressive region has to be 0.020 long, which is one third of the radius, making the inner diaphragm diameter dimension 0.120. Assuming the sensor will be working at low pressures in the region of 10 psi or less, the diaphragm thickness (to avoid behaving like a membrane) needs to be about 0.003 thick and the outside diameter, allowing for a wall thickness of 0.010, would be 0.140. This is for optimum signal performance. The minimum outside diameter size could be 0.090 without the temperature sensor and with lower signal performance.

The SS-018 is made from 1.0 ohm-cm resistivity P doped Silicon. The contact pads and back cure of the gage are metalized and shorted. Only the 0.013 long center section is active and is approximately 3,000 ohms at ambient temperature. The SS-018 has gold pads on the ends of the gage, gold lead wires off the pads, and a single crystal miniature gage that resists corrosion and
has a mean time to failure of 99 years. The impedance is high enough for wireless transmission and the gage factor is approximately 200, permitting an output signal 67 times higher than a foil gage with a gage factor of 3.

This gage is already in use in a miniature pressure sensor measuring the heart pressure profile through the left Ventricle wall. It was decided that the sensor should be a flush diaphragm for best pressure transduction at 0.100 diameter (2.5mm), and be made of Titanium 6AL4V which is corrosion resistant and body compatible. Some reasonable wall thickness was required, which lead to the decision to use a wall thickness of 0.010 (1/4 mm), leaving the diaphragm 0.080 in diameter and plenty of room to install the four 0.018 gages onto the inside diaphragm. These gages are wired into a fully active bridge. There is no room for a temperature sensor and the diameter is not optimum. Smaller overall diameter was traded for less output without any other performance compromises. Data communication for this sensor is a handheld computer held near the coil (within a few inches) to read the sensor data.

3.2 Implantable Optimum Pressure Sensing Design.

Figure 1 shows the sensor with strain gage and temperature sensor location for optimum performance. Strain gages are wired into a fully active four-legged bridge as shown in the wiring diagram. ST-037-022-5000N is the temperature sensor, located across the radial inflection point (neutral axis) to optimize performance.
3.3 Wireless Considerations

The major benefit of wireless communication for implantable medical sensors is fairly obvious: it’s non-intrusive and avoids the many problems with tethered wired sensors. It’s also important to avoid implanted power sources that have limited life. The good news is there are passive wireless technologies, covered by international (ISO) standards, which meet most implantable medical device requirements. The transceivers are commercially available and relatively inexpensive.

The passive wireless technology most commonly used for implantable medical devices is “passive high-frequency”, or HF, operating at 13.56MHz. Multiple semiconductor companies offer HF transceivers and interrogators that comply with the ISO 15693 standard and can be used with or without a battery. There is also a Near Field Communication (NFC) standard published by the NFC Forum that supports HF tags compliant with the ISO 14443 A and B standards.

The HF transceiver chips, pictured in Figure 1A, can be as small as 0.08 by 0.08 (2mm by 2mm) and about 0.03 (0.75 mm) thick.

![Figure 1A](image)

NFC or a plug-in interrogator. The interrogator provides power through its transmission to prompt the chip to broadcast back a unique ID and the measured data. The data can be displayed by the app and stored as part of medical records. The range for HF passive operation is typically less than 6 inches, depending on the size of the antenna coil and the transmitted energy from the interrogator. A major benefit of Micron’s semiconductor strain gages is the high-impedance options, potentially up to 30,000 ohms, which dramatically reduces the power required by the sensor to deliver the data to the wireless transceiver.

The four strain gages are connected into a fully active bridge at the solder tabs at the sidewall of
the sensor. Two wires from the Temperature Sensor are also connected to the solder tabs on the sidewall. A miniature flex connector will be bonded to the sidewall and all sensing connections will terminate on the flex that connects to the microprocessor ("MP"). The MP will correct pressure offset, Balance Tc, Sensitivity Tc and any non-linearity. Connected to the MP is the transceiver, which is connected to the communication coil (antenna) via a body compatible cable, thereby allowing the antenna to be located under the skin anywhere convenient on the body.

All components will need to be sealed and body compatible, which is best optimized by having one container housing the Sensor, MP and communicator, with a cable connecting to a remote sensing coil. It should be possible, by design, for the container to be 0.120 in diameter and 0.375 long. Anchors can be put onto the sides of the sensor depending and what functions and where the sensor is being used. The sensor microprocessor and communicator will be one component inside the sensor. The size of a commercially available 13.56MHz antenna is shown in Figure 2.

![Antenna Diagram](image)

Although the strain gages are available, it would be a simple change to increase the 3,000-ohm impedance of the present gages to 30,000 ohms, making the circuit much more sensitive and enabling communication at a much longer distance.

3.4 Medical Sensor Solutions using Semiconductor Strain Gages.

While the above section describes a pressure temperature sensor, the miniature size, high impedance and sensitivity opens up many IMPLANTABLE MEDICAL possibilities.

It would be possible to design a miniature version of the water tunnel or wind tunnel force sensors measuring longitudinal force (bending in two dimensions 90 degrees from each other) and torsional forces, simultaneously, on one miniature rod. This rod could be attached to operating tools allowing a specialist doctor in Berlin to operate robotically on a patient in Madrid with full tactical and video feedback as if he were in the operating room himself. The miniature,
high resistance and high sensitivity gages make all of this possible. The operating tool could advise when a tissue is first touched, show the force on the tissue, what angle the tool is at, and could be made to tell if the tissue is diseased.

4. CONCLUSIONS

Semi-conductive strain gages offer significant benefits that make them the obvious choice for a diversity of applications, including medical, industrial, robotic, precision instruments, infrastructure, aerospace, and defense applications. Benefits include Size (Micron Instrument’s semiconductor strain gages typically require less than 2% of the area needed for a metal-foil gage, and are as small as .018” long, with an active area of .011”, and .0004” thick); Sensitivity and Signal Output (the Gage Factor (GF) for metal-foil gages is typically 1 to 4. In contrast, Micron Instruments’ semiconductor strain gages have a GF as high as 200 – roughly two orders of magnitude higher; Life Cycles (metal-foil gages usually fail from fatigue after 10 thousand to ten million cycles. Micron Instruments’ semiconductor strain gages will operate for an infinite number of cycles provided that operating strain is kept under 500 µ-strain and the maximum full-scale strain is kept under the one µ-strain precision elastic limit for the material the gage is being bonded to); Precision Temperature Compensation and Gage Matching (semiconductor strain gages have large temperature coefficients of resistance (TCR) making single gage strain measurements difficult unless used at a constant temperature. Micron Instruments’ semiconductor strain gages are predominantly used in half-bridge and full-bridge configurations, which compensate for temperature and deliver highly accurate strain output. Micron Instruments uses advanced instrumentation for precision measurement of gage slope and intercept. This temperature characterization is then used to carefully match gage sets for use in half or full bridges); and Resistance (metal-foil gages typically offer an impedance range of 120Ω to 5,000Ω. Micron Instruments is driving the high end of strain gage impedance, currently as high as 50,000Ω, and expected to reach 100,000Ω in the near future. This is particularly important for passive wireless sensing).