

KS kulite®
STRAIN GAGE
MANUAL

LEADER IN SEMICONDUCTOR
STRAIN GAGE TECHNOLOGY
SINCE 1959

Handwritten notes on a blue background:

$$\frac{\Delta R}{R} = \frac{1}{3}(\pi_{11} + 2\pi_{12} - \pi_{14})$$

$$\frac{\Delta V}{V} = \frac{\Delta R_x + \Delta R_y}{2R_x + \Delta R_x - \Delta R_y}$$


$C_{11} = C_{12} = C_{13} = C_{14}$
constant current

OPF - 1000-125 gao

$$= \frac{I_{B1} - I_{B2}}{I_{B1}} = \frac{I(1 - \dots)}{I}$$

parallel resistor

for $R = 100 \text{ K}\Omega$ then



$\frac{\Delta R}{R} = \dots$

$$\frac{\Delta V}{V} = \dots$$

$$\frac{\Delta R}{R} = \frac{1}{3}(\pi_{11} + 2\pi_{12} - \pi_{14})$$

Introduction

The semiconductor strain gage may be thought of as a strain sensitive resistor. Generally when bonded to a stressed member, its resistance changes as a function of applied strain. This characteristic makes it useful in the fields of stress analysis, physical measurements, testing, transducer and instrumentation manufacture.

A typical semiconductor strain gage consists of a strain sensitive crystal filament to which leads are attached. Most Kulite gages are also available encapsulated. Encapsulation embeds the gage in a protective epoxy/glass matrix. Encapsulation of the gage enhances the durability of the gage, and facilitates handling of the gage, while also providing electrical isolation from the mounting surface.

When compared to conventional metallic wire and foil gages, Kulite semiconductor gages offer some significant advantages:

- (1) Higher sensitivity
- (2) Smaller sizes
- (3) Higher resistance
- (4) Higher fatigue life
- (5) Lower hysteresis
- (6) Lower non-linearity
- (7) Increased temperature envelope

Measurements at significantly higher frequencies, faster rise times, lower signal levels, and at a wider range of ambient temperatures are now possible due to the advantages of semiconductor gages over metal foil gages.

Kulite gages can be used for construction of transducers that may be used for manufacturing various items such as industrial scales, prosthetic limbs, load cells and soil cells. One may even take advantage of the higher sensitivity to obtain high level signals to drive low cost indicating, recording and control systems without the need for amplification. Custom gage configurations (gage factor, TCR, TCGF, size, resistance, etc.) are available to combine all of the above capabilities and customize the gage for any given application.

For over 50 years Kulite Semiconductor Products, Inc has fabricated all of our strain gages in-house in its own state of the art manufacturing facility. In addition to our line of silicon semiconductor strain gages, Kulite offers strain gage training seminars and gaging services for the installation of gages onto customer supplied hardware. Kulite's customers are encouraged to speak with our highly trained staff of Engineers and Scientists. When customers call Kulite with a question, such as an application issue, a product issue, a materials issue, or a compensation issue they can be sure to speak with extremely knowledgeable personnel to quickly help solve their problem.

DISCLAIMER

All product specifications and data are advisory only and are subject to change without notice.

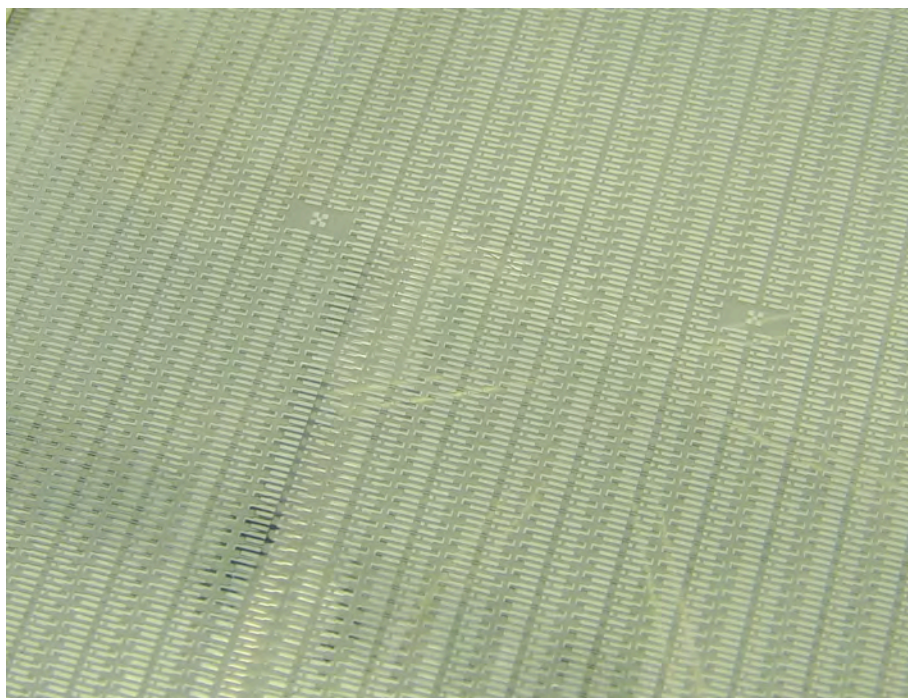
Kulite Semiconductor Products, Inc., its affiliates, agents, and employees, and all persons acting on its or their behalf (collectively, "Kulite Semiconductor Products"), disclaim any and all liability for any errors, inaccuracies or incompleteness contained herein or in any other disclosure relating to any product.

Kulite Semiconductor Products, Inc., disclaims any and all liability arising out of the use or application of any product described herein or of any information provided herein to the maximum extent permitted by law. The product specifications do not expand or otherwise modify Kulite Semiconductor Products, Inc., terms and conditions of purchase, including but not limited to the warranty expressed therein, which apply to these products.

No license, express or implied, by estoppel or otherwise, to any intellectual property rights is granted by this document or by any conduct of Kulite Semiconductor Products, Inc.

The products shown herein are not designed for use in medical, life-saving, or life-sustaining applications unless otherwise expressly indicated. Customers using or selling Kulite Semiconductor Products, Inc., products not expressly indicated for use in such applications do so entirely at their own risk and agree to fully indemnify Kulite Semiconductor Products, Inc., for any damages arising or resulting from such use or sale. Please contact authorized Kulite Semiconductor Products, Inc., personnel to obtain written terms and conditions regarding products designed for such applications.

Product names and markings noted herein may be trademarks of their respective owners.



Wafer Fabricated- Unseparated

FORWARD

The purpose of this catalog is to provide our customers with an understanding of how our silicon strain gages are designed, how they operate, how they differ from metal or foil gages, and how they may be used to obtain accurate results. In addition, we have provided information on how to order our gages. However, no book can replace speaking directly with our Engineering Staff and we encourage our customers to contact our factory for a conversation about the benefits of using our technology. We look forward to speaking with you about your application and how Kulite can help you obtain the best results possible at a competitive price point.

Kulite silicon strain gages were developed by Dr. Anthony D. Kurtz over 50 years ago. The manufacturing process has been perfected over those years and yields the finest quality gages commercially available today.

We are fortunate to have at Kulite one of the most experienced workforce available. Our production staff have years of experience manufacturing silicon strain gages and has developed some of the best techniques to ensure the highest quality and best matching of our gages.

Table of Contents

Section I

Piezoresistance in Semiconductors	1-2
Piezoresistivity.....	1
Gage Factor (GF).....	1
Gage Factor Control.....	2

Section II

Gage Characteristics	3-9
Resistivity	3
Gage Output	5
TCR.....	6
TCGF.....	6
Apparent Strain.....	6
Bonded Resistance	6
Linearity.....	7
Hysteresis.....	7
Maximum Strain Range	8
Fatigue Life	8
Frequency Response.....	8
Advantages of Semiconductor Strain Gages Over Metal Foil Gages.....	8
Strain Gage Selection	9

Section III

Strain Gage Selection	10-13
Gage Construction.....	10
Gage Resistivity.....	11
Gage Factor Polarity.....	11
Gage Resistance (Geometry/Resistivity).....	12
Gage Length.....	12
Kulite Semiconductor Strain Gage Characteristics and Selection Table.....	13

Section IV

Strain Gage Application Notes	14-17
Introduction.....	14
Strain Gage Construction.....	14
Electrical Lead Length	15
Strain Limits.....	15
Radius of Curvature.....	15
Maximum Operational Temperature.....	15
Power Dissipation – Self Heating.....	15
Bonded Resistance	16
Apparent Strain.....	16
Null and Sensitivity Compensation	17
Strain Gage Resistance Matching	17
The Effect of Noise on Resolution and Accuracy in Kulite Semiconductor Strain Gages.....	17

Section V

Strain Gage Installation Notes18-21
Packaging18
Strain Gage Installation Instructions18
Surface Preparation18
Cleaning.....19
Cement/Epoxy.....19
Insulation.....19
Trimming20
Extension Leads20
Bonding – Bare Gages20
Bonding – Encapsulated Gages21
Moisture Protection21

Section VI

Strain Gage Usage - Basic Circuitry.....22-26
Wheatstone Bridge.....22
Dynamic Measurements.....23
Static Measurements.....24
Gage Factor Compensation.....26
Constant Current26
Excitation Voltage.....26

Section VII

Temperature Compensation Techniques For Semiconductor Strain Gage Sensors.....27-48
Introduction.....27
Equivalent Circuit Resistance and TCR.....29
Span (Sensitivity) Compensation30
Empirical Span (Sensitivity) Compensation.....32
Empirical Span (Sensitivity) Compensation with an Input Shunt.....35
Bridge Null and Null Shift Compensation.....37
Solutions of the Null Compensation Equations.....42
Empirical Bridge Null Compensation.....43
Empirical Bridge Null with Null Shift Compensation.....45
The Effect of Null and Null Shift Compensation on the Gages Strain Sensitivity.....47

Section VIII

Gaging Services.....49
Training Services.....49
Gage Matching Services.....50
Appendix A- Selecting Strain Gages: Silicon vs. Metal Foil.....51
Appendix B- Sample Procedure for Specimen Surface Preparation and Gage Bonding59
Strain Gage Characteristics and Selection Table60

Section I

PIEZORESISTANCE IN SEMICONDUCTORS

Piezoresistivity

The principle employed in silicon semiconductor strain gages is the piezoresistance effect, which is defined as the change in electrical resistivity with applied stress. All materials exhibit this effect to some degree, but in certain semiconductors the effect is very large, and appreciable change in resistivity occurs with applied stress. The resistance change occurs under all conditions of static and dynamic strain.

For a semiconductor, the resistivity ρ is inversely proportional to the product of the number of charge carriers N_i and their average mobilities μ_{ave} . This may be expressed as equation (1) Where e is the electronic charge.

$$(1) \quad \rho = \frac{1}{eN_i\mu_{ave}}$$

The effect of an applied stress is to change both the number of carriers and their average mobility; the magnitude and the sign of the change will depend on the specific semiconductor, its carrier concentration and its crystallographic orientation with respect to the applied stress. For simple tension or compression, when the current through the gage is along the stress axis, the relative change in resistivity $\Delta\rho/\rho_0$ is given by:

$$(2) \quad \frac{\Delta\rho}{\rho_0} = \Pi_L \sigma = \Pi_L \epsilon Y$$

Where Π_L is the longitudinal piezoresistive coefficient and σ is the stress, ϵ is strain and Y is the modulus of elasticity, also known commonly as Young's modulus, for the semiconductor material. For silicon, $Y_{si} = 27 \times 10^6 \text{ lbs/in}^2$. For other stress systems similar equations result with different values of the piezoresistive coefficients.

Gage Factor (GF)

Gage factor is the term used to define the fractional change in resistance of a gage with applied strain. The larger the gage factor, the higher the resistance change and the resulting output, resolution, etc. Metal wire and foil gages have gage factors between 2 and 4. Kulite semiconductor gages have gage factors between 35 and 200. Therefore, Kulite gages can measure very low strain levels, i.e. microstrain, where foil gages cannot due to the low signal level.

Thus, gage factor (GF) is given by equation (3).

$$(3) \quad GF = \frac{\Delta R}{R_0 \varepsilon} = 1 + 2\nu + \Pi_L Y$$

In Equation (3) ν is Poisson's ratio, Y is Young's modulus for the semiconductor material, ε is strain, ΔR is the strain induced gage resistance change and R_0 is the zero strain gage resistance value. The first two terms represent the change in resistance due to dimensional changes while the last term represents change in resistivity with strain.

Gage Factor Control

Kulite strain sensitive elements are fabricated from monocrystalline silicon material. Single crystal silicon is an extremely robust material which displays many highly desirable mechanical characteristics such as, high yield strength, high shear strength, good thermal conductivity, low hysteresis, and high linearity. Electrically, the characteristics of the gage can be altered by adding a quantity of electrically active impurities to the silicon through a process called diffusion and by changing the gages physical layout. The combination of these techniques provides an extremely wide latitude of gage characteristics and allows for Kulite to custom design a gage specifically for each customers needs.

For semiconductors with a relatively high number of carriers (so-called degenerate semiconductors) having carrier concentrations on the order of 10^{20} carriers/cm³, the gage factor is essentially independent of both temperature and strain. Equation (4) expresses the ideal gage factor (GF) formula.

$$(4) \quad GF = \frac{\Delta R}{R_0 \varepsilon} \quad \text{Constant (independent of strain and temperature)}$$

Gages made from this material require few if any correction factors or tables to obtain highly accurate data. As the number of carriers is reduced, the gage factor begins to exhibit some variation with temperature and strain. For the extreme case of semiconductors containing fewer than 10^{17} carriers/cm³, the gage factor is markedly temperature and strain dependent and is given by equation (5)

$$(5) \quad GF = \frac{T_0}{T} (GF_0) + C \left(\frac{T_0}{T} \right)^2 \varepsilon$$

where (GF_0) is the room temperature zero strain gage factor. For this case appropriate corrections for both temperature and strain dependence must be made. These issues are discussed in a later section.

Semiconductor technology makes available a wide range of piezoresistive characteristics suitable for strain gage construction. The extensive variety of Kulite gages represent combinations of features to provide optimum results in a wide variety of applications. Some of the characteristics of semiconductor strain gages are discussed in Section II.

Section II

GAGE CHARACTERISTICS

Resistivity

Resistivity, a measure of the electrically active impurity concentration in a semiconductor, is the single characteristic which most completely describes the piezoresistive properties of a semiconductor. Semiconductor materials used for manufacturing strain gages range in resistivity from 0.0005 ohm-cm to 1.0 ohm-cm. The relationship between resistivity and impurity concentration, also known as dopant density, is an inverse one. That is, as the impurity concentration increases, the resistivity decreases. The most important resistivity dependent characteristics are Gage Factor (GF), Temperature Coefficient of Gage Factor (TCGF), Temperature Coefficient of Resistance (TCR) and Linearity.

The curves in Figure (1) illustrate how GF, TCGF, and TCR vary with P-type impurity concentration for silicon. Figures (2) and (3) are plots of percentage resistance change with strain and temperature for P-type gages of varying resistivities.

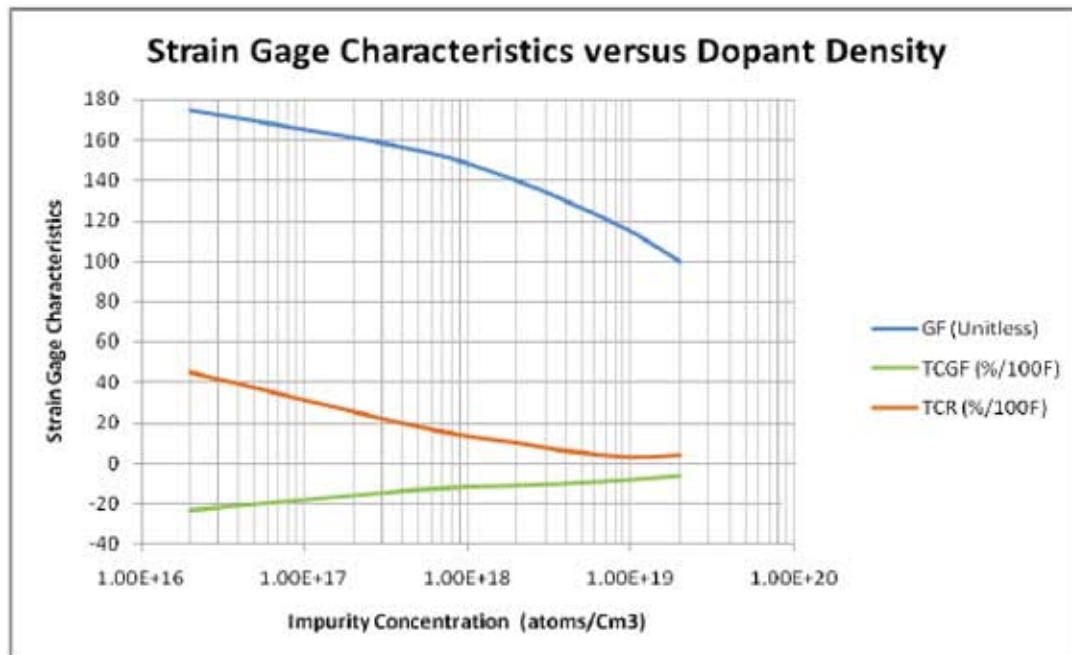


Figure 1

Reduction of gage factor (GF). Gage factor may be decreased from a high of about 175 to a low of about 100. This is illustrated in Figure (2) where $\Delta R / R_0$ is plotted as a function of applied strain. Resistivity level can be determined by gage resistivity alpha code where C type gages have the lowest resistivity and H type gages have the highest resistivity.

