APPLICATION NOTE: AN-100

Selecting Strain Gages
Silicon vs Metal Foil

(General Strain Measurement)

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Introduction

Semiconductor (silicon) strain gages have revolutionized strain measurement since their invention at Bell Telephone Laboratories in the early 1950s. In the early 1960s, attributed to the work of Dr. Anthony Kurtz, and W.P. Mason, R.N. Thurston the first silicon strain gages became commercially available. It was greatly expected that silicon strain gages would replace foil strain gages in most strain measurements, but the transition has been slow. Foil gages have a low gage factor and therefore only have a good output in high strain areas. If the foil gage used at a lower strain point, the output signal becomes too weak to use effectively. Silicon gages are extremely rugged, yet produce powerful signals and allow for a wide bandwidth and short response time. These features are necessary for accurate strain measurements in many applications. The following technological overview describes and compares the advantages of both technologies and showcases why the latest silicon based strain gages are rapidly becoming the superior choice throughout the industry. Figure 1 shows a comparison of Metal-Foil and Silicon strain gages.

CHARACTERISTIC	METAL-FOIL	SILICON
Size for 1000 Ω	~0.04 in^2	~0.0004 in^2
Gage Factor	1 to 3	50 to 200
Resistance	120 Ohms to 5K Ohms	120 Ohms to 10K Ohms
TCR	1%/100F Typical	+10 to +20%/100 F Typical
TCGF	-3%/100F	-1 to -16%/100 F Typical
Fatigue Life	10E4 to 10E7 Cycles	infinite at <500 µstrain
Operating Strain	500 to 10,000 µstrain	500 to 1,000 µstrain
Transverse Strain Sensitivity	3% Typical	1% Typical
Power Density	1 to 15 Watts/in^2	25 TO 150 Watts/in^2
Resolution	.1 µstrain Typical	.005 µstrain Dynamic
Gaged Null Stability	Good*	Good*
Long-Term Drift	Good*	Good*
Operating Temperature	Cryogenic to +350 F	Cryogenic to +750 F***
Resulting Sensor Compliance	Y microinches	Y/100 microinches
Sensor Thermal Zero Shift	<±1%FSO/100F	±1%FSO/100F**
Sensor Thermal Sensitivity Shift	±1%/100F	±1%/100F Typical**
Sensitivity to Thermal Transients	Low	Low**
Other Mechanical Inputs Sensitivity	Low*	Low*
Sensor Acceleration Sensitivity	Low	Extremely Low (100 Times less)
Sensor Output at 500 µstrain	10 mV FSO	500 mV FSO
Sensor Frequency Response	[0 to n] Hertz	[0 to 100n] Hertz

* Mounting Dependent
** With Proper Thermal Compensation
*** Higher Temperature SOI gages Available with Special Mounting

Table 1: Comparison of Foil and Silicon Strain Gages

Gage Factor-Sensitivity

Gage factor is a measurement of the sensitivity of the strain gage and is defined as the resistance change per unit of initial resistance divided by the applied strain.

$\Delta R = GF \times R \times \varepsilon$

> ΔR: Change in resistance measured to calculate force
>
> GF: Gage Factor
>
> R: Initial resistance of the gage
>
> ε: Strain

Foil gages have a gage factor of 1 to 4, while silicon gages have a gage factor of 30 to over 200.

Sensitivity – Output Signal

Looking at the change in resistance vs. strain it is easy to see why foil gages can only be used in relatively high stress areas. Due to the low gage factor of foil gages, strain levels need to be around 4000 microstrain to produce an acceptable signal. But even at those strain levels the signal is weak, and low-level electrical noise affects the resolution of the sensor. The silicon gages operate at strain levels as low as only 50 to 500 microstrain, while still producing signals that are many times stronger then foil gages. To achieve resolution a force sensor using foil gages must exhibit resolution down to 1×10^{-5} ohms in many cases, which is very difficult to achieve. To make matters worse, induced electrical noise can mask this small change in resistance. Measurements based on silicon gages produce a strong signal output with extremely high electrical noise immunity.

Frequency Response - Higher Bandwidth & Lower Response Time

The use of filtering can reduce induced electrical noise to acceptable levels on most foil gage transducers, however filtering sacrifices the bandwidth and response time of the transducer. Measurements on rotating parts or other dynamic measurements must be done at high sampling rates. When silicon gages are used filtering requirements are reduced thus allowing for wide bandwidth and extremely fast response times. For all practical purposes, piezoresistive devices have no inherent limitation on frequency response. The theoretical limitation on the frequency response of semiconductor crystals is on the order of 10^6 *Mhz*. The limitation on the response of a strain gage is a function of the ability to transmit strain into it. Thus, it is a function of the characteristics of the stressed member, the bonding technique, and the relationship between the gage length and the wave length of the propagated wave. The shorter the gage length, the higher the frequency response. Transducers using silicon gages have made demanding measurements much easier.

Linearity

The accuracy of strain measurement is directly related to the linearity of the strain gage. Although no strain gage is perfectly linear, results with Kulite Semiconductor gages are as good as the best obtained with conventional metal gages due to the low strain levels needed. When considering linearity, consideration must be given not only to the single element resistance change with strain, but also to the measuring circuit in which the gage is used.

