Technical Note – TN-1
Issue: 11 Oct 2024

General Information about Semiconductor Strain Gages

Summary

The main attributes of semiconductor strain gages are: high gage factor, small physical size, and flexible gage placement in sensing structures due to their small size. Special attention must be paid to the electrical configuration of the semiconductor strain gages in a Wheatstone bridge because the semiconductor strain gage resistances change noticeably with any fluctuations in temperature. Sensitivity of the Wheatstone bridge signal output to thermal loads can be mitigated through improved strain gage manufacturing methods and consistent gage installation practices. The methods and materials used to install metal foil strain gauges can generally be employed to install semiconductor strain gages.

A. General Mechanical and Electrical Characteristics

The general mechanical and electrical characteristics of Piezo-Metrics' line of semiconductor strain gages is shown in Table 1. The properties for a specific type of strain gage may be found at https://www.piezo-metrics.com/product-catalog.

Table 1 – Semiconductor Strain Gage Characteristics

Mechanical Property	Units	Range
design operating strain	micro-strain	50 to 500
temperature limits[a]	C	-40 to 85
fatigue life	cycles	greater than 10^6
gage factor	--	90 to 170
gage overall length	inch (mm)	0.018 to 0.25 (0.45 to 6.4)
gold lead length	inch (mm)	0.4 (10)
Electrical Property	**Units**	**Range**
resistance	ohms	15 to 2000
TCR[b]	%/100F (%/C)	5 to 45 (0.09 to 0.81)
design excitation voltage	VDC	2 to 5
maximum power per gage[c]	mW	less than 5

[a] limited by adhesive used to bond strain gage to the sensor structure
[b] Temperature Coefficient of Resistance
[c] power must be below value to prevent self-heating effects

Contact: www.piezo-metrics.com • sales@piezo-metrics.com
4584 Runway Street • Simi Valley, CA 93063
(805) 522-4676

B. Null Balance and Temperature Compensation of Full-Bridge Configuration

If semiconductor strain gages are directly installed into a constant voltage Wheatstone bridge, it is likely that the null balance, i.e. the bridge output at no load, would be non-zero. Also, the bridge output would be very sensitive to any temperature changes the strain gages may experience. To bring the bridge to a near zero output condition at no load and to have the bridge self-compensate for changes in temperature, the bridge must be nulled and compensated using a set of series and shunt resistors in the bridge circuit. Note this compensation can also be accomplished electronically.

Figure 1 shows the null-balance and temperature compensation resistors which could be added to the basic Wheatstone bridge circuit. The resistors consist of the series resistor, RS, and parallel resistor, RP, before the bridge, the RZ1 and RZ4 shunt resistors acting on gages G1 and G4, respectively, and RB2 and RB3 series resistors acting on the left and right branches, respectively, in the bridge. Only one shunt resistor, RZ1 or RZ4, is needed and only one series resistor, RB2 or RB3, is needed. The values for these resistors are calculated using the strain gage resistances measured in the gauged sensor at zero and full-scale load over the desired operating temperature range.

Figure 1 shows why semiconductor strain gages cannot be used in a standard metal foil bridge configuration. Without the temperature compensation resistors, the bridge output would be too sensitive to temperature fluctuations and result in low signal-to-noise ratios that would make the signal unusable.

To wire the bridge, the RED is connected to the positive source, the BLK and YEL are connected to the negative source, the GRN is connected to the positive signal line and the WHT is connected to the negative signal line.

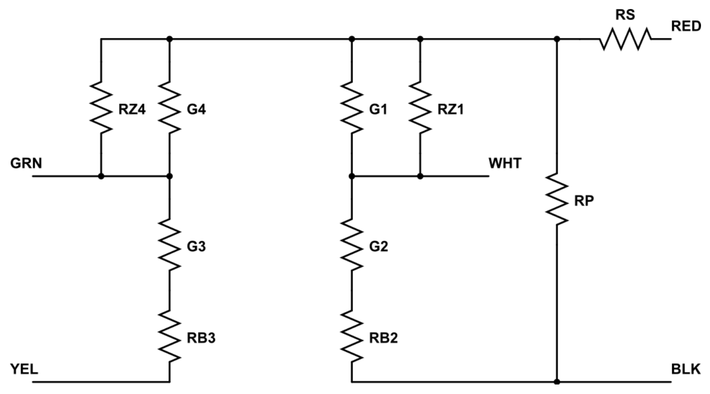

Figure 1 – Compensation resistors to achieve null output at zero load and compensation for temperature changes in a constant voltage bridge. Yellow and Black leads are connected together in the final bridge configuration.