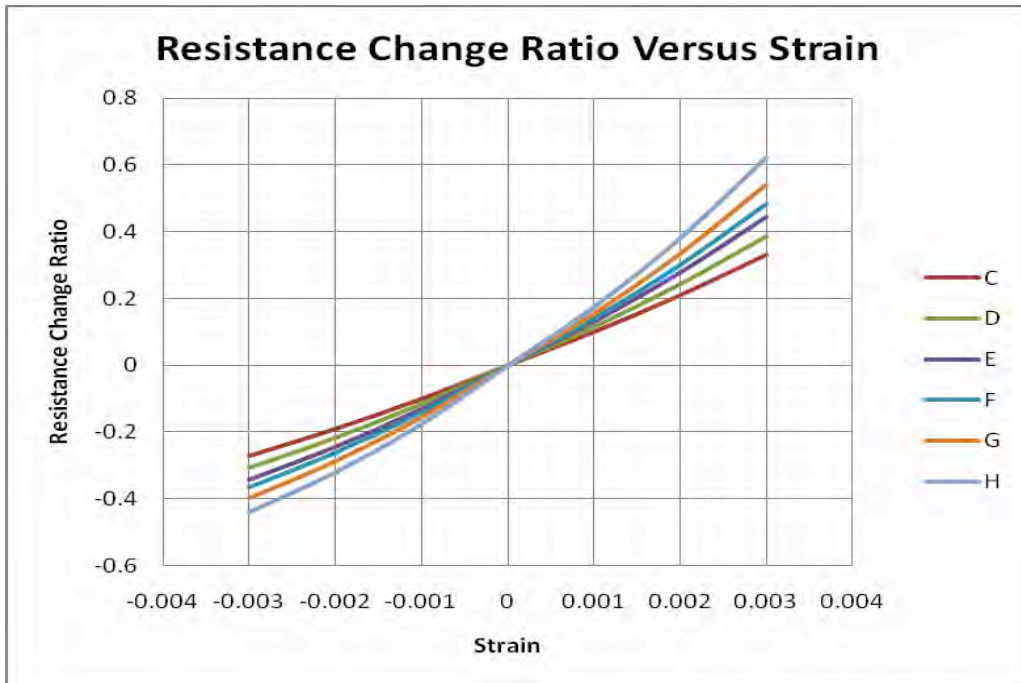


Figure 2

Increase in linearity. The single element nonlinearity at 1000 microstrain may be improved over 10 times. This is also illustrated in Figure (2). The lower the resistivity the higher the inherent linearity.

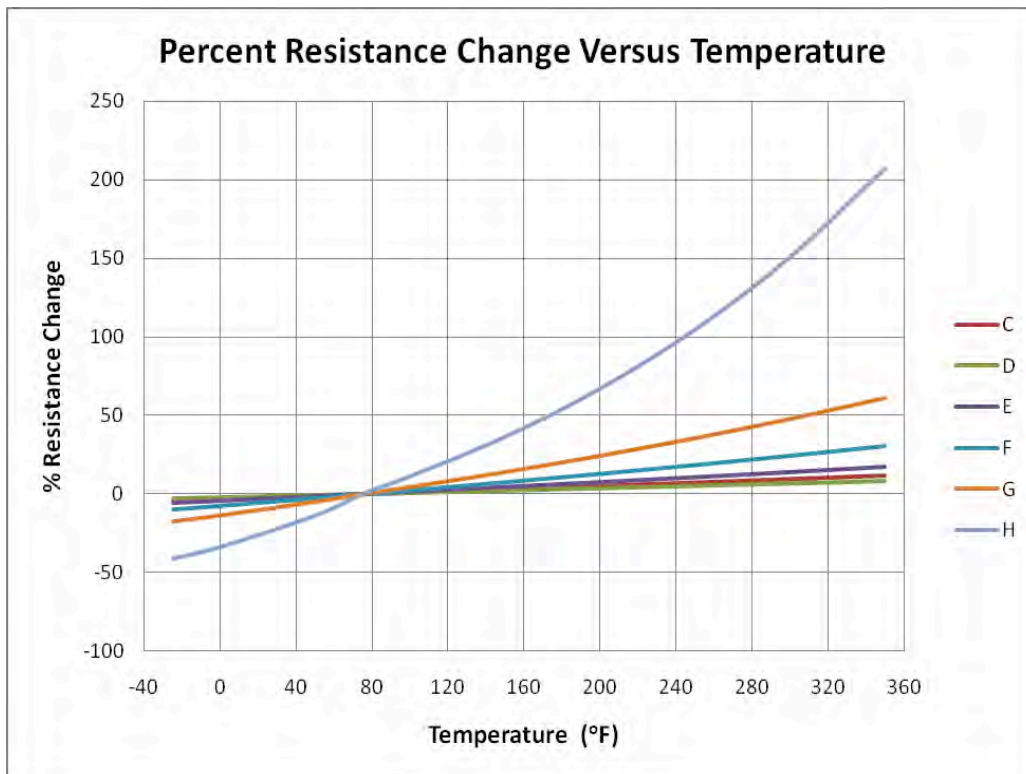


Figure 3

Reduction in temperature coefficient of resistance (TCR). The temperature coefficient of resistance may be reduced from 50%/100°F to about 2%/100°F. The decrease of temperature coefficient of resistance with decreasing resistivity is illustrated in Figure (3).

Reduction in temperature coefficient of gage factor (TCGF). The temperature coefficient of gage factor may be decreased from -23%/100°F to -6%/100°F by decreasing resistivity.

Reduction in radiation sensitivity. Along with reducing resistivity, increased impurity concentrations markedly reduce radiation's effect on resistivity, gage factor, and temperature characteristics. Piezoresistive strain gages are majority carrier devices without depletion layer isolation, which also reduces the sensitivity to radiation.

Increase in operating temperature range. In general, the lower the resistivity, the greater the operating temperature range. Gages with impurity concentrations greater than 2×10^{19} impurities/cm³ are suitable for cryogenic applications.



Strain Gage Fabrication Area

Gage Output

$$(6) \quad \text{Voltage out} = \frac{(\text{Voltage in}) \times (GF) \times (\text{Total Strain})}{4}$$

Equation (6) relates the output voltage of a 4 arm Wheatstone bridge circuit to input voltage, strain and the gage factor of the semiconductor gages. Total strain is the arithmetic sum of strain magnitudes in all four arms of a Wheatstone bridge assuming tension and compression in adjacent arms of a four gage bridge.

TCR

Temperature Coefficient of Resistance (TCR) describes the electrical resistance change of the gage with temperature. TCR, is defined by equation (7).

$$(7) \quad \frac{\Delta R}{R} = TCR \cdot \Delta T$$

where R is Resistance and T is temperature. The difference between the temperature (T) and a reference temperature (T_0) is ΔT TCR is given in %/100°F.

TCGF

Temperature Coefficient of Gage Factor (TCGF) describes the change in gage factor for the gage with temperature. This characteristic is described by TCGF, or Temperature Coefficient of Gage Factor. TCGF is given in %/100°F. ΔGF is the temperature induced gage factor change. Analogous to TCR, TCGF is defined by equation (8).

$$(8) \quad \frac{\Delta GF}{GF} = TCGF \cdot \Delta T$$

Apparent Strain

The coefficient of linear thermal expansion of Kulite gages is low. Therefore, the differential thermal expansion caused by most of the materials to which the gages are bonded causes a thermal strain to be exerted on the gage. This thermal strain when added to the resistance change of the gage with temperature results in an “apparent strain” output of the gage. To eliminate this erroneous signal see Section VII on compensation techniques for null and null shift.

Bonded Resistance

The same phenomenon that causes “apparent strain”, the mis-match of strain gage to specimen temperature coefficient of expansion, gives rise to bonded resistance. Bonded resistance is resistance of the bonded strain gage, which may be different from the unbonded strain gage resistance value. If elevated temperatures are used during the bonding process, the gage will adhere to the specimen at a point in time where both are expanded. When cooling takes place, the specimen will shrink a different amount than the strain gage inducing a resistance change in the gage. This effect can be compensated out using techniques detailed in Section VII under null and null shift compensation.

Linearity

Although no strain gage is perfectly linear, results with Kulite Semiconductor gages meet or exceed the best obtained with conventional metal gages. Linearity is typically stated as the maximum percentage deviation from least squares best fit over ± 500 microstrain.

When measuring 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. The effect of circuitry on linearity will be discussed in the Strain Gage Usage- Basic Circuitry Section. Relative resistance change is a function of strain and is illustrated in Figure (2). Single element linearities are shown on the Kulite Semiconductor Strain Gage Information/Selection Table. To achieve optimum linearity, the following advice should be borne in mind:

1. The lower the resistivity, the better the linearity. Higher resistivities are somewhat more non-linear.
2. Gages are very linear in tension, so for example in a one quarter Wheatstone bridge the gage should sense strain in tension for best linearity.
3. Non-linearity increases with increasing strain. For example, a 4 arm Wheatstone bridge will be more linear than a 2 arm (half bridge) Wheatstone bridge at the same output level, because the 4 arm Wheatstone bridge gages have half the strain when compared to the 2 arm Wheatstone bridge.
4. When two gages are used, one in tension and one in compression in adjacent arms of a Wheatstone bridge, the non-linear terms tend to cancel out because they increase the resistance by the same amount while the linear terms are of opposite signs and therefore add.

Hysteresis

Theoretically, mono-crystalline silicon is a perfectly elastic material with no plastic region up to and above 1,200°F(600°C) at strain levels below 3000 μ strain. Thus, any hysteresis in a strain gage installation is generally a function of the bonding material, or hysteresis in the stressed structure. Transducers using Kulite gages regularly exhibit hysteresis of less than 0.05%



Strain Gage Fabrication Area

Maximum Strain Range

Quality assurance tests are performed to ensure that all Kulite gages can be subjected to a tensile strain in excess of 3000 microstrain. Every lot of gages is statistically sampled and destructively tested to assure quality control of ultimate strain. Most gages can actually be used for measurement of strain to 5000 microstrain in tension and even higher in compression. Encapsulated gages can be applied to radii as low as 1/4" and bare gages can be applied to radii as low as 1/20" with little loss in useful strain measurement range.

Fatigue Life

Data indicates that silicon semiconductor strain gages exhibit significantly better fatigue life than conventional metallic gages. Tests on standard semiconductor strain gages in excess of 10,000,000 cycles have been performed with no failure, at strains on the order of ± 500 microstrain.

Frequency Response

For all practical purposes, piezoresistive devices have no inherent limitation on frequency response. The theoretical limitation for 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 relation between the gage length and the wave length of the propagated wave. In general, the shorter the gage length, the higher the frequency response of the gage will be. The Strain Gage Characteristics and Selection table in Section III lists characteristics of standard Kulite strain gages.

Advantages of Semiconductor Strain Gages Over Metal Foil Gages

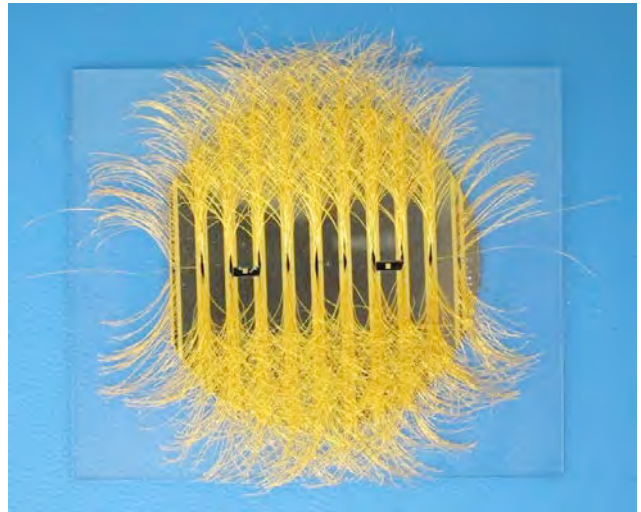
Please see article AN-100 "Selecting Strain Gages: Silicon vs. Metal Foil" for a discussion on the benefits of silicon semiconductor strain gages. It can be found in Appendix A at the end of this manual. Also, it is available for download from our website www.kulite.com.

Strain Gage Selection

One of the best aids in deciding which gage to use, and how to use it, is to carefully reference Kulite's Strain Gage Selection section of this manual. The Strain Gage Selection Section of this manual describes in detail the selection process. An illustrated chart along with a code for each strain gage characteristic follows. An example of how to order a particular type of gage is included. Kindly contact Kulite with any further questions.



***Strain Gage Lead Attachment
(In Process)***



***Strain Gage Lead Attachment
(Complete)***

Section III

STRAIN GAGE SELECTION

This section provides information to utilize the Kulite strain gage identification code, used when ordering Kulite strain gages, and the strain gage characteristics and selection table.

STRAIN GAGE IDENTIFICATION AND ORDERING

(Example)

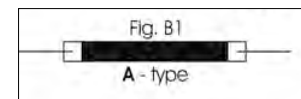
ACP - 120 - 300

Gage Construction	Gage Resistivity	Gage Factor Polarity	Gage Resistance	Gage Length
A – Bare straight gage Welded axial leads Figure B1	C D E F G H (Controlled by dopant level)	P – Positive	In ohms at 75°F A gage ± 10% nom U gage ± 10% nom S gage ± 20% nom A set ± 2% match U set ± 2% match S set ± 4% match	In thousandths of inch within ±5%
A	C	P	120	300

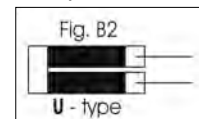
Gage Construction

The first letter designates mechanical construction of the gage, and there are currently the following types:

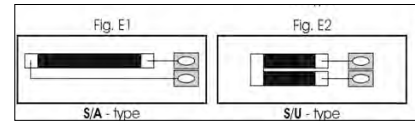
1. The “A” type is a straight, bare silicon gage with welded gold alloy leads for higher temperature operation. The leads for an “A” type gage are oriented axially to the gage. Bare gages ensure the most intimate contact of the gage to the bonded surface, but do require some experience in handling and bonding. (See Figure B1)(i.e. ,The “A” in P/N ACP-120-300)



2. The “U” type designates a compact length bare 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. This gage is also supplied with welded gold alloy leads. (See Figure B2)



3. The “S” type is a ruggedized (encapsulated) gage construction with solder tab terminals incorporated into the epoxy/glass matrix. External wires are optional and may be attached or removed with conventional soldering techniques. Encapsulated gages can be either “A” or “U” type gages. Encapsulated “S” type gages are abbreviated as “S/A” or “S/U” depending upon the shape. Solder tabs can withstand solder temperatures of up to 450°F. (See Figures E1 and E2)



For all gages supplied with electrical leads, such as A and U type gages, Kulite guarantees a minimum 0.5" lead length with the typical length being 0.625". Kulite can provide specialized lead lengths to meet customer needs. For information on this contact Kulite.

Gage Resistivity

The second letter in the gage code designates resistivity (doping level) of the semiconductor. These characteristics are abbreviated by the alpha code designation – C,D,E,F,G or H. (i.e., The “C” in P/N ACP-120-300). Resistivity is inversely proportional to the concentration of electrically active impurities in the semiconductor material, and is the single characteristic which most completely describes the piezoresistive properties. For details see Section II. Semiconductor materials used for manufacturing strain gages range in resistivity from 0.0005 ohm-cm to 1 ohm-cm. Note that there are six resistivity levels listed in the Strain Gage Characteristics and Selection Table at the end of this section. Each resistivity level is designated by a gage doping code (C through H), and within each gage doping code there is a whole family of gage configurations listed. The prime performance characteristics of interest for each resistivity level are listed – GF, TCR, TCGF, and linearity.

Generally customers will use strain gages in sets of four that are bonded in a four-active arm Wheatstone bridge to the specimen that is to be strain monitored. Therefore, Kulite supplies our standard catalog strain gages in matched sets of four specifically for this purpose. All Kulite gages that are sold in sets are tested at the factory and matched together by their resistance value. This resistance matching permits better Wheatstone bridge output performance with respect to linearity, output characteristics, and thermal compensation. Custom matching criteria can be specially ordered from Kulite and single unmatched gages may also be available.

Gage Factor Polarity

The third letter in the gage code designates the characteristic of gage factor polarity. All Kulite gages are positive polarity. The polarity is achieved by doping the semiconductor with an acceptor impurity. For the P type crystal, the crystallographic axis of maximum strain sensitivity is along the <111> direction. P type gages are extremely stable and exhibit low TCGF, TCR's and good linearity. The letter “P” is used exclusively to represent the positive polarity. (i.e., The “P” in P/N ACP-120-300 will indicate positive polarity gage).