Hysteresis and Repeatability

Theoretically, mono-crystalline silicon is a perfectly elastic material with no plastic region up to temperatures as high as 1200°F. Thus, any hysteresis in a strain gage installation is generally a function of the mounting cement/epoxy/glass, or hysteresis in the stressed structure. Transducers using Kulite gages regularly exhibit hysteresis of less than 0.05%. Foil gages use a plastic backing along with an epoxy film to mount them to the transducer. The plastic backing is more likely to exhibit creep and hysteresis. Silicon gages are mounted directly to the transducer with epoxy. Various new silicon gage mounting methods have been introduced by Kulite, using microcoats of epoxy or glasses that reduce hysteresis and repeatability even further.

Output (Sensitivity) Shift vs. Temperature

One shortcoming that silicon strain gages exhibit is a shift in output with change in temperature. There are two different temperature-related problems: one is that the resistance of the strain gage changes with the change in temperature and the other is that the gage factor changes with the change in temperature. A change in gage resistance, due to change in temperature can cause a zero shift. A change in gage factor due to a change in temperature causes a span or gain shift. Silicon gages have a larger span shift than foil gages. Foil and silicon gage's zero shift is similar due to the use of the Wheatstone bridge. However, zero and span shift temperature problem has been solved using a variety of compensating techniques. Regardless of the type of gage used, temperature effects ultimately depend on the type of compensation method used.

Device Reliability – Fatigue & Creep

In the past most strain gages were used for static and quasi-static measurement applications. Now more users are using them for dynamic measurements which can lead to issues of fatigue. Fatigue of strain gages can be a problem for users that need to measure cyclic stress for millions of cycles. Over time a metal strain gage can creep causing a shift in the measurement as well as eventually failure due to fatigue. Silicon strain gages are made from single crystal silicon; there for there is virtually no creep over the entire lifetime of the device. Also because there are very few crystal defects in the Silicon it has an extremely long lifetime even at high cycle rates.

High Temperature Capability –Silicon-On-Insulator (SOI) Technology

Kulite's patented fusion bonded Silicon-On-Insulator (SOI) technology is used for the fabrication of high temperature silicon piezoresistive strain gages. The SOI fabrication process using fusion bonding to permanently attach the strain gage to an insulating oxide layer that provides superior electrical isolation between the active portion of the gage and the substrate to which it is mounted (i.e., the steel beam). In contrast, wire and foil gages require an additional insulating film between the gage and the substrate, leading to reduced accuracy and higher hysteresis effects. In contrast to gages made using earlier methods, SOI gages are much more stable, have high sensitivity to strain (high gage factor) and very low sensitivity to temperature (low temperature coefficient of gage factor). The SOI gages are fabricated using the state-of-the-art MEMS techniques utilizing precision processing, thus allowing the design to be customized for other applications (i.e., size, shape, targeted resistance, etc.) while preserving all of the benefits of the technology.

Size

Silicon strain gages can be micromachined to be extremely small and could be produced in the following design layouts:

1 The "A" type is a straight, bare silicon gage with welded gold alloy leads for higher temperature operation. The leads for an "A" type gage are oriented axially to the gage.

2 The "U" type designates a large element gage in the form of a "U". The two legs of one "U" are geometrically parallel, but electrically in series, connected to each other by a shorting link across the base of the "U". This construction is designed for maximum resistance in a minimum size with single-ended lead configuration.

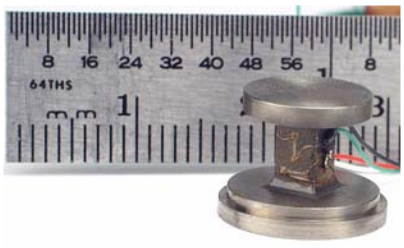
3 The "S" type is a ruggedized gage construction with solder tab terminals incorporated into the epoxy/glass matrix instead of nickel ribbon leads. External wires are optional and may be attached or removed with conventional soldering techniques. It can be either a straight ("A") or u ("U") shaped gage.

Bare gages insure the most intimate contact of the sensor to the bonded surface, but do require some experience in handling and bonding.

Custom gage designs and encapsulations are available to optimize both the mounting configuration and the temperature capability of the device.

Subminiature Load Cells

The ability to fabricate very small, high sensitivity, SOI strain gages enables Kulite to manufacture subminiature load cells.



The subminiature load cells above are shown with and without a protective sleeve. The typical combined error due to nonlinearity and hysteresis is less than 0.1% of the full scale output. Similar installations can be done on any small mechanical piece where strain measurement is needed.

Conclusion

Strain measurements using foil gages have a poor reputation for reliability in the tough environments. Many users have either avoided using these foil gage sensors due to their poor durability, or have implemented designs with severe performance sacrifices attributed to their gage related limitations. Measurements with silicon strain gages, having a low noise output, a small, rugged design, and a high sampling rate act as ideal candidates for enabling strain measurement in difficult harsh environments. Additionally, the latest Silicon-On-Insulator (SOI) technology enables the fabrication of the high temperature strain gages with enhanced performance characteristics. These gages, as well as all other silicon based strain gages, are easily optimized for specific customer applications and have been shown to be truly superior to their foil gage counterparts.