Table 2 shows typical temperature compensation and calibration results for a set of 25 psi (170 kPa) pressure transducers. The target null balance was zero mV. The target full-scale span was 100 mV. It can be seen that the null balance varies over the temperature range and is different for each sensor. The span is consistent over the temperature range and from sensor to sensor.

Table 2 – Temperature Compensated and Calibrated Pressure Transducer Results

Temp	Value (mV)	Unit A	Unit B	Unit C
75F (24C)	zero Full-Scale Span	2.95 103.73 100.78	0.48 99.97 99.49	-1.28 99.2 100.48
30F (-1C)	zero Full-Scale Span	1.89 103.46 101.57	0.16 100.06 99.9	-3.67 97.08 100.75
130F (54C)	zero Full-Scale Span	3.79 104.74 100.95	1.85 101.6 99.75	1.71 102.34 100.63
25 psi (170 kPa) transducers, 5 VDC excitation				

C. Strain Gage Installation Considerations

The methods and materials developed by companies such as Micro-Measurements (https://micro-measurements.com/accessories), HBM (https://www.hbm.com/en/0400/strain-gauge-accessories/) or Kyowa (https://product.kyowa-ei.com/en/products/accessories) to install metal foil gauges can be employed to install semiconductor strain gages. In general, two-part epoxies such as the Micro-Measurement M-Bond 610 work quite well for typical industrial applications.

Preparation of the location to be gauged may follow the Micro-Measurements and HBM guidelines for abrading and degreasing the area. After this initial preparation step, the area must be coated with a uniform thin film of epoxy to create an electrically insulating layer between the semiconductor strain gage and metal sensor structure to prevent electrical shorts.

Bonding the semiconductor strain gage involves applying a uniform film of epoxy to the bottom of the gage and then gently lowering the gage into position on the sensor structure. Once on the structure, the capillary forces of the adhesive will hold the gage in place while the epoxy cures.

Micro-Measurements or HBM materials can be used to protect gages exposed to the environment.

Figure 2 shows the typical interconnections used with semiconductor strain gages. The strain gage gold leads are soldered to a set of terminal pads bonded next to the strain gage. Insulated magnet wires bring the strain gage signal to a second set of terminal pads which are located in a central position on the sensor body. Client conductor leads going to a client connector or magnet wires going to the temperature compensation and calibration circuitry are then soldered onto the second set of terminal pads.

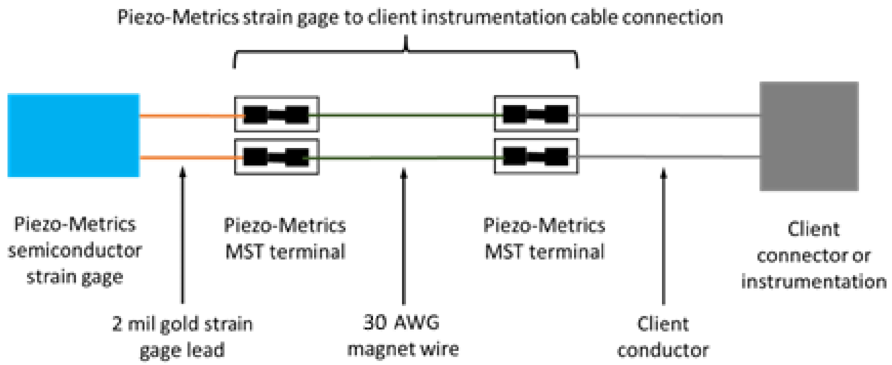

Figure 2 – Interconnection between semiconductor strain gage and client instrumentation

D. Factors Affecting Strain Measurement Accuracy

The strain signal from a full-bridge Wheatstone bridge is governed by

$$\frac{e_0}{E_{exc}} = \frac{1}{4}\left(\frac{\Delta R_1}{R} - \frac{\Delta R_2}{R} + \frac{\Delta R_3}{R} - \frac{\Delta R_4}{R}\right) \quad (1)$$

where

e_0 is the bridge output,

E_{exc} is the bridge excitation voltage,

R is the nominal strain gage resistance,

ΔR_n is change in resistance of strain gage n,

$\Delta R_n/R$ is equal to $GF\ \varepsilon$,

GF is the gage factor, and

ε is the surface strain.