Gage Resistance (Geometry/Resistivity)

The central group of digits in the gage designation specifies nominal gage resistance in ohms. Gages are available in a wide range of resistances and sizes. Resistance values range from 15 ohms to 10,000 ohms and active gage lengths vary from .010" to .250"(10 mils to 250 mils). A gage's resistance is determined not only by its length and cross section, but also by its resistivity. When designing a strain gage for a specific resistance or size there is a wide latitude in gage geometries possible, because gage resistivity can vary over several orders of magnitude. When choosing a gage for a specific application, one technique is to select the appropriate gage doping code needed based on gage factor and temperature characteristics from the Strain Gage Characteristics and Selection table located at the end of this section, then selecting the specific gage from this group based on size, length, resistance, and gage shape. The number following the first dash of the part number is the gage resistance value. (i.e. , The "120" in P/N ACP-**120**-300 will indicate a 120Ω gage.)

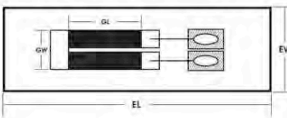
Gage Length

The last group of digits defines the overall physical length (not electrically active length) of the semiconductor sensor exclusive of lead wires in thousands of an inch. Kulite standard gages range in length from .060 (thousands of an inch) to .250 (thousands of an inch). Custom sizes are available through special order. The Strain Gage Identification and Ordering Table should be used in conjunction with the Strain Gage Characteristics and Selection Table to select, compare and confirm the specifications of each gage for specific applications. The last section of the part number will always be a three digit code to illustrate the size in thousands of an inch. For example, 090 will indicate 90 mils (0.090 inches) or for our sample, the "300" in P/N ACP-120-**300** will indicate 300 mils length gage.

The gages listed on this page represent our standard catalog of general purpose gages. Kulite also offers custom strain gage design and manufacturing for special applications. Please contact Kulite for details on custom sizes, resistance, performance characteristics, or any special gage requirements for your application including gaging services available at Kulite.

STRAIN GAGE CHARACTERISTICS AND SELECTION TABLE

GAGE DOPING CODE	GAGE CHARACTERISTICS	PART NUMBER	FIGURE	EFFECTIVE LENGTH (GL)	GAGE WIDTH (GW)	ENCAPSULATION	
						LENGTH ±10% (EL)	WIDTH ±10% (EW)
C	GF + 100	ACP - 15 - 150	B1	.100	.020		
	TCR + 4	ACP - 30 - 150	B1	.100	.010		
	TCGF - 6	ACP - 120 - 300	B1	.250	.009		
	Linearity ± 0.2	UCP - 120 - 090	B2	.060	.020		
		S/ACP - 120 - 300	E1	.250	.009	.500	.210
S/UCP - 120 - 090	E2	.060	.020	.280	.140		
D	GF + 115	ADP - 250 - 220	B1	.186	.09		
	TCR + 3	ADP - 350 - 300	B1	.250	.010		
	TCGF - 8	UDP - 350 - 175	B2	.140	.016		
	Linearity ± 0.2	S/ADP - 350 - 300	E1	.250	.010	.500	.210
		S/UDP - 350 - 175	E2	.140	.020	.350	.140
E	GF + 130	UEP - 350 - 090	B2	.060	.020		
	TCR + 6	AEP - 350 - 220	B1	.170	.009		
	TCGF - 10	AEP - 500 - 300	B1	.250	.010		
		UEP - 350 - 060	B2	.030	.020		
	Linearity ± 0.2	S/AEP - 500 - 300	E1	.250	.010	.500	.210
S/UEP - 350 - 090	E2	.060	.020	.280	.140		
F	GF + 140	AFP - 500 - 090	B1	.060	.010		
	TCR + 10	AFP - 350 - 090	B1	.060	.010		
	TCGF - 11	UFP - 750 - 090	B2	.060	.020		
		S/AFP - 500 - 090	E1	.060	.010	.280	.140
	Linearity ± 0.2	S/UFP - 750 - 090	E2	.060	.020	.280	.140
G	GF + 155	AGP - 350 - 090	B1	.060	.010		
	TCR + 18	AGP - 500 - 090	B1	.060	.010		
		AGP - 1000 - 300	B1	.250	.010		
	TCGF - 13	UGP - 1000 - 090	B2	.065	.020		
		UGP - 1000 - 060	B2	.030	.020		
Linearity ± 0.2	S/AGP - 1000 - 300	E1	.250	.010	.500	.210	
S/UGP - 1000 - 090	E2	.060	.020	.280	.140		
H	GF + 175	AHP - 10000 - 220	B1	.170	.009		
	TCR + 45	AHP - 10000 - 300	B1	.250	.009		
		UHP - 5000 - 060	B2	.030	.020		
	TCGF - 23	S/AHP - 10000 - 220	E1	.170	.009	.250	.150
		S/AHP - 10000 - 300	E1	.250	.009	.500	.210
Linearity ± 0.2	S/UHP - 5000 - 060	E2	.030	.020	.250	.140	

Gage Types		Gage Geometry	
Fig. B1 A - type	Fig. B2 U - type		
Fig. E1 S/A - type	Fig. E2 S/U - type		

Actual GF value is within ± 5% of the specified value at 75°F. GF is a unitless quantity. TCR and TCGF is given in %/100°F and referenced from 75°F. Linearity is maximum percentage deviation from best fit curve over ± 500 microstrain.

Section IV

STRAIN GAGE APPLICATION NOTES

Introduction

Semiconductor strain gages are passive devices which do not generate any voltage or current when stressed. Only their resistance changes with strain. To get useful signals from them to drive instruments such as oscilloscopes, galvanometers, oscillographs, meters, and servo instruments, they must be coupled with other circuit elements and a power source. The choice of circuit configuration depends on the application, the types of strain gages selected, and the type of readout instrument used. The most common technique is to use four gages to form a Wheatstone bridge circuit, which provides a voltage output sensitive to strain.

Figure (4) shows a four active arm Wheatstone bridge circuit where R_1 through R_4 are strain gages. For this bridge to function correctly R_2 and R_4 need to be stressed in tension, and R_1 and R_3 stressed in compression or vice-versa.

When creating the testing apparatus and procedure, it is important to remember that good engineering design dictates the use of generous safety margins.

Strain Gage Construction

Data in this section describes the construction, lead configuration, and dimensions of Kulite's product line of standard strain gages. There are two basic strain gage types: the bare gages, including the "A", and "U" series, which consist of the strain sensitive semiconductor element and its leads, and the encapsulated "S"-type gages with solder tabs, in which the strain sensitive element is encapsulated between layers of epoxy-impregnated glass paper. The bare gages offer the user smaller size, lower costs, and more uniform strain transmission, while encapsulated gages are recommended for general use where ruggedness, ease of handling, built-in electrical isolation, and ease of wiring are important. Finally, an "A" gage is a single straight gage and a "U" gage has two straight gages forming the arms of a U for maximum resistance in minimum space.

Encapsulated gages, like conventional backed foil gages, are relatively easy to handle, but must be clamped or weighted during the cement curing cycle. Clamping of bare gages is not necessary, except when mounting on a curved surface. Because of the fragility of a bare gage, however, more care and experience in bonding is generally required. Experienced personnel at Kulite Semiconductor Products, Inc., welcome the opportunity to advise the user on how to overcome any installation challenges which may be encountered during their gaging activities.

Electrical Lead Length

For all gages supplied with electrical leads, such as A, and U type gages, Kulite guarantees a minimum 0.5" lead length with the typical length being 0.625". Kulite can provide specialized lead lengths for custom orders. For custom orders or any additional information please contact Kulite.

Strain Limits

Maximum strain capability is determined primarily by the gage thickness, the perfection of the semiconductor crystal lattice, the gage surface finish and the elastic modulus of the semiconductor crystal. Kulite gages are guaranteed to strain levels of 3500 microstrain in tension. Many will operate to strains as high as 5000 microstrain in tension 7000 microstrain in compression. The precompression due to cementing at elevated curing temperatures on materials with high thermal expansion coefficients (see Bonded Resistance) necessarily limits the compression range but can in some cases can be used to advantage by increasing the range of applied tension. The gage factors stated on each package are those for a strain of 500 microstrain in tension.

Radius of Curvature

Although flat bonding surfaces generate the best results, encapsulated gages can conservatively be bonded to curved surfaces of as low as ¼" radius, while bare gages can be applied to radii as low as 1/20" with little loss in useful strain range.

Maximum Operational Temperature

The maximum operational temperature for Kulite gages to function properly is determined primarily by the following criteria: The gage type, the type of epoxy used, the insulation material, and the type of solder used. The gage type, either encapsulated or bare, has the most direct effect on the maximum operational temperature. For encapsulated gages, types S/A or S/U, the maximum operational temperature is limited by the encapsulation material to a temperature of 240°F (121°C). Bare gages, types A or U, do not suffer from this limitation and can achieve a maximum operational temperature of 600°F (315°C). The cement or epoxy used to affix the gage, the insulation material, if used, and the solder type can all effect the maximum operational temperature.

Power Dissipation – Self Heating

Maximum current level to be used through the gages is governed by the amount of self-heating allowable. This is known as i^2R heating. Higher gage resistance increases the heat input for a given current, and therefore increases self-heating. The acceptable self-heating level is higher if time is allowed for thermal stabilization, as measurement accuracy is reduced, or if a lower temperature coefficient gage is used. Because of all these variables it is difficult to define a maximum current. As a rough guide, gages longer than about .150 inches, well bonded to a large heat sink, can sustain power dissipation levels of 20 to 50 milliwatts with acceptable zero stability and levels as high as 100 milliwatts

without damage if good zero stability is not required. These figures should be derated by about 50% for shorter gages.

It is best for any application to determine the maximum current under the specific conditions of test or else to use a rather conservative figure; the high gage factor of Kulite gages certainly reduces the need for a high current. To avoid self-heating of unmounted, low-resistance gages when measuring them with a bench model DC Wheatstone bridge instrument, it is advisable to replace the internal 4.5 volt source with a 1.5 volt external battery. A thin cement line, high thermal conductivity cement, and bonding the gage to high thermal conductivity material increases heat dissipation and allows higher currents for the same self-heating.

Bonded Resistance

The linear thermal expansion coefficients of silicon semiconductor gages are low compared with most other materials. The differential expansion, between a gage and the substrate to which it is bonded, upon cooling from an elevated curing temperature to room temperature, will put the gage in a state of compression. For a "P" type gage the resistance will decrease relative to the unbonded state. For example, an AEP-500-300 gage ($GF = +130$, $R_{G0} = 500$ ohms, $C_s = 1.7 \times 10^{-6}/^{\circ}F$) epoxy bonded on stainless steel ($C_m = 9.6 \times 10^{-6}/^{\circ}F$) and cured at $350^{\circ}F$ will experience a compression upon cooling of 2212 microstrain which reduces its resistance by 144 ohms. This precompression effect is minimized by curing at temperatures just above the operating range. Recording the gage resistance at each step in the installation process can be valuable in determining final bond quality. When several gages are installed in a bridge configuration, care should be taken to ensure that all the gages are bonded with identical shrinkage. A thick epoxy layer has also been shown to cause the bonded resistance effect. A strain gage bonded using a thick layer of 8121 epoxy, and then cured at $300^{\circ}F$, can display 1000 microstrain in compression at room temperature. The expression for bonded resistance is found in the static measurement section of the "Strain Gage Usage - Basic Circuitry Section".

Apparent Strain

The gage resistance of a bonded gage changes with temperature from two principal causes: the inherent positive temperature coefficient of resistivity of the semiconductor and the differential thermal expansion between semiconductor and substrate. This apparent strain occurs independently of any applied mechanical strain and must be minimized or taken into account for accurate static measurements. Thick epoxy layers and encapsulating the gage in epoxy can cause apparent strain effects by themselves.

The expression for apparent strain is found in the static measurement of the section of the "Strain Gage Usage - Basic Circuitry".

One method for cancelling most of this "apparent strain" is by the use of a dummy gage (an identical gage held at the same temperature which does not undergo strain) in a half bridge configured

Wheatstone bridge, which is the same method currently employed with metal gages. Refer to section VII for other compensation techniques. Please contact Kulite with any questions or concerns.

Null and Sensitivity Compensation

The effect of thermal strains on the null output of Wheatstone bridge circuits formed from semiconductor gages can be minimized with the proper circuitry technique. Temperature induced resistance changes of adjacent arms of a bridge tend to cancel, but perfect compensation is rarely achieved due to inherent variations between matched gages themselves and the manner in which they are mounted (See Bonded Resistance Section). The effective TCR of a gage as a bridge element (see Equivalent Circuit Resistance and TCR) can be reduced to any desired value by choosing an appropriate shunt and/or series resistor of zero TCR. The use of “dummy-active” gage pairs as adjacent bridge elements is another common technique for temperature compensation. One simple trimming technique for improving the zero shift or no-load temperature compensation utilizes an experimentally determined shunt resistor across the gage with the higher TCR, and then a series resistor can then be found which corrects for the change in resistance introduced by the shunt.

For a full discussion of compensation techniques please see Section VII.

Strain Gage Resistance Matching

To achieve the best output signal from a Wheatstone bridge identical strain gages are needed. The most critical electrical parameter is the gage resistance. Mis-matched gages will give rise to zero strain output signals and non-linearity of the output signals. All gage sets sold by Kulite are resistance matched at the factory for the convenience of the customer.

The Effect of Noise on Resolution and Accuracy in Kulite Semiconductor Strain Gages

Noise is a limiting factor on the resolution and accuracy of all electromechanical measurements. There are many different types of noise phenomena common to both semiconductor and foil strain gages, such as, “white noise” which is characterized as wide-band higher frequency stochastic noise, $1/f$ or “flicker noise” which is generally low frequency noise as the name implies, and “popcorn noise” which is comprised of high amplitude short duration spikes. For simplicity sake we can distill this down to a noise “floor” level inherent to the two different technologies. For a filtered signal of $< 1000\text{Hz}$ Kulite semiconductor strain gages display a RMS Noise floor of 0.04 microstrain whereas foil gages are on the order of 1.5 to 2 microstrain. Considering the rule of thumb of a 10 to 1 signal to noise ratio for an accurate measurement a Kulite Semiconductor strain gage can achieve a resolution of 0.4 microstrain, as compared to a foil gage’s resolution of 15 to 20 microstrain. Generally with good electrical connections and twisted wiring a noise floor level of $10^{-6} (\text{Microstrain})^2/\text{Hz}$ is achievable across a wide frequency band for Kulite strain gages.

Section V

STRAIN GAGE INSTALLATION NOTES

Packaging

All Kulite gages are packaged in plastic tubes and are then placed into custom designed protective packaging insulated by use of packing foam or Styrofoam and cardboard. Bare (unbacked) gages are very fragile and must be handled gingerly. While encapsulated gages are more rugged than bare gages, they are still somewhat fragile and must be handled with care as well.

Use caution when removing the gages from their packaging. It is recommended to remove the gages from the tubes by first removing the plugs from their plastic tubes and gently shaking the gages out over a clean piece of paper. Do not pull the gage out by its leads if it appears that the gage is snagged inside. NEVER touch the crystal element. Once the gages are unpacked, they may be handled with blunt tweezers by the leads only.

KULITE SEMICONDUCTOR PRODUCTS, INC. One Willow Tree Road, Leonia, New Jersey 07605 Tel: 201 461-0900	
THIS PACKAGE CONTAINS SEMICONDUCTOR STRAIN GAGES	
CAUTION!	
Unbacked gages are very fragile. Never remove gages from tubes using tweezers or touch the crystal element.	
TYPE	
LOT No.	
GAGE FACTOR	± @75°F
RESISTANCE	± Ohms

Standard Label

Strain Gage Installation Instructions

Appendix B provides a step by step procedure for mounting a strain gage onto a sample for testing or monitoring. This is a general procedure to familiarize the customer with the materials and techniques necessary to mount a semiconductor strain gage. Generally, if a supplier provides specific instruction for the use of their products, i.e. epoxy vendor, those instructions take precedence over any information provided in Appendix B. Please contact the factory with any questions or concerns.

Surface Preparation

The area under the gage, whether it is flat or curved, must have a surface smoothness to avoid breaking the gage during installation. Any loose scale or rust should be removed from metal surfaces prior to bonding. If the surface is excessively rough, smooth it, or if it is highly polished, roughen it with 240 grit emery paper to enhance cement/epoxy adherence. The final scratches should be perpendicular to the strain direction adherence. A lightly sandblasted surface generally provides an excellent bonding surface to metals, especially those which form oxide films. Porous or pitted surfaces should be first coated with a thin layer of filler epoxy (e.g. Epoxylite 8121) then cured, and then sanded before cementing the gage in place.

Cleaning

Cleaning of the specimen area before bonding is extremely important. The surface must be meticulously free of grease, oil, or wax. A grease or oil solvent such as toluol should be used first, followed by MEK, acetone or trichloroethylene. For verification that a surface is sufficiently cleaned, a fresh white swab drawn across the cleaned area should show no trace of debris or staining. Follow all manufacturer's instructions and warnings while using solvents. All wiping actions must be in one direction using a single slow stroke and not a back-and-forth motion. It is recommended that the surface be blown dry using nitrogen so that the contaminants will not redeposit upon the just cleaned surface. The cleaned surface should be gaged within 15 minutes of cleaning. Do not touch the cleaned surface with fingers as new oils may be deposited upon the area.