Each strain gage in the bridge will change resistance, ΔR_n, in response to a variety of external influences, namely, mechanical forces and thermal loads. In the ideal case, the sensor mechanical design will isolate the strain gages to see only the mechanical forces of interest and the strain gage design and sensor electronics will eliminate any thermal effects from the bridge output signal.

Designing a sensor structure geometry to impose pure tension/compression or pure shear strain on a strain gage for a given force, moment or torque is well-known and is not dealt with here. The pathways where thermal loads affect strain gage resistance is less well known and so will be discussed further.

Referring to Figure 3, in its most basic form, the surface strain in the sensor structure is transferred to the strain gage through the adhesive bondline. The meaning of the abbreviations are shown in Table 2.

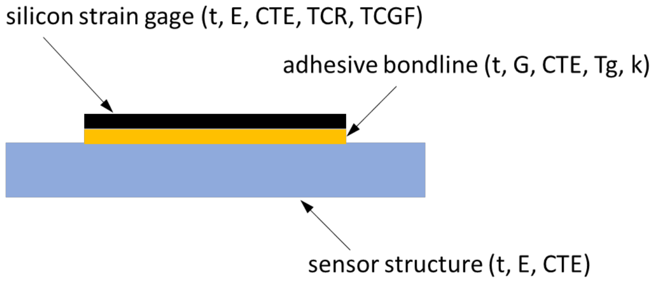

Figure 3 – Basic components and properties in a strain gage installation. See Table 3 for abbreviations.

Table 3 – Meaning of Abbreviations in Figure 3

Abbreviation	Meaning
t	thickness
E, G	tensile, shear modulus
CTE	coefficient of thermal expansion
Tg	glass transition temperature
k	thermal conductivity
TCR	temperature coefficient of resistance
TCGF	temperature coefficient of gage factor

It can be seen that thermal loads will affect all the materials in different ways because each material possesses its own value for coefficient of thermal expansion. As each material expands or contracts differentially to temperature, the differential strains from the sensor structure and the adhesive bondline will be transferred to the strain gage. The result is that a change in resistance in the strain gage will be measured by a temperature change alone.

The temperature coefficient of resistance of the strain gage, which has a positive value, will cause the strain gage resistance to change with temperature. The higher the temperature, the higher the strain gage resistance will be. If the strain gage is used without compensation circuitry, the bridge output signal will change even though there is no change in mechanical load.

The temperature coefficient of gage factor of the strain gage, which has a negative value, will cause the bridge output to drop with increasing temperature. The higher the temperature, the lower the strain gage resistance will be. If the strain gage is used without compensation circuitry, the bridge output signal will change even though there is no change in mechanical load.

Thermoset adhesives are commonly used to bond the strain gage to the sensor structure. The adhesive's shear modulus will change as a function of temperature depending on its glass transition temperature. If the temperature is approaching or is above the adhesive's T_g, the strain transfer efficiency will decrease resulting in a lower strain reading. Being a polymer, the adhesive bondline also acts as a thermal insulating layer. The heat transfer to and from the strain gage, and therefore the temperature experienced by the strain gage and the gage resistance, will be a function of the adhesive's thermal conductivity and the thickness of the bondline.

The stability of the full-bridge output is not only dependent on how each individual strain gage reacts to thermal loads, it is dependent on how all four strain gages react together to the thermal loads. As equation 1 shows, if each strain gage acts independently of each other to thermal loads, the bridge output signal could vary widely and very unpredictably. There are many reasons that the strain gages would change resistance independently of each other under a thermal load:

1. the TCR of each strain gage is slightly different from the other,
2. the TCGF of each strain gage is slightly different from the other,
3. the thickness of each strain is slightly different from the other,
4. the bondline thickness under each strain gage is slightly different from the other,
5. the crosslinking in the bondline under each strain gage is slightly different from the other,
6. the placement or orientation of each strain gage is slightly different from the other.

The first three reasons (items 1 to 3) are mitigated by the methods used to fabricate the semiconductor strain gage. Close control of the ingot doping process to obtain a uniform volume resistance, and therefore TCR and TCGF, across a wafer is mandatory. At the strain gage fabrication stage, close control over the dimensional tolerances of the strain gage and careful matching of the gages that form the set of four strain gages used in a full-bridge will minimize thermal effects on the bridge output signal.

The last three reasons (items 4 to 6) are mitigated by the consistency of the semiconductor strain gage installation method. Controlling the thickness of the adhesive bondline for each strain gage and ensuring the same bondline thickness exists across all strain gages in the full-bridge is critical. Controlling the cure cycle to fully cure the adhesive in a uniform manner across all strain gages is essential. Accurately placing and orienting each strain gage in their designated location on the sensor structure is obligatory.

Piezo-Metrics has strived and continues to strive to improve its semiconductor strain gage fabrication processes to deliver the most uniform set of strain gages to its customers. The Piezo-Metrics' gaging services staff, with its decades of experience, possess the technical skills needed to ensure consistent and reliable semiconductor strain gage installation in customer-supplied sensor structures. Piezo-Metrics continues to invest in technologies that will increase semiconductor gage installation consistency and reduce semiconductor strain gage installation time.

E. Precision_Matched™ Semiconductor Strain Gages

Piezo-Metrics invested in the development of a new process to fabricate semiconductor strain gages in much higher volumes than in the past. The motivation for this investment was to reduce the amount of labor per strain gage and to increase the dimensional uniformity of the strain gages. By design, the process produces matched sets without requiring the resistance of each strain gage to be measured and hand matched. The strain gages from this new process forms Piezo-Metrics' new product line called Precision_Matched™ strain gages.

The Precision_Matched™ gage set matching tolerance is determined by the uniformity of the resistivity across the wafer. The gage-to-gage variations of 540 ohm and 1050 ohm nominal resistance gages were measured for sets of two (2), four (4) and eight (8) strain gages. Table 4 shows the measured gage-to-gage variations as a function of nominal gage resistance and set size. The measured variations are typical of the Precision_Matched™ family of strain gages.

Table 4 – Typical gage-to-gage variations for set sizes of 2, 4 and 8.

Resistance (ohms)	Set Size (---)	Variation (%)	Variation (ohms)
540	2	0.31	1.7
540	4	0.44	2.4
540	8	0.52	2.8
1050	2	0.71	7.5
1050	4	1.05	11.0
1050	8	1.78	18.7

F. Reporting of Precision_Matched™ Strain Gage Metrics

The Precision_Matched™ strain gages are characterized on a Lot basis rather than on an individual basis to take advantage of the uniformity that the new process brings. Characterization on a Lot basis means that a statistically relevant sample is removed from the Lot and characterized in terms of gage resistance, Temperature Coefficient of Resistance (TCR) and Gage Factor (GF). These Lot-based metrics are used for quality control and Lot acceptance. An example set of Lot metrics is given in Table 5.

Table 5 – Example Lot metrics for 540 ohm strain gages

Metric	Value
Gage resistance (ohms)	540 +/- 12
TCR (% per 100F)	25 +/- 2
Gage Factor (--)	150 +/- 3

PIEZOMETRICS™, Inc.

The end-user is assured that the sets coming from the Lot of strain gages will fall within the Lot-based metrics. More importantly, the tolerance within a gage set is much tighter than the tolerance of the Lot as was previously discussed in Section E.

Piezo-Metrics will be providing the Lot-metrics for the Precision_Matched™ gages to the end-user. The gage-to-gage variation data is considered Piezo-Metrics' proprietary data.

G. Additional Information

For more information about any of the topics discussed in this Technical Note, please visit the Piezo-Metrics website at www.piezo-metrics.com and enter questions into the Customer Service Agent. Questions can be similar to:

'tell me more about SC strain gages'

'tell me more about temperature compensation'

'tell me more about strain gage installation'

Contact: www.piezo-metrics.com • sales@piezo-metrics.com
4584 Runway Street • Simi Valley, CA 93063
(805) 522-4676