Cement/Epoxy

Kulite Semiconductor gages are installed in much the same fashion as conventional strain gages—by epoxying them to the surface of a body whose strain is to be sensed. We recommend epoxy cements such as Epoxylite premixed 8121. This epoxy works well with Kulite gages for the majority of applications and sensing environments. Cements containing solvents, such as Duco Household Cement or Baldwin SR-4 Cement, should not be used to bond encapsulated gages since the impervious glass matrix will not readily allow solvents to escape, making curing cycles difficult.

The choice of bonding cement is dictated primarily by the operating temperature of the installation. Epoxy cements are available with cures ranging from 24 hours at room temperature to less than 1 hour at 350°F. The ultimate temperature and life of any organic cement is limited by oxidation and sublimation effects. Short term tests, especially for dynamic strain measurements, have been performed successfully at temperatures as high as 600°F and as low as -450°F. Instructions supplied by the manufacturer for mixing the cement ingredients and selecting the time-temperature curing cycle should be closely followed.

It should be noted that a thick epoxy layer can cause bonded resistance and apparent strain effects. Encapsulating the gage in epoxy and thick epoxy coats should be avoided due to these undesirable effects.

Insulation

Encapsulated gages are electrically insulated by the supporting epoxy-glass matrix and may be bonded directly to a metallic surface. For electrical insulation of bare gages, there are two commonly used techniques. Select the method best suited to your application.

- a) Precoat the specimen surface with the same cement which will be used to bond the gage. The precoat should be made as thin as possible (.001 inches or less). Heating the specimen surface to temperatures of about 130°F will facilitate the thinning of some epoxies. The next step is a partial cure of the precoat. The final step is the application of a fresh epoxy layer over the

precoat to bond the gage to the specimen. This technique causes the partially cured precoat to redissolve, enhancing the bond between the gage and the specimen.

- b) “Float” the gage on top of a thin layer of wet epoxy cement. Generally, the surface tension of epoxies will prevent the gage from grounding to the specimen. This method gives the best results but requires the most care.

Trimming

Encapsulated gages may be trimmed to somewhat smaller size if necessary. Trimming must be done with care to avoid nicking the leads or breaking the element. The closer the gage is trimmed, the more carefully it must be handled, although trimming does not affect its ability to sense strain correctly. On special order Kulite will provide smaller gages as well as gages of different lead configurations. Only highly experienced users should attempt to trim gages. Please contact Kulite prior to attempting a trimming operation.

Extension Leads

Extension leads, if desired, may be welded or soldered by conventional techniques after curing. The extension wires must first be securely anchored or cemented near the gage to prevent a damaging pull on the gage leads. They should be as heavy as practical—preferably not lighter than #18 wire gage if long runs are involved. Note that 0.6 ohms of lead resistance connected to a 120-ohm gage reduces output by 0.5%, so good electrical contact is important.

To solder a new wire to the contact pad, first tin the edge of the wire, then apply the soldering iron to the wire until the solder on the wire and the gage flow together. The same technique is used for encapsulated gages having pretinned solder tab terminals.

The gold plated pads of most “A” and “U” type gages are easily soldered with conventional tin-lead solders. Equivalent lead free solder may also be used. Adjust the tip temperature of a small soldering iron to a value just above the gold-tin eutectic temperature of 535°F. Apply the iron to the pretinned extension wire in contact with the gold plated lead until the solder melts and flows. Remove the iron as quickly as possible to avoid overheating.

CAUTION: Do not tug on lead wires to test solder joints, this may damage the gage.

Silver, copper, or nickel ribbon or wire extensions may be welded to gold plated leads by either capacitor discharge or resistive welding. Welding energies depend on extension lead size. A typical welding energy level is 0.5 watt-second.

Bonding - Bare Gages

Coat the precoated specimen area with a thin layer of the cement to be used. Smooth it out carefully and examine to be sure there are no lumps, bubbles, or voids in the cement.

Grasp one gage lead with tweezers. Never hold or pull on both leads at one time. Drop the gage in the wet cement and position by pulling one lead wire slowly. After the gage is in the desired location and it has been ascertained that it is flat and right side up (leads on top of crystal), cure the cement. Do not apply pressure to the gage during cure.

The high level of surface tension found in some cement, and the increasing viscosity of rapidly drying cements may cause difficulty when trying to position the gage during the mounting process. In these cases it may be necessary to position the gage in the wet cement by pushing gently on its edge with a sharp soft plastic or wooden applicator instead of by pulling on the leads.

When bonding a bare gage to a convex curved surface, Teflon tape can be used to clamp the gage.

Bonding - Encapsulated Gages

Spread a thin (.001" or less), even layer of cement over the area to be gaged and also the back side of the gage. Gently, press the gage down into the cement, being careful not to form air bubbles. Since the matrix is translucent, bubbles can be seen if they do develop and they can be pressed out to the edges with a soft plastic or wooden applicator. The gage can be repositioned somewhat at this time although excessive movement may create new bubbles or leave insufficient cement under the gage.

Use a weight or light spring clamp to provide about 5 to 10 psi pressure over the gage during cure. A Neoprene rubber pressure pad about 1/16 inch thick is recommended for uniform pressure distribution. Do not use "C" clamps. Teflon may be placed under the leads to prevent them from being cemented down or covered with cement. If the block applying pressure is small, it may be sufficient to bend the leads up out of the way. If the leads do become cemented down, they can be easily peeled out of the cement after curing by starting at the outer end and pulling straight up. Any remaining cement should be cleaned from the area of the joint with a razor blade before soldering or welding.

A second piece of Teflon should be used between the block applying pressure and the gage to prevent the block from being cemented down. It is sometimes advisable to use pressure sensitive tape to secure the Teflon and prevent movement of the gage with application of pressure. Care should be taken to apply the cementing pressure normal to the surface to which the strain gage is mounted or the gage may slip during the curing cycle.

Moisture Protection

Semiconductor gages are generally less sensitive to humid environmental conditions than conventional wire or foil gages because of their larger signal-to-noise ratio. For applications where moisture induced drift is a problem or very small strains are to be measured, waterproofing of the gages and their exposed leads is strongly advised. Protective coatings such as microcrystalline wax, neoprene, or glyptal varnish are all usable, depending upon the degree of exposure. This is ordinarily applied in the form of several thin coats heated to 150°F in a humidity chamber according to the manufacturer's instructions.

Section VI

STRAIN GAGE USAGE- BASIC CIRCUITRY

Wheatstone Bridge

The most popular circuit for use with all types of strain gages is the Wheatstone bridge. Bridge circuits can be made by using from 1 to 4 strain gages, at least one of which is active (it changes resistance with strain). The main benefit of the bridge circuit is that it converts the strain-induced resistance change of the gage into a voltage change which can then be measured more directly and accurately with conventional instruments.

The Wheatstone bridge is normally energized by applying a regulated voltage across two opposite corners. A voltage output proportional to the product of the excitation voltage and the resistance changes of the strain gages appears across the signal terminals. For conventional wire and foil gages, the signal level is measured in terms of millivolts; semiconductor strain gages can produce signals of up to a volt or even higher.

The sensitivity of a constant voltage strain gage bridge circuit is generally discussed in terms of the ratio of the change of signal voltage to the excitation voltage for some fixed strain value.

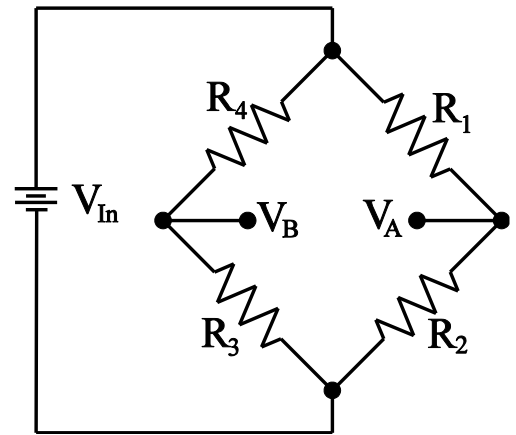


Figure 4

For a four-arm bridge, as shown in Figure (4) where R_1 , R_2 , R_3 , and R_4 are strain gages, the output equation is shown by equation (9).

$$(9) \quad \frac{\Delta V_{Out}}{V_{In}} = \frac{\Delta V_A - \Delta V_B}{V_{in}} = \frac{R_2 + \Delta R_2}{R_1 + \Delta R_1 + R_2 + \Delta R_2} - \frac{R_3 + \Delta R_3}{R_3 + \Delta R_3 + R_4 + \Delta R_4} - \left[\frac{R_2}{R_1 + R_2} - \frac{R_3}{R_3 + R_4} \right]$$

Good circuitry design dictates that whenever possible the two adjacent arms of the bridge should change equally but in opposite directions under strain. This will eliminate temperature induced changes from the output voltage. This condition is achieved, for example, in the special case of a cantilever beam where R_1 and R_3 , the tension gages and R_2 and R_4 the compression gages are equal. Equation (10) represents the formula for this special case.

$$(10) \quad \frac{V_{Out}}{V_{In}} = \frac{V_A - V_B}{V_{In}} = \frac{\Delta R}{R} = \varepsilon \cdot GF$$

Thus, the bridge output voltage is linear with applied strain for any gage which exhibits a characteristic of $\Delta R / R_0$.vs. $\varepsilon = \text{constant}$.

In some cases, it may be advantageous to use a constant current source to power the Wheatstone bridge, such as when the objective is to obtain temperature compensation for output sensitivity or when it is necessary to improve linearity with high resistivity gages. With a single gage excited by constant current either with or without a series resistor (see Figure (5)) “circuit non-linearity” is eliminated and the voltage change across the gage is purely a function of the resistance change.

In half-bridge and full-bridge circuits the nonlinearity of the high resistivity gages is such that even if adjacent gages are strained equally and opposite, their resistance changes differ. Thus, the current through them and hence the bridge calibration changes if excited by constant voltage. Improved linearity can be obtained with constant current excitation. Simply put, constant current forces a constant i^2R drop through each resistor, as opposed to constant voltage which does not, which in itself cause the resistor self heating to stay stable at the calibration point.

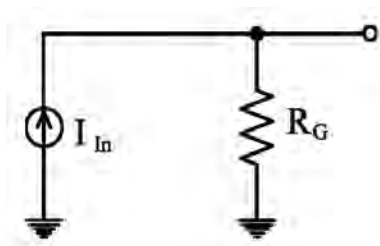


Figure 5
Constant Current Excitation

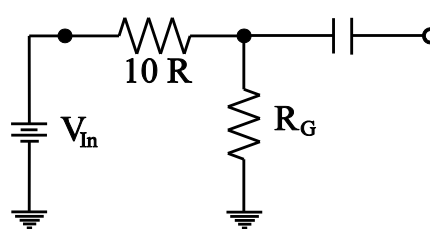


Figure 6
Constant Voltage with Span

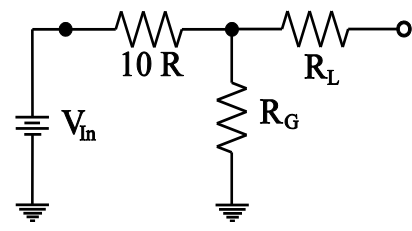


Figure 7
Constant Voltage Excitation
Coupled through a Load Resistor

Dynamic Measurements

For high frequency or fast rise time strain signals physically shorter gages are preferred. Generally the shorter the gage the greater the bandwidth it can pick up.

Circuits for making dynamic strain measurements are the simplest. For these applications, the “apparent strain” is not significant and baseline shifts may be neglected since generally the observer is only concerned with rapidly occurring strain variations. Figures (5), (6) and (7) represent typical circuit configurations used for dynamic measurements.

Figure (5) represents a single strain gage excited by a constant current source. The voltage across the strain gage will then be $I(R + \Delta R)$ and will be a very linear function of strain. Also, the gage sensitivity will not change with temperature for those gage installations which meet the requirements of constant current compensation explained below. Figure (6) represents a single gage excited by constant voltage. A large series dropping resistor is necessary so that resistance changes of the strain gage results in voltage changes across it. The characteristics of this circuit are very similar to those of Figure (5) since it becomes a constant current circuit as the series resistor’s value approaches infinity. The AC voltage component of the strain gage signal is coupled into a readout instrument such as an oscilloscope through a capacitor. A variation of this circuit is shown in Figure (7) where the signal is coupled into the

read-out instrument through a load resistor, R_L . The circuit RC time constant is selected based on the dynamic response desired and the characteristics of the read-out instrument.

Static Measurements

All strain gages, including semiconductor and metal/foil, exhibit two temperature-dependent characteristics: (1) their resistance changes with temperature and (2) their gage factor changes with temperature. These variations are generally larger for semiconductor gages than for metal gages. In addition, the thermal expansion of semiconductor materials used in gage construction is much lower than those of the metals to which the gages are usually bonded. Thus, as the temperature changes from that at which the gages were bonded, the gages are subjected to a thermally induced strain in addition to load-produced strains. This is known as “apparent strain”. Proper circuitry can do much to isolate wanted from unwanted signal effects thus allowing the researcher to obtain accurate measurements.

Apparent Strain is defined as that strain calculated from resistance changes produced by factors other than load-induced strains. Principally, it is the combination of the temperature coefficient of resistivity of the semiconductor plus differential thermal expansion effects. It is given by equation (11).

$$(11) \quad \varepsilon_A = \left[(C_m - C_s) + \frac{TCR}{G_f} \right] (T - T_0)$$

G_f = Gage factor (unitless)

C_m = Coefficient of thermal expansion of material to which gage is bonded (inches/inch/°F)

C_s = Coefficient of thermal expansion of gage (inches/inch/°F)

TCR = Temperature coefficient of resistance (ohms/ohm/°F)

$T - T_0$ = Temperature difference from reference temperature T_0 (°F)

Bonded Resistance is the resistance of the strain gage after being bonded to the specimen. Bonded resistance is caused by the same phenomena as apparent strain, and exists when bonding between the strain gage and specimen takes place at an elevated temperature. Equation (12) gives the change in resistance due to bonding, and Equation (13) gives the strain gage’s bonded resistance value.

$$(12) \quad \Delta R = R_G G_F (C_m - C_s) (T - T_0)$$

$$(13) \quad R_B = R_G - \Delta R$$

R_B = Strain gage resistance value after bonding (Bonded Resistance Value) (ohms)

R_G = Strain gage resistance value before bonding (ohms)

ΔR = Change in gage resistance due to bonding (ohms)

G_F = Gage factor (unitless)

C_m = Coefficient of thermal expansion of material to which gage is bonded (inches/inch/°F)

C_s = Coefficient of thermal expansion of gage (inches/inch/°F)

$T - T_0$ = Temperature difference from reference temperature T_0 (°F)

As an example, take a AGP-1000-300 gage bonded to an aluminum beam. Curing took place at 270°F in an oven. The gage factor of a G gage is 155. From the equation for gage resistance change referenced to 70°F, $\Delta R = 344.1\Omega$ and thus $R_B = 655.9\Omega$ where the unbonded gage was $R_G = 1000\Omega$.

The simplest technique for eliminating apparent strain effects is the Wheatstone bridge circuit. Either two strain gages (Figure 8)(half-bridge) or four (Figure 4)(full bridge) may be used. This technique utilizes the fact that the resistance changes of two gages in adjacent arms of a bridge will subtract if the two gages are subjected to the same temperature, their apparent strain contributions will cancel. Of course, it is necessary that one of the gages be unstrained or both gages be strained in opposite directions to obtain a load-responsive signal.

Due to inherent variations between gages, perfect apparent strain compensation cannot be obtained even when using gages from the same lot. A trimming or matching operation can be performed, when desired, to improve zero or no-load temperature compensation. A simple trim technique utilizes an experimentally selected shunt resistor across the gage with the higher temperature coefficient. The apparent strain compensation techniques described above can be utilized with all Kulite gages. For an in depth discussion of compensation techniques see Section VII.

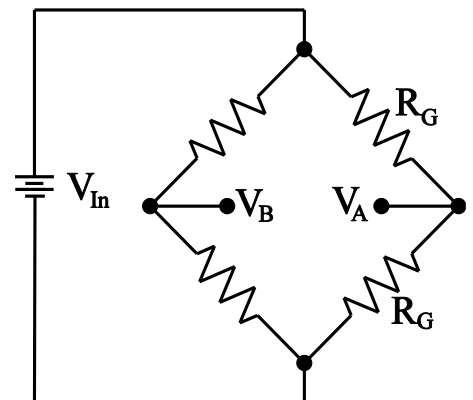


Figure 8
Half Bridge Configuration

Gage Factor Compensation

Kulite offers strain gages with a wide range of gage factor temperature coefficients (TCGF) ranging from -6% for “C” type to -23%/100°F for “H” type. Several different compensation techniques can be employed depending on the characteristics of the gage selected. See Section VII on sensitivity compensation techniques.

Constant Current

Two Gage Factor compensation techniques utilize the temperature coefficient of resistance (TCR) to wholly or partially compensate for the temperature coefficient of Gage Factor. If a strain gage bridge as shown in Figure (4) is composed of gages with a bonded temperature coefficient of resistance $TCR + (C_m - C_s) \times GF$ expressed in %/100°F equal to the TCGF and is excited with constant current, the output voltage will be independent of temperature. This occurs because the bridge excitation voltage will be increasing at the same rate at which the gage factor decreases. This condition is very closely met when type “F” gages are used on NiSpan, Type “C” gages on aluminum, or Type “E” gages on carbon steel.

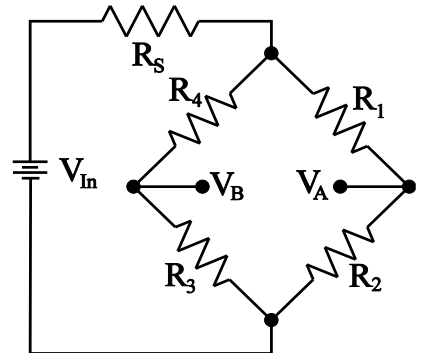


Figure 9
Constant Voltage with Span Resistor

For higher resistivity gages, the use of constant current excitation will produce over compensation, with bridge output increasing with temperature. Gages of this type can be readily compensated by using constant voltage excitation and a series dropping resistor (span resistor) as illustrated in Figure (9). For some particular value of R_s , the bridge excitation voltage can be made to increase at the same rate at which the Gage Factor decreases, thus obtaining temperature compensation. A R_s of approximately 1.5 times nominal gage resistance will produce temperature compensation for Type “G” gages mounted on steel. For all strain gage types see (Section VII) on span compensation and empirical span compensation.

Excitation Voltage

The maximum excitation voltage which can be applied to semiconductor gages is limited by the heat dissipation from the gage to the member to which it is bonded. The heat dissipation is a function of gage size, thickness of glue line, thermal mass of structure, thermal conductivities of cement and structure, and ambient temperature and circulation factors.

For gage lengths from 0.15 to 0.25 inches, power dissipations of from 20 mw to 50 mw will generally provide acceptable stability performance with no damage to the gage. Higher power levels up to about 100 mw can be employed when good zero stability is not required and when the bonding cement is not adversely affected by the gage self heating temperature.

For gage lengths less than .150" one should derate the above figures by about 50%.

Section VII

TEMPERATURE COMPENSATION TECHNIQUES FOR SEMICONDUCTOR STRAIN GAGE SENSORS

Introduction

Semiconductor strain gage characteristics are temperature dependent. In particular, the resistance of an unbonded gage increases with temperature while the strain sensitivity, or gage factor, decreases with temperature. To properly utilize semiconductor gages for accurate measurements of mechanical strain, it is necessary to compensate the gage output signals against undesirable temperature effects. Compensation can generally be accomplished with simple circuit techniques using passive shunt or series resistor elements whose resistance is temperature independent. The object of these application notes is to examine the techniques for compensating strain gage bridges for null and null shift with temperature and adjustment of the bridge excitation voltage to offset the decrease in strain sensitivity. Relations are derived for calculating the values of the compensation resistors from knowledge of the strain gage parameters and the measured effects of temperature on signal output.

The basic piezoresistive effect for a gage of unstrained resistance R and gage factor G in response to some applied strain ε is:

$$(14) \quad \frac{\Delta R}{R} = G\varepsilon$$

The linear temperature dependence of G and R may be written as follows:

$$(15) \quad G_T = G_0(1 + \beta\Delta T)$$

$$(16) \quad R_T = R_0(1 + \alpha_B\Delta T)$$

$$(17) \quad \alpha_B = \alpha + (C_m - C_s)G$$

In these equations the subscript (0) refers to some reference (room) temperature, the subscript (T) refers to some elevated temperature $T = T_0 + \Delta T$, β is the temperature coefficient of gage factor TCGF. (in this case β is negative) and α_B is the bonded temperature coefficient of resistance TCRB. TCRB consists of two parts, an intrinsic TCR (α) which is always positive, and an apparent thermal strain contribution arising from the difference between the thermal expansion coefficient of the metal substrate C_m on which the gage is bonded and of the semiconductor material C_s . In these notes the

units of α and β are $\%/100^\circ\text{F}$ and the units of C are $\text{ppm}/^\circ\text{F}$. The gage parameters α , β , and G_0 are controlled by the impurity doping level, or resistivity, of the semiconductor crystal. Kulite gage resistivities are designated by the letters C, D, E, etc., and range from .0005 ohm-cm to 1.0 ohm-cm. Table I below lists the thermal properties for P-Type gages. Table II lists the thermal expansion coefficients of some of the materials on which strain gages are commonly mounted.

Table I

Thermal Properties of Kulite Silicon Gages			
Resistivity	G_0 (unitless)	TCR (α) ($\%/100^\circ\text{F}$)	TCGF (β) ($\%/100^\circ\text{F}$)
C	100	4	-6
D	115	3	-8
E	130	6	-10
F	140	10	-11
G	155	18	-13
H	175	45	-23

Table II

Thermal Expansion Coefficient by Material	
Material	Expansion Coefficient C ($\text{ppm}/^\circ\text{F}$) @ 68°F
Aluminum	12.8
Brass	10.6
Carbon steel	6
Concrete	6.7
Copper	9.4
Glass	4.7
Gold	7.8
Iron	6.2
Lead	16.1
Magnesium	14.4
Nickel	7.2
Pine	18.9
Platinum	5
PVC	28.9
Sapphire	2.9
Silicon Carbide	1.5
Silicon	1.7
Silver	10
Stainless steel	9.6
Steel	6.7
Tungsten	2.5

$$1 \text{ ppm}/^\circ\text{F} = 10^{-2}\%/100^\circ\text{F}$$

Equivalent Circuit Resistance and TCR

We have defined the temperature dependence of a strain gage resistance element to be:

$$(18) \quad R_{Gage} = R_{G0}(1 + \alpha_{Gage} \Delta T)$$

When a series resistance R_s and/or parallel resistance R_p having zero (TCR) are added to the element, as shown by Figure (10), the resistance value and TCR value of the gage can be modified. The equivalent circuit resistance is given by equation (19).

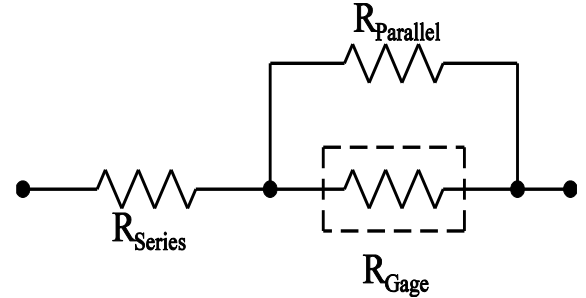


Figure 10
Equivalent Resistance Circuit

$$(19) \quad R_{eq} = R_s + \frac{R_p R_{Gage}}{R_p + R_{Gage}} = R_{eq0}(1 + \alpha_{eq} \Delta T)$$

Analyzing the equivalent circuit for the case where a series resistor is used without a shunt (parallel) resistor, R_{eq0} and α_{eq} are given by equations (20) and (21).

$$(20) \quad R_{eq0} = R_{G0} + R_s$$

$$(21) \quad \alpha_{eq} = \frac{\alpha_{Gage}}{1 + \frac{R_s}{R_{G0}}}$$

Analyzing the equivalent circuit for the case where a shunt (parallel) resistor is used without a series resistor, R_{eq0} and α_{eq} are given by equations (22) and (23).

$$(22) \quad R_{eq0} = \frac{R_p R_{G0}}{R_p + R_{G0}}$$

$$(23) \quad \alpha_{eq} = \frac{\alpha_{Gage}}{1 + \frac{R_{G0}}{R_p}}$$

It can be noted from equations (20) and (21) the magnitude of equivalent resistance R_{eq0} increases with the addition of R_s , while the equivalent α_{eq} is reduced. From equations (22) and (23) it can be seen

that the magnitude of equivalent resistance R_{eq0} decreases with the addition of R_p , while the equivalent α_{eq} is reduced. Using both resistors it is possible to adjust R_{eq0} to a range of values and simultaneously reduce α_{eq} to some lower value.

Span (Sensitivity) Compensation

Span compensation is the technique of using either a series resistor with constant voltage excitation or a shunt resistor with constant current excitation to compensate for loss of strain sensitivity with increasing temperature, as shown by equation (15). According to equation (16), the resistance of bonded P-type gages always increases with temperature. Providing TCRB is greater than TCGF, it is possible to select a resistor which acts as a voltage divider in the constant voltage case or a current divider in the constant current case in such a way as to increase the voltage at the gage at a rate equal to the decrease in gage factor with temperature. The choice of constant voltage or constant current and ability to compensate a specific gage type for span sensitivity is dictated by the temperature characteristics of the gage and the expansion properties of the substrate.

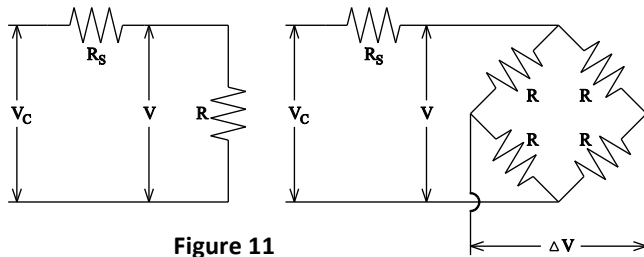


Figure 11
Constant Voltage Configuration

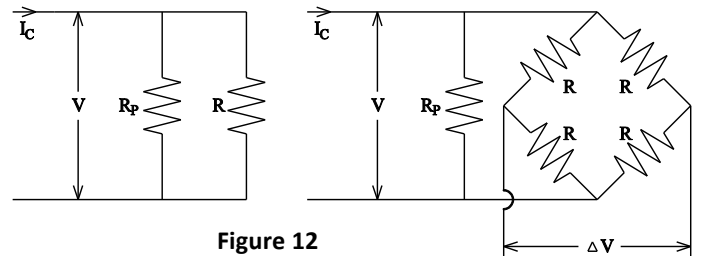


Figure 12
Constant Current Configuration

Figures (11) and (12) illustrate the divider circuits for which the excitation voltage at the gage, or gage bridge input, is:

$$(24) \quad V = V_c \left(\frac{R}{R_c + R} \right) \text{ constant voltage } V_c, R_c \equiv \text{series } R_s$$

$$(25) \quad V = I_c R_c \left(\frac{R}{R_c + R} \right) \text{ constant current } I_c, R_c \equiv \text{shunt } R_p$$

R is the gage resistance and R_c , turns out to be the same circuit resistance -by Thevenin's Theorem, (for either case). Note that for a symmetrical bridge of four gages of resistance R , the bridge input resistance is also R and changes with temperature according to equation (16). The analysis, therefore, is

equally valid for a single gage or symmetrical bridge, constant voltage or constant current. At the reference temperature T_0 the voltage signal output ΔV in response to an applied strain ε is:

$$(26) \quad \Delta V_0 = V_A \left(\frac{R_0}{R_c + R_0} \right) G_0 \varepsilon$$

where V_A stands for V_C at constant voltage or $I_c R_c$ at constant current. At the higher temperature $T = T_0 + \Delta T$, ΔV becomes:

$$(27) \quad \begin{aligned} \Delta V_T &= V_A \left(\frac{R_T}{R_c + R_T} \right) G_T \varepsilon \\ &= V_A \left[\frac{R_0 (1 + \alpha_B \Delta T)}{R_c + R_0 (1 + \alpha_B \Delta T)} \right] G_0 (1 + \beta \Delta T) \varepsilon \end{aligned}$$

If R_c is too small, then $\Delta V_T < \Delta V_0$ and the system is said to be undercompensated. If R_c is too large, then $\Delta V_T > \Delta V_0$ and the system is overcompensated. The proper value of R_c to use is found by equating equations (26) and (27). The exact result is:

$$(28) \quad R_c / R_0 = |\beta| \left[\frac{\alpha_B}{1 + \alpha_B \Delta T} - |\beta| \right]^{-1}$$

$$(29) \quad \alpha_B > \frac{|\beta|}{1 - |\beta| \Delta T}$$

For this methodology to succeed equation (29) must be true. Example an “F” gage ($TCGF = -11\%/100^\circ F$) over a $200^\circ F$ temperature range results in $\alpha_B > 14.1\%$. As the TCR of an “F” gage is 10% with a gage factor of 140, utilizing equation (17) the expansion coefficient of the material the gages are bonded to must be $C_m > 5.8 ppm$ for a successful compensation to occur.

We have tacitly assumed that our output signal ΔV wants to be proportional to strain ε , independent of temperature. The elastic modulus E of most materials, however, decreases with temperature according to:

$$(30) \quad E_T = E_0 (1 + \gamma_m \Delta T)$$

Where γ_m , the temperature coefficient of elastic modulus, is typically about -2%/100°F for most metals. For many strain monitoring operations this effect is part of the phenomenon to be studied, but if applied force of pressure is to be monitored this effect must also be removed from the signal. For the signal output to be proportional to a stress σ applied to the substrate material, then instead of equations (26) and (27) we have:

$$(31) \quad \Delta V_0 = V_c \left(\frac{R_0}{R_c - R_0} \right) G_0 \frac{\sigma}{E_0}$$

$$(32) \quad \Delta V_T = V_c \left(\frac{R_T}{R_c + R_T} \right) G_T \frac{\sigma}{E_T}$$

The effect of introducing γ is to replace β , the gage TCGF by an effective TCGF which is β_B .

$$(33) \quad \beta_B = \beta_S - \gamma_M$$

Where β_S is the TCGF of the gage and γ_M is the temperature coefficient of the elastic modulus for a specific material. This leads to equation (28) becoming equation (34).

$$(34) \quad \frac{R_C}{R_0} = |\beta_B| \left[\frac{\alpha_B}{1 + \alpha_B \Delta T} - |\beta_B| \right]^{-1}$$

Empirical Span (Sensitivity) Compensation

If the capability exists to test the gaged structure that is to be monitored, both over the temperature and load range expected during monitoring, the following methodology will provide a more accurate temperature and output compensation when compared to the theoretical compensation technique previously described. Figure (13) shows the test circuit schematic. The Wheatstone bridge illustrated in the figure is made up of at least 2 bonded strain gages. For the first phase a test voltage is applied, typically $V_T = 5VDC$, and the following 3 parameters are

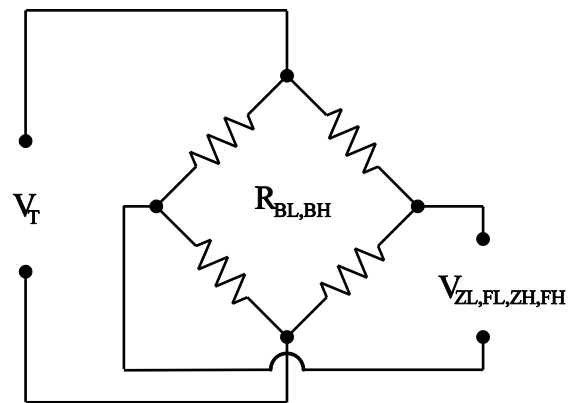


Figure 13
Test Schematic

collected at the low end of the temperature range. The first is the bridge input impedance R_{BL} , the second is the bridge output voltage at zero applied strain V_{ZL} , and the final is the bridge output voltage at the full applied strain V_{FL} . From this data the net output span can be calculated as $V_{NL} = V_{FL} - V_{ZL}$. If the structure is small enough to fit into a thermal chamber then the testing can be done at any time, but if the structure is large or fixed in place this phase of the test should be done during the coldest part of the day during which monitoring is planned to take place. The following phase of testing should take place when the structure is at the highest temperature that is expected to occur during monitoring. This is easily done if a thermal chamber can be used. If a thermal chamber cannot be used data should be collected during the hottest part of the day in which monitoring is planned to take place. The same test voltage is applied and the following 3 parameters are collected at the high end of the temperature range. The first is the bridge input impedance R_{BH} , the second is the bridge output voltage at zero applied strain V_{ZH} , and the final is the bridge output voltage at the full applied strain V_{FH} . From this data the net output span can be calculated as $V_{NH} = V_{FH} - V_{ZH}$.

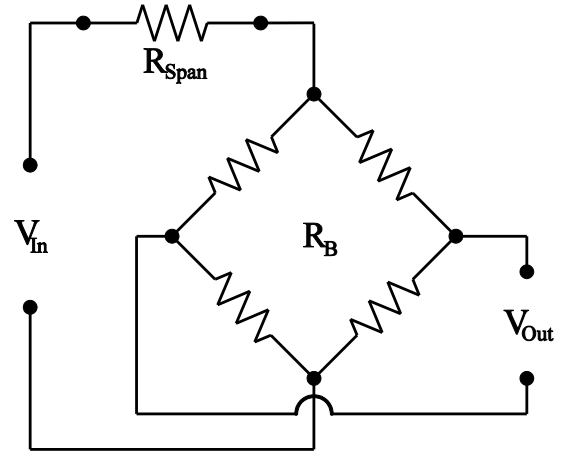


Figure 14
Span Compensation Schematic

The simplest output compensation occurs with the use of a span resistor and adjustment of the input voltage. This will result in a Wheatstone bridge output voltage that is insensitive to any ambient environmental temperature shifts during strain monitoring. Figure (14) shows the circuit schematic to be used during the strain monitoring. Using Equation (35) the span resistor can be calculated. Using equation (36) the input voltage can be calculated to result in a selected net output span V_{NS} for the Wheatstone bridge.

$$(35) \quad R_{Span} = \frac{R_{BL} R_{BH} (V_{NL} - V_{NH})}{(R_{BH} V_{NH} - R_{BL} V_{NL})}$$

$$(36) \quad V_{In} = \frac{V_{NS} V_T (R_{BL} + R_{Span})}{V_{NL} R_{BL}}$$

Finally, the relationship between strain and Wheatstone bridge output voltage is given by equation (37). Where $R_{BA} = (R_{BL} + R_{BH})/2$ and G is the room temperature gage factor. The strain is in PPM and is unitless.

$$(37) \quad \frac{\Delta L}{L} = \varepsilon = \left(\frac{10^6}{G} \right) \left(\frac{V_{Out}}{V_{in}} \right) \left(\frac{R_{BA} + R_{Span}}{R_{BA}} \right)$$

For example, a steel beam is gaged with a full Wheatstone bridge of "D" gages and testing can be performed on it prior to the beam being monitored. The beam is to be monitored for a week outdoors 24 hours a day. The first phase of testing will be performed during the coolest part of the day in the night. The temperature at this time of the day is 30°F. A test voltage (V_T) of 5 volts is applied and the following parameters are measured. The bridge input impedance (R_{BI}) is measured to be 865.1Ω, the zero load output voltage (V_{ZL}) is measured to be 2mV, and the full load output voltage (V_{FL}) is measured to be 207mV. This results in a net output voltage (V_{NL}) of 205mV. The second phase of testing will be performed during the hottest part of the day in the afternoon. The temperature at this time of the day is 130°F. A test voltage (V_T) of 5 volts is applied and the following parameters are measured. The bridge input impedance (R_{BH}) is measured to be 952.4Ω, the zero load output voltage (V_{ZH}) is measured to be -1mV, and the full load output voltage (V_{FH}) is measured to be 192mV. This results in a net output voltage (V_{NH}) of 193mV. Utilizing equation (35), a span resistor can be calculated from the test data and results in $R_{span} = 1528.7\Omega$. The input voltage (V_m) can now be calculated utilizing equation (36) and is 13.5V_{DC} for a net output span of 200mV.

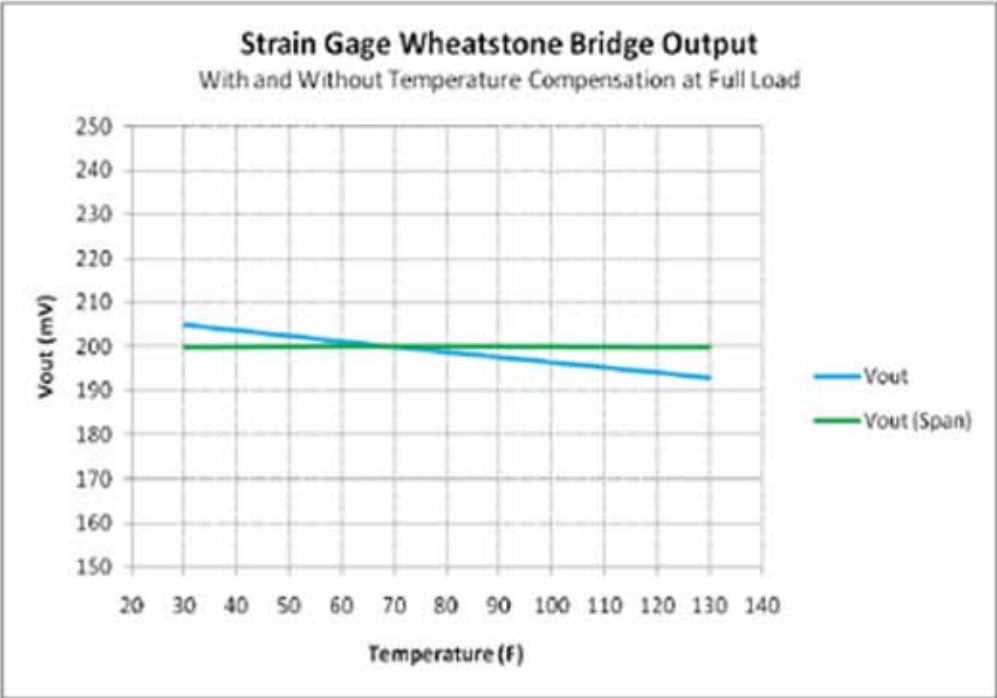


Figure 15

Utilizing the results generated by equations (35) and (36) and based off the figures given in the above example, Figure (15) charts the Wheatstone bridge output over temperature and demonstrates the effect of span temperature compensation on the Wheatstone bridge over the temperature range tested. As can be seen in Figure (15) the span compensation desensitizes the Wheatstone bridge output to the ambient temperature. Given that a fully loaded beam will generate an output voltage of 200mV, equation (37) can be used to determine the strain to be 346 μstrain (346 PPM strain). This measured strain in the beam occurs at the points where the gages are applied, and additionally is the average magnitude of the strain that each gage individually experiences.

Empirical Span (Sensitivity) Compensation with an Input Shunt

An alternative circuit topology exists that compensates a Wheatstone bridge gage circuit similarly to the span compensation. This topology is shown in Figure (16), and adds a span resistor and an input shunt resistor to the Wheatstone bridge test circuit. There are two inherent advantages to this circuit topology, the first is that it allows a fixed voltage or current source to be used in place of a variable source, and the second is the ability to set the net output voltage at a specific temperature point located between the high and low temperature values.

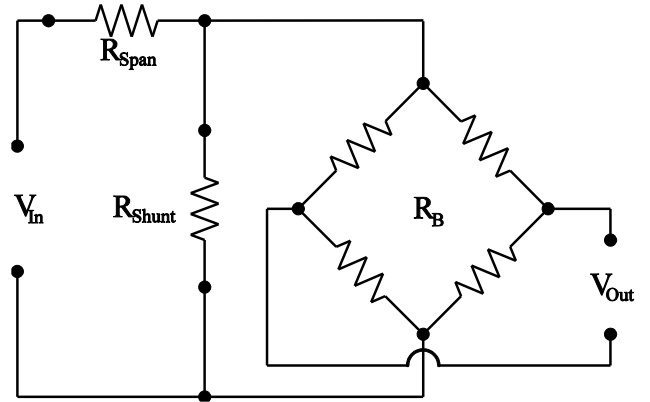


Figure 16

Span with Input Shunt Schematic

The methodology for calculating the span and the shunt resistors is identical to that used for the previously described span only method with the exception of a third phase of testing to collect data at a temperature point between the high and low points. For the third phase of testing the same test voltage is applied as for the preceding phases and the following 3 parameters are collected at some midpoint of the temperature range. The first is the bridge input impedance R_{BM} , the second is the bridge output voltage at zero applied strain V_{ZM} , and the final is the bridge output voltage at the full applied strain V_{FM} . From this data the net output span can be calculated as $V_{NM} = V_{FM} - V_{ZM}$. Equation (38) allows the calculation of a coefficient R_Q , which in turn allows for the calculation of coefficient Q generated from Equation (39) where V_{in} is the preselected input voltage, V_T is the test voltage, V_{NS} is the selected net output span for the Wheatstone bridge at the midpoint temperature.

$$(38) \quad R_Q = \frac{R_{BL} R_{BH} (V_{NL} - V_{NH})}{(R_{BH} V_{NH} - R_{BL} V_{NL})}$$

$$(39) \quad Q = \left(\frac{V_{in}}{V_T} \right) \left(\frac{V_{NM}}{V_{NS}} \right) \left(\frac{R_{BM}}{R_{BM} + R_Q} \right)$$

Coefficient Q determines whether or not the coefficients V_{NS} and V_{in} have been selected correctly as $Q > 1$ must be true for this configuration to function properly. If Q is greater than one then equation (40) will provide the value of the span resistor and equation (41) will provide the value of the shunt resistor.

$$(40) \quad R_{Span} = QR_Q$$

$$(41) \quad R_{Shunt} = \left(\frac{Q}{Q-1} \right) R_Q$$

Finally, the relationship between strain and Wheatstone bridge output voltage is given by equation (42), where G is the room temperature gage factor. The strain is in PPM and is unitless.

$$(42) \quad \frac{\Delta L}{L} = \varepsilon = \left(\frac{10^6}{G} \right) \left(\frac{V_{Out}}{V_{in}} \right) \left(1 + R_{Span} \left(\frac{1}{R_{Shunt}} + \frac{1}{R_{BM}} \right) \right)$$

For example, a steel plate is gaged with a full Wheatstone bridge of “D” gages and calibration testing can be performed on it prior to the plate being installed and used for process monitoring. The plate is small and will fit into a thermal chamber. The plate will be exposed to temperatures from -30°F to 270°F. Phase one test will occur at 80°F, where a test voltage (V_T) of 6 volts is applied and the following parameters are measured. The bridge input impedance (R_{BM}) is measured to be 909Ω, the zero load output voltage (V_{ZM}) is measured to be 1mV, and the full load output voltage (V_{FM}) is measured to be 240mV. This results in a net output voltage (V_{NM}) of 239mV. The second phase of testing will be performed at -30°F. A test voltage (V_T) of 6 volts is applied and the following parameters are measured. The bridge input impedance (R_{BL}) is measured to be 810Ω, the zero load output voltage (V_{ZL}) is measured to be 2mV, and the full load output voltage (V_{FL}) is measured to be 256mV. This results in a net output voltage (V_{NL}) of 254mV. The final phase of testing will be performed at 270°F with the same test voltage V_T of 6V. The bridge input impedance (R_{BH}) is measured to be 1080Ω, the zero load output voltage (V_{ZH}) is measured to be -1mV, and the full load output voltage (V_{FH}) is measured to be 210mV. This results in a net output voltage (V_{NH}) of 211mV. From this collected data R_Q can be calculated using equation (38) which results in $R_Q = 1699\Omega$. If the preselected input voltage, V_{in} , is chosen to be 20V_{DC}, and the selected net output span for the Wheatstone bridge at 80°F, V_{NS} , as 250mV, then equation (39) allow the calculation of Q as 1.111. This results with a $Q>1$ so we may proceed with using equations (40) and (41) to calculate R_{Span} as 1888Ω and R_{Shunt} as 17005Ω.

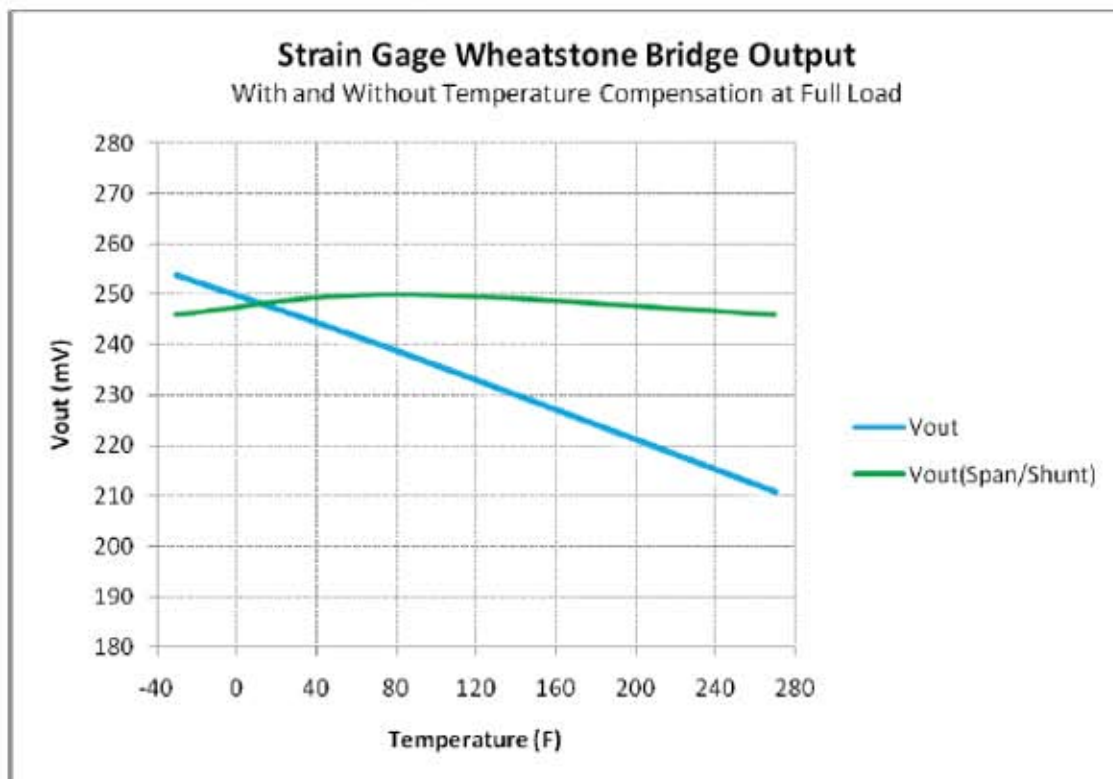


Figure 17

Utilizing the results generated by equations (40) and (41) and based off the figures given in the above example, Figure (17) charts the Wheatstone bridge output over temperature and demonstrates the effect of span with shunt temperature compensation on the Wheatstone bridge over the temperature range tested. As can be seen in Figure (17) the span with shunt compensation desensitizes the Wheatstone bridge output to the ambient temperature. Given that a fully loaded plate will generate an output voltage of 250mV, equation (42) can be used to determine the strain to be 346 μ strain (346 PPM strain). This measured strain in the plate occurs at the points where the gages are applied, and additionally is the average magnitude of the strain that each gage individually experiences.

Bridge Null and Null Shift Compensation

Figure (18) illustrates a symmetrical Wheatstone bridge of four P-type semiconductor gages. When excitation voltage is applied across terminal C and D, the null (no load) output voltage across A and B will be zero only if the bridge is exactly balanced, namely:

$$(43) \quad R_2 R_4 = R_1 R_3$$

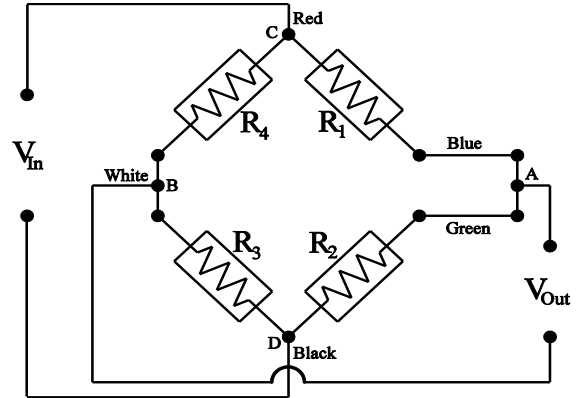


Figure 18
CONVENTIONS FOR AN OPEN BRIDGE
CIRCUIT

Furthermore, the null will shift with temperature unless the effective TCR of each arm is identical, or at least

$$(44) \quad \left(1 + \frac{\Delta R_2}{R_2}\right) \left(1 + \frac{\Delta R_4}{R_4}\right) = \left(1 + \frac{\Delta R_1}{R_1}\right) \left(1 + \frac{\Delta R_3}{R_3}\right)$$

over the operating temperature range. It is inherently impossible to fabricate a set of four gages bonded to a force collector and ensure that each gage resistance and bonded TCR are identical. Any real bridge, therefore, will display some non-zero null and null shift, and these can have either sign. Compensation is provided by leaving node A open, so that an external shunt and/or series resistor can be added to either arm 1 or arm 2 of the bridge. The technique is to measure the null V_0 and resistance values R_{i0} ($i = 1, 2, 3, 4$) at some reference temperature T_0 and again at maximum temperature $T = T_0 + \Delta T$ measure the null V_T and resistances R_{iT} ($i = 1, 2, 3, 4$). It is always possible to find a single series resistor R_s and a single parallel resistor R_p which will drive V_0 and V_T to zero. We have shown in the previous section entitled, "Equivalent Circuit Resistance and TCR", that the effective TCR of the

resistance arm is lowered by the addition of either R_s or R_p , while the resistance is increased with R_s and decreased with R_p . In effect, we are forcing the balance condition at the temperature extremes. If the uncompensated null shift is linear with temperature, then the compensated null will be zero at all intermediate temperatures between T_0 and T .

Let x_i be the fractional change in resistance of R_i due to temperature effects over the temperature range ΔT . Theoretically x_i can be expressed as:

$$(45) \quad R_{iT} = R_{i0}(1 + x_i)$$

$$(46) \quad x_i = \frac{\Delta R_i}{R_{i0}} = [\alpha_i + (C_m - C_s)G_i]\Delta T + \varepsilon_{iT}G_i$$

Where ε_{iT} is any thermal strain developed in the force collector to which the gages are bonded. The nulls V_0 and V_T for constant voltage input V_i are:

$$(47) \quad V_0 = V_i \frac{R_{20}R_{40} - R_{10}R_{30}}{(R_{10} + R_{20})(R_{30} + R_{40})}$$

$$(48) \quad V_T = V_i \frac{R_{2T}R_{4T} - R_{1T}R_{3T}}{(R_{1T} + R_{2T})(R_{3T} + R_{4T})}$$

And to first order in x_i the null shift $\Delta V = V_T - V_0$ is:

$$(49) \quad \Delta V \cong \frac{V_i}{4} [(x_2 + x_4) - (x_1 + x_3)]$$

Suppose both V_0 and ΔV are positive. According to equation (49) we want to decrease x_2 . Equation (47) requires that we either increase R_1 or else decrease R_2 . Shunting R_2 with R_p will both decrease x_2 and decrease R_2 . Depending upon the relative magnitude of V_0 and ΔV it is necessary to add R_s to R_1 if R_p in arm 2 has not sufficiently reduced R_2 , or add R_s to R_2 if R_2 has been reduced too far. The addition of R_s to either arm, however, will further reduce the x of that arm and upset the initial null

shift compensation provided by R_p in arm 2. Clearly then, the null and null shift cannot be compensated independently since the effects of R_s and R_p interact.

To simplify the analysis we introduce the following dimensionless quantities:

$$(50) \quad \left(1 + \frac{R_{10}}{R_{20}}\right) \left(1 + \frac{R_{30}}{R_{40}}\right) \frac{V_0}{V_i} = 1 - \frac{R_{10}R_{30}}{R_{20}R_{40}}$$

$$(51) \quad \left(1 + \frac{R_{1T}}{R_{2T}}\right) \left(1 + \frac{R_{3T}}{R_{4T}}\right) \frac{V_T}{V_i} = 1 - \frac{R_{1T}R_{3T}}{R_{2T}R_{4T}}$$

We assume for now that both arm 1 and arm 2 have a series element and a parallel element added to them as in Figure (19). For any real case either R_{s1} or R_{s2} will be zero and either R_{p1} or R_{p2} will be infinite. Using the notation of (Equivalent Circuit Resistance and TCR) the equivalent resistance of arms 1 and 2 are:

$$(52) \quad (R_{j0})_{eq} = R_{j0} \left(S_j + \frac{1}{1 + P_j} \right)$$

$$(53) \quad (R_{jT})_{eq} = R_{j0} \left[\left(\frac{S_j}{1 + x_j} \right) + \left(\frac{1}{1 + P_j(1 + x_j)} \right) \right]$$

$$(54) \quad S_j = \frac{R_{sj}}{R_{j0}}, \quad P_j = \frac{R_{j0}}{R_{pj}}, \quad j = (1,2)$$

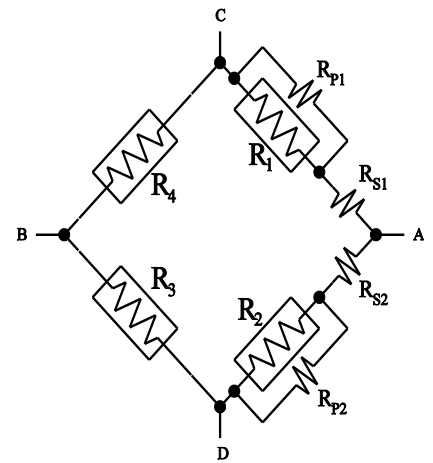


Figure 19

CIRCUIT FOR ANALYSIS OF SERIES- SHUNT RESISTOR ADDITIONS TO BRIDGE ARMS 1 AND 2

The balance condition equation (43) for zero null at T_0 and T are now written in the following way:

$$(55) \quad \frac{R_{30}(R_{10})_{eq}}{R_{40}(R_{20})_{eq}} = 1 \quad \& \quad \frac{R_{3T}(R_{1T})_{eq}}{R_{4T}(R_{2T})_{eq}} = 1$$

Putting equations (50), (51), (52), and (53) into (55) we generate two simultaneous equations for s and p, namely

$$(56) \quad (1-V_0) \left(S_1 - \frac{P_1}{1+P_1} \right) - \left(S_2 - \frac{P_2}{P_2} \right) = V_0$$

$$(57) \quad (1-V_T) \left[\frac{S_1}{1+x_1} - \frac{P_1(1+x_1)}{1+P_1(1+x_1)} \right] - \left[\frac{S_2}{1+x_2} - \frac{P_2(1+x_2)}{1+P_2(1+x_2)} \right] = V_T$$

These equations can be solved exactly for four cases: $S_1 = P_1 = 0$, $S_1 = P_2 = 0$, $S_2 = P_2 = 0$, $S_2 = P_1 = 0$. Because they are quadratic in S and P, however, the solutions are algebraically complicated. A much simpler solution follows if we realize that S, P, x, and V are small quantities for most real cases. We also assume that the magnitudes of $R_{i0} = R_{iT}$ ($i = 1,2,3,4$) and therefore $x_1 = x_2 = x_3 = x_4$. The effects of small differences in these quantities are actually reflected in the measured values of V_0 and ΔV . It is not necessary in this approximation to measure the individual resistances at both temperatures. A measurement of the input resistance only, call it R , at T_0 and T will suffice, since each arm resistance is approximately equal to the input (or output) resistance in a symmetrical bridge. With the following approximations:

$$(58) \quad R_{i0} = R_0, \quad R_{iT} = R_T \quad (i = 1,2,3,4)$$

$$(59) \quad x_i = x = \frac{R_T - R_0}{R_0} \ll 1$$

$$(60) \quad V_0 = 4 \frac{V_0}{V_i} \ll 1, \quad V_T = 4 \frac{V_T}{V_i} \ll 1, \quad \Delta V = 4 \frac{\Delta V}{V_0} \ll 1$$

$$(61) \quad S = \frac{R_s}{R_0} \ll 1, \quad p = \frac{R_0}{R_p} \ll 1$$

the equations (56) and (57) reduce simply to:

$$(62) \quad (S_2 - S_1) = 1/2 \left[\frac{\Delta V}{x} - V_0 \right]$$

$$(63) \quad (p_2 - p_1) = 1/2 \left[\frac{\Delta V}{x} + V_0 \right]$$

and in terms of measured quantities:

$$(64) \quad R_{s2} - R_{s1} = \frac{2R_0}{V_i} \left[\frac{R_0}{\Delta R} \Delta V - V_0 \right]$$

$$(65) \quad \frac{1}{R_{p2}} - \frac{1}{R_{p1}} = \frac{2}{R_0 V_i} \left[\frac{R_0}{\Delta R} \Delta V + V_0 \right]$$

When the right hand side of (64) or (65) is positive, then arm 2 must be compensated; and when it is negative, arm 1 must be compensated. Table III is a tabulation of the null compensation solutions for all cases of interest.

Table III

SOLUTIONS OF THE NULL COMPENSATION EQUATIONS

ΔV	V_0	$\frac{R_0}{\Delta R} \Delta V - V_0 $	Circuit Schematic	R_s	R_p
+	+	+		$\frac{2R_0}{V_{In}} \left[\frac{R_0}{\Delta R} \Delta V - V_0 \right]$	$\frac{R_0 V_{In}}{2 \left[\frac{R_0}{\Delta R} \Delta V + V_0 \right]}$
+	-	+		$\frac{2R_0}{V_{In}} \left[\frac{R_0}{\Delta R} \Delta V + V_0 \right]$	$\frac{R_0 V_{In}}{2 \left[\frac{R_0}{\Delta R} \Delta V - V_0 \right]}$
-	+	+		$\frac{2R_0}{V_{In}} \left[\frac{R_0}{\Delta R} \Delta V + V_0 \right]$	$\frac{R_0 V_{In}}{2 \left[\frac{R_0}{\Delta R} \Delta V - V_0 \right]}$
-	-	+		$\frac{2R_0}{V_{In}} \left[\frac{R_0}{\Delta R} \Delta V - V_0 \right]$	$\frac{R_0 V_{In}}{2 \left[\frac{R_0}{\Delta R} \Delta V + V_0 \right]}$
+	+	-		$\frac{2R_0}{V_{In}} \left[V_0 - \frac{R_0}{\Delta R} \Delta V \right]$	$\frac{R_0 V_{In}}{2 \left[\frac{R_0}{\Delta R} \Delta V + V_0 \right]}$
-	+	-		$\frac{2R_0}{V_{In}} \left[\frac{R_0}{\Delta R} \Delta V + V_0 \right]$	$\frac{R_0 V_{In}}{2 \left[V_0 - \frac{R_0}{\Delta R} \Delta V \right]}$
-	-	-		$\frac{2R_0}{V_{In}} \left[V_0 - \frac{R_0}{\Delta R} \Delta V \right]$	$\frac{R_0 V_{In}}{2 \left[\frac{R_0}{\Delta R} \Delta V + V_0 \right]}$
+	-	-		$\frac{2R_0}{V_{In}} \left[\frac{R_0}{\Delta R} \Delta V + V_0 \right]$	$\frac{R_0 V_{In}}{2 \left[V_0 - \frac{R_0}{\Delta R} \Delta V \right]}$

As an illustration consider a bridge of 350Ω “D” type gages excited by $V_i = 5.0$ volts. At 75° the null is $V_0 = -20.0$ mV, and the input resistance is $R_0 = 350$ ohms. At 175°F the null is $V_T = -15.0$ mV, and the resistance R_T is 385 ohms. Thus $\Delta V = +5$ mV, $\Delta R = 35$ ohms, and the weighted differential voltage ΔW is

$$\Delta W = \frac{R_0}{\Delta R} |\Delta V| - |V_0| = \frac{350(0.005)}{35} - 0.020 = 0.030$$

Where ΔV is positive, V_0 is negative, and ΔW is positive, and referring to table III these parameters match the second case where a series resistor must be added to arm 2 with a value of

$$R_s = \frac{2R_0}{V_{IN}} \left[\frac{R_0}{\Delta R} \Delta V + |V_0| \right] = \frac{(350)(0.005)}{35} = 9.8\Omega$$

and the gage in arm 2 must be shunted with a resistor whose value is:

$$R_p = \frac{R_0 V_{IN}}{2 \left[\frac{R_0}{\Delta R} \Delta V - |V_0| \right]} = \frac{(350)(5.0)}{2 \left[\frac{(350)(0.005)}{35} \right]} = 29,167\Omega$$

Again, as in the discussion of span compensation, this analysis is essentially a guide in choosing the correct compensation circuit. Final values of the resistors are best determined by a trimming operation of the null output over the entire temperature range.

Empirical Bridge Null Compensation

A Wheatstone bridge is always assembled from four resistive elements. In the ideal case each of these resistive elements has the same resistance, which in turn leads to a bridge output of zero. This is almost never the real world case. These elements inherently have non-zero magnitude differences so the output of the unstressed Wheatstone bridge will rarely be zero, and this value is known as the null output for the bridge. A Wheatstone bridge consisting of gages having tolerance of just 0.05%, (most have much higher tolerances) can lead to an output zero at no load of 2.5% full scale output. With the application of a single low TCR resistor, either a series resistance added to one of the bridge elements, or a parallel resistance shunting one of the elements, the unstressed bridge output voltage can be set to zero.

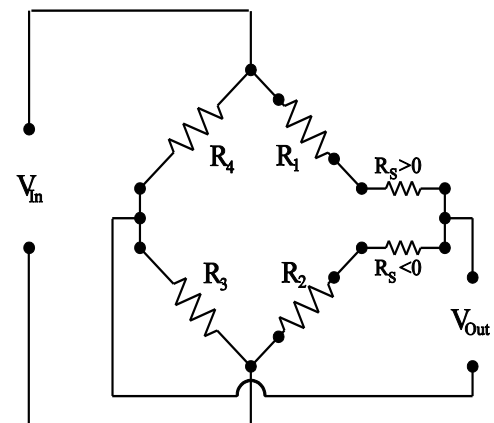


Figure 20
Series Resistor Location for Null
Compensation

The procedure for a null compensation is as follows. After the bridge is assembled a test voltage is applied, the output voltage of the bridge is measured, and then the input impedance of the bridge is measured. Figure (20) shows the circuit schematic for the application of a series resistor to correct a non-zero bridge output at zero strain. Equation (66) gives the solution for a series resistance, and also the resistor position in Figure (20). If R_s results in a positive value, a series resistor of the calculated magnitude is placed in the upper arm, if R_s is a negative value, then a series resistor of the calculated magnitude is placed in the lower arm.

$$(66) \quad R_s = 4R_{In} \frac{V_{Out}}{V_{In}}$$

For example, a Wheatstone bridge consisting of 4 bonded strain gages, when tested with a test voltage of $V_{In} = 5V$, results in a input resistance $R_{In} = 350\Omega$, and a $V_{Out} = -20mV$. Equation (66) results in a series resistor $R_s = -5.6\Omega$. From this result a 5.6Ω resistor is placed in the bottom leg, and when V_{out} is now measured the result is $V_{out} = 0.1mV$. Both of these null compensation techniques will affect thermal shifts, so if measurements over a temperature range are needed the next section should be used.

Figure (21) shows the circuit schematic for the application of the correcting parallel (shunt) resistor. Equation (67) gives the solution for a parallel (shunt) resistance, and also the resistor position in Figure (21). If R_p results in a positive value a series resistor of the calculated magnitude is placed in the upper arm, if R_p is negative value then a series resistor of the calculated magnitude is placed in the lower arm.

$$(67) \quad R_p = - \frac{\left(1 - \left| \frac{4V_{Out}}{V_{In}} \right| \right)}{\frac{4V_{Out}}{V_{In}}} R_{In}$$

For example a Wheatstone bridge consisting of 4 bonded strain gages, when tested with a test voltage of $V_{In} = 5V$, results in a input resistance $R_{In} = 500\Omega$, and a $V_{Out} = 15mV$. Equation (67) results in a shunt (parallel) resistor $R_p = -41167\Omega$. From this result a 41176Ω resistor is placed in the bottom leg, and when V_{out} is now measured the result is $V_{out} = 0.2mV$.

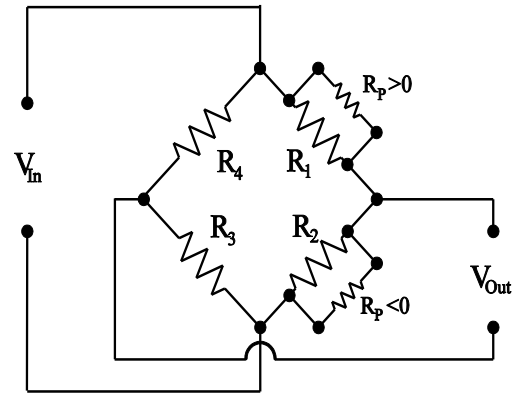


Figure 21
Shunt Resistor Location for Null Compensation

Empirical Bridge Null with Null Shift Compensation

The small differences in the magnitude of the gage resistors has been seen to cause large null output voltages, and if the TCR values of the bonded gages are not equal then the null output will change with temperature. Apparent strain and bonded resistance effects will also affect the null and null shift of a Wheatstone bridge. With the application of two single low TCR resistors, one a series resistance added to one of the bridge elements, and the second a parallel resistance shunting one of the elements, the unstressed bridge output voltage can be set to zero, and be desensitized to temperature. Plus the same technique will also compensate for apparent strain and bonded resistance effects simultaneously. Figure (22) shows the circuit schematic for the application of the series and parallel resistor to correct the temperature dependant bridge null output. Equation (68) gives the solution for the series resistance, and also the resistor position in Figure (22). If R_s results in a positive value a series resistor of the calculated magnitude is placed in the upper arm, if R_s is negative value then a series resistor of the calculated magnitude is placed in the lower arm.

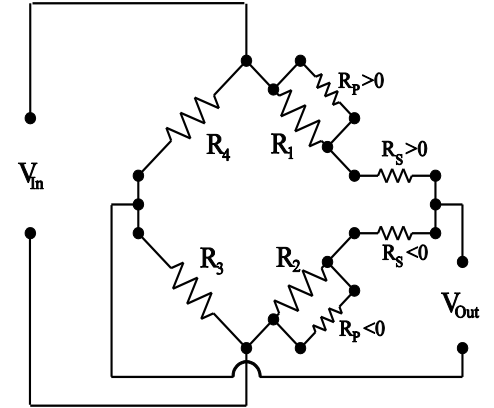


Figure 22
Series and Shunt Resistor Locations
for Null and Null Shift Compensation

$$(68) \quad R_s = \left[\frac{4}{\left(\frac{R_H - R_L}{R_R} \right) + \left(\frac{1}{R_L} - \frac{1}{R_H} \right) R_R} \right] \left(\left(R_H - R_L \right) \frac{V_R}{V_{in}} - \left(\frac{V_H - V_L}{V_{in}} \right) R_R \right)$$

Equation (69) gives the solution for the parallel (shunt) resistance, and also the resistor position in Figure (22). If R_p results in a positive value a shunt resistor of the calculated magnitude is placed across the upper arm, if R_p is negative value then a shunt resistor of the calculated magnitude is placed across the lower arm.

$$(69) \quad R_p = \left[\left[\frac{-4}{\left(R_H - R_L \right) \frac{1}{R_R} + \left(\frac{1}{R_L} - \frac{1}{R_H} \right) R_R} \right] \left(\left(\frac{1}{R_L} - \frac{1}{R_H} \right) \frac{V_R}{V_{in}} + \left(\frac{V_H - V_L}{V_{in}} \right) \frac{1}{R_R} \right) \right]^{-1}$$

If the capability exists to test the gaged structure that is to be monitored over the expected temperature range, the following methodology will provide the data needed for the null temperature compensation calculations. For the first phase an input voltage is applied, typically $V_{in} = 5V_{DC}$, and the following two parameters are collected at the low end of the temperature range. The first is the bridge input impedance R_L , the second is the bridge output voltage at zero applied strain V_L . If the structure is small enough to fit into a thermal chamber then the testing can be done at any time, but if the structure is

large or fixed in place this phase of the test should be done during the coldest part of the day, at the lowest temperature expected to occur during actual monitoring. The following phase of testing should take place when the structure is at the middle of the temperature range that is expected to occur during monitoring. This is easily done if a thermal chamber can be used. If a thermal chamber cannot be used data should be collected sometime between the hottest, and the coolest part of the day, at the highest temperature expected to occur during actual monitoring. The same test voltage is applied and the following two parameters are collected at the middle of the temperature range. The first is the bridge input impedance R_R , the second is the bridge output voltage at zero applied strain V_R . The final phase of testing should take place when the structure is at the highest temperature that is expected to occur during monitoring. This is easily done if a thermal chamber can be used. If a thermal chamber cannot be used data should be collected during the hottest part of the day, at the highest temperature expected to occur during actual monitoring. The same test voltage is applied and the following two parameters are collected at the high end of the temperature range. The first is the bridge input impedance R_H , the second is the bridge output voltage at zero applied strain V_H .

For example, a small steel plate is gaged with a full Wheatstone bridge of “D” gages and calibration testing can be performed on it prior to the plate being installed and used for process monitoring. The plate is small and will fit into a thermal chamber. The plate will be exposed to temperatures from -30°F to 170°F . Phase one test will occur at -30°F , where an input voltage (V_{in}) of 5 volts is applied and the following parameters are measured. The bridge input impedance (R_L) is measured to be 320Ω , the zero load output voltage (V_L) is measured to be 39.1mV . The second phase of testing will be performed at 70°F . The same input voltage is applied and the following parameters are measured. The bridge input impedance (R_R) is measured to be 355Ω , the zero load output voltage (V_R) is measured to be 42.3mV . The final phase of testing will be performed at 170°F with the same input voltage V_{in} of 5V. The bridge input impedance (R_H) is measured to be 390Ω , the zero load output voltage (V_H) is measured to be 44.9mV . Using equation (68) to calculate R_S results in $R_S = 1.8\Omega$. This is a positive number so a 1.8Ω series resistor is added to R_1 . Using equation (69) to calculate R_P results in $R_P = -12453\Omega$. This is a negative number so a 12453Ω shunt resistor is added across R_2 .

The schematic for the compensated Wheatstone bridge circuit is shown in Figure (23). Utilizing the results generated by equations (68) and (69) and based off the figures given in the above example, Figure (24) charts the Wheatstone bridge null output over the temperature range from this example, and demonstrates the effect of the null offset with null shift compensation technique. As can be seen in Figure (24) the null offset with shift compensation technique desensitizes the Wheatstone bridge output to the ambient temperature while setting the null output to zero.

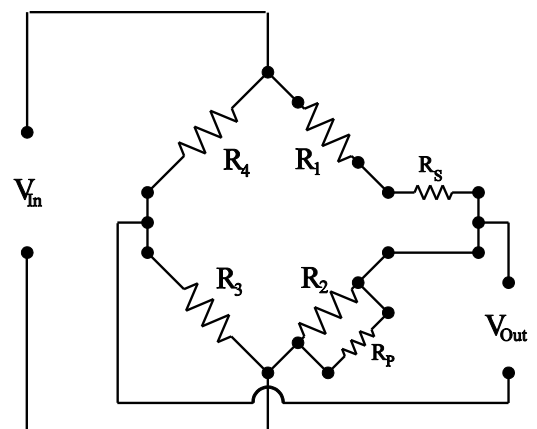


Figure 23
Series and Shunt Resistor Locations for Example Given in Text

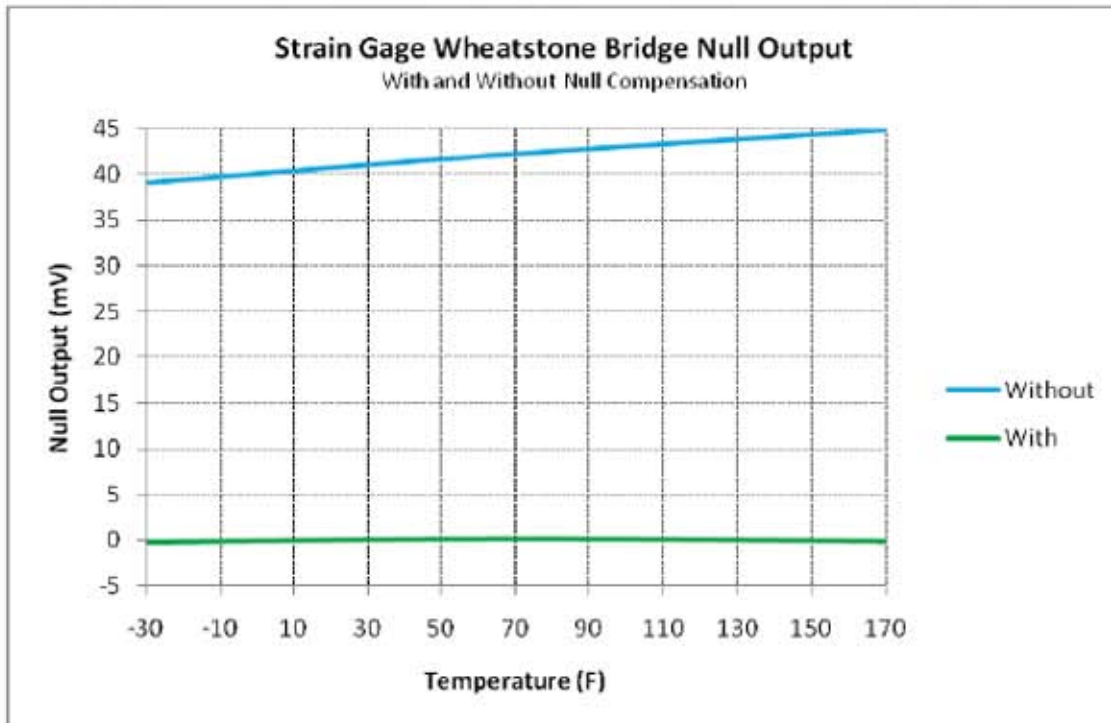


Figure 24

The Effect of Null and Null Shift Compensation on the Gage's Strain Sensitivity

Section VII has covered the use of low TCR resistors to compensate the null output of a Wheatstone bridge circuit made up of semiconductor strain gages over a temperature envelope. The section entitled "Equivalent Circuit Resistance and TCR" demonstrates the compensation resistor's ability to desensitize the semiconductor strain gage's temperature characteristics. Unfortunately, this technique also affects the gage's sensitivity with respect to strain, but the effect on strain sensitivity is at a much lower magnitude.

The following example will demonstrate the differences in magnitude of the various mechanical and thermal characteristics modified by adding a null offset compensation resistor to a Wheatstone bridge circuit, specifically the bridges Null offset, Null offset shift with temperature, input resistance, and sensitivity to strain.

Table IV

Pre-Compensation Wheatstone Bridge Characteristics				
Ambient Temperature (°F)	Input Resistance (Ω)	Bridge Null Output (mV)	Bridge Full Scale Output (mV)	Bridge Net Full Scale Output (mV)
70	1000	10	110	100
170	1100	11	N/A	N/A

Utilizing equation 67 and the data given in table IV we can calculate a shunt resistor to correct the 10mV offset that exists at room temperature in the example. From the data given, R_p will be 124k Ω and will be placed across gage R_2 , as shown in figure 21. Table V shows the bridge characteristics after the compensation resistor is added to the circuit.

Table V

Post Compensation Wheatstone Bridge Characteristics				
Ambient Temperature (°F)	Input Resistance (Ω)	Bridge Null Output (mV)	Bridge Full Scale Output (mV)	Bridge Net Full Scale Output (mV)
70	998	0	99.8	99.8
170	1098	0	N/A	N/A

Looking at the data contained within table V we can see that the use of a compensation resistor has reduced the Null output by 10mV or 10% and reduced the Null shift by 1mV or 1%. The input resistance has been reduced by 2 Ω or 0.2% and the sensitivity has been reduced by only 0.2mV or 0.2%, all the percentages are referenced to the net full scale output value. This reduction of sensitivity is very slight and in most cases can be ignored, but please remember that the use of span (sensitivity) compensation can also be used to correct for this effect while it is also correcting for the effect of TCGF on the sensitivity.

Section VIII

GAGING SERVICES

Kulite engineering and production facilities regularly serve customers with special gaging services. This, of course, can be from initial development of gages and systems to complete production. We offer any combination the following services: temperature compensation, bonding, mounting gages to customer supplied hardware, and calibration of bridge networks on our customers' equipment.

Our modern facilities staffed by highly experienced engineering and scientific personnel can offer capable backup services for your work regardless of your familiarity with semiconductor strain gages. Please feel free to contact our factory for further information.

TRAINING SERVICES

Kulite offers training seminars and workshops to assist customers in developing and improving their skills and techniques for use with silicon semiconductor strain gages. Our program can be custom designed to reflect each individual's specific needs. Basic knowledge of electronics, physics and measurement tool usage is assumed.

Kulite incorporates various training methodologies such as informal lecture, instructor demonstration, and hands-on training. We augment the training with presentations of the latest technology in gage design and application. Topics of the training include strain gage selection, surface preparation, mounting and handling on flat and curved surfaces, epoxy curing techniques, and compensation. Troubleshooting and error correction techniques will also be discussed. In addition to using various Kulite supplied surfaces for practice, customers may bring their own beams and hardware.

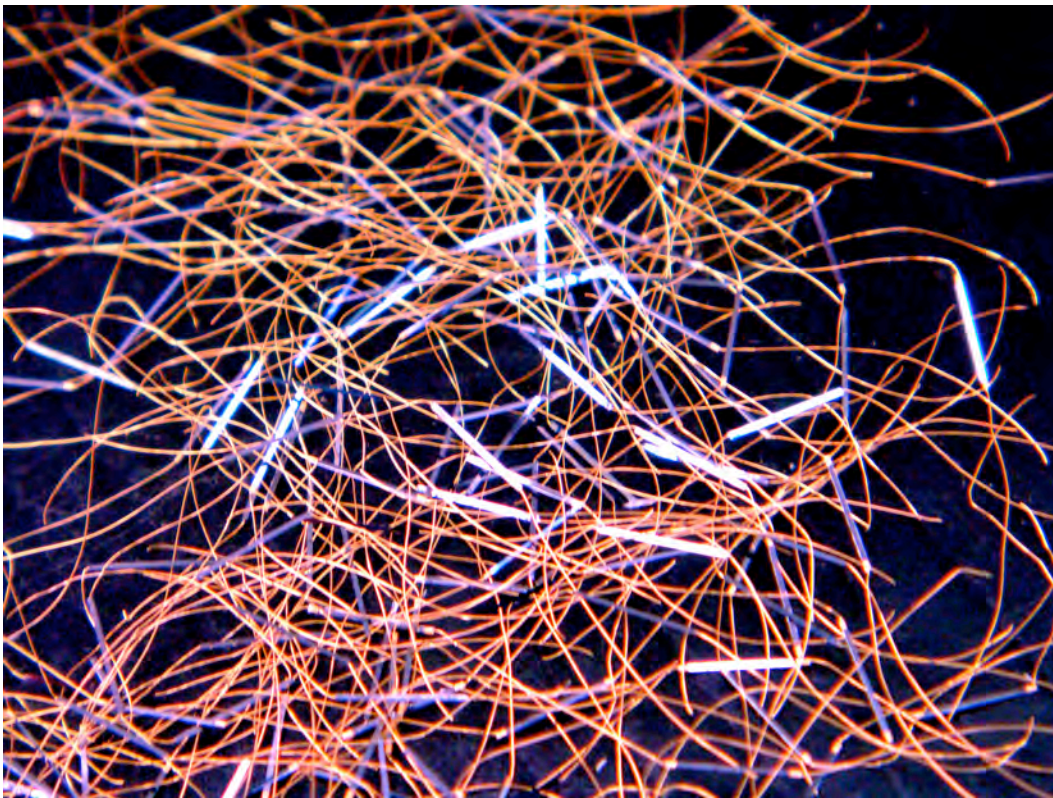
Kulite will supply all of the necessary tools for handling and mounting the strain gages. A plant tour and lunch are available. All courses will be conducted at our main manufacturing facility located in Leonia, New Jersey.

Please contact Kulite for current price schedules and a sample syllabus. Kulite will be happy to provide a list of area hotels and directions from Newark Airport upon request.

GAGE MATCHING SERVICES

Kulite gage sets are matched at the factory to provide the customer with a group of gages that will work well together. Kulite offers customer specific for matching criteria for use in creating gage sets. Please contact Kulite for further information.

Continuous development and refinement of our products may result in specification changes without notice. Please contact Kulite Representatives for latest product information.



A-Type Gages After Separation, Prior to Straightening and Matching

Appendix A

APPLICATION NOTE: AN-100

Selecting Strain Gages Silicon vs Metal Foil

(General Strain Measurement)

Alex A. Ned, Senior Vice President Sensor Operations
Joe VanDeWeert, Technical Director Miniature Transducers

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, W.P. Mason, and 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 viable output in high strain areas. If the foil gage is 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 characteristics of both technologies and showcases why the latest silicon based strain gages are rapidly becoming the superior choice throughout the industry. Table 1 shows a comparison of Metal-Foil and Silicon strain gages.

CHARACTERISTIC	METAL-FOIL	SILICON
Size for 1000 Ω	$\sim 0.04 \text{ in}^2$	$\sim 0.0004 \text{ in}^2$
Gage Factor	1 to 4	30 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	10^4 to 10^7 Cycles	infinite at $<500 \mu\text{strain}$
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
Noise "Floor" Level	$2 \times 10^{-3} (\mu\text{strain})^2/\text{Hz}$	$1 \times 10^{-6} (\mu\text{strain})^2/\text{Hz}$
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	$<\pm 1\% \text{FSO}/100\text{F}$	$\pm 1\% \text{FSO}/100\text{F}^{**}$
Sensor Thermal Sensitivity Shift	$\pm 1\%/100\text{F}$	$\pm 1\%/100\text{F}$ 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 Typical	500 mV FSO Typical
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 Metal 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.

$$\Delta R = GF \times R \times \epsilon$$

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 metal foil gages can only be used in relatively high stress areas. Due to the low gage factor of metal 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 than foil gages. To achieve a useful level of resolution a force sensor using metal 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, due to their high gage factor.

Frequency Response - Higher Bandwidth and Lower Response Time

The use of filtering can reduce induced electrical noise to acceptable levels on most metal 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 challenging 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 silicon semiconductor gages are as good as the best obtained with conventional metal gages due to the low strain levels needed. To maximize 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 at strain levels under 3000 μ strain. 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 characteristic that silicon strain gages exhibit is a shift in output with change in temperature. There are two different temperature-related phenomena: 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, the zero and span shift with temperature phenomena has been removed using a variety of compensating techniques. Regardless of the type of gage used, the magnitude that temperature effects the strain sensitive output ultimately depends upon the type of compensation method used.

Device Reliability – Fatigue and Creep

In the past most strain gages were used for static and quasi-static measurement applications. Now many 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 failing due to fatigue. Silicon strain gages are made from single crystal silicon; for that reason there is virtually no creep over the entire lifetime of the device. Also because there are virtually zero 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 are 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-Shaped (“U”) gage.

Bare gages insure the most intimate contact of the sensor to the bonded surface, but do require 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 metal foil gages have a poor track record for reliability in 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 found by customers to be truly superior to their foil gage counterparts.

Appendix B

SAMPLE PROCEDURE FOR SPECIMEN SURFACE PREPARATION AND GAGE BONDING

Part I – Epoxy Beam Surfaces (pre-coat) (For both bare and encapsulated gages)

1. Sandblast appropriate areas. Subject beam to ultrasonic cleaning for 10 minutes in Isopropyl alcohol.
2. Preheat oven and hot plate to (200°F).
3. Warm beam on hot plate for 15 minutes to facilitate flow of epoxy.
4. Apply thin layer of 8121 epoxy to all sandblasted surfaces with (8450) brush.
5. Cure in oven at (200°F) for 15 +\ 5 minutes.
6. Remove from oven, place on hot plate at (200°F) and apply 2nd coat of epoxy to previous areas.
7. Cure in oven at (200°F) for 30 +\ 5 minutes.
8. Remove from oven, place on hot plate at (200°F) and apply 3rd coat of epoxy to previous areas.
9. Cure in oven for 1.5 hours at (200°F).

Part II – Preparing Gages (For bare gages only)

1. Bend leads to sit perpendicular to gage body.
2. Cut leads approximately 1/3” longer than the length of the gage body.

Part III –Setting Gages (For both bare gages and encapsulated gages)

1. Warm beam on hot plate at (200°F) for 15 ± 5 minutes.
2. Apply a thin layer of 8121 epoxy with a (3/0) brush. Pick up gages by the gage body using a brush (3/0) and set down into the epoxy for the gages proper location. **After placing each gage, add additional epoxy to the next designated area.**
3. Place on hot plate for minimum of 1 hour.
4. Cure in oven at (250°F) for 4 hours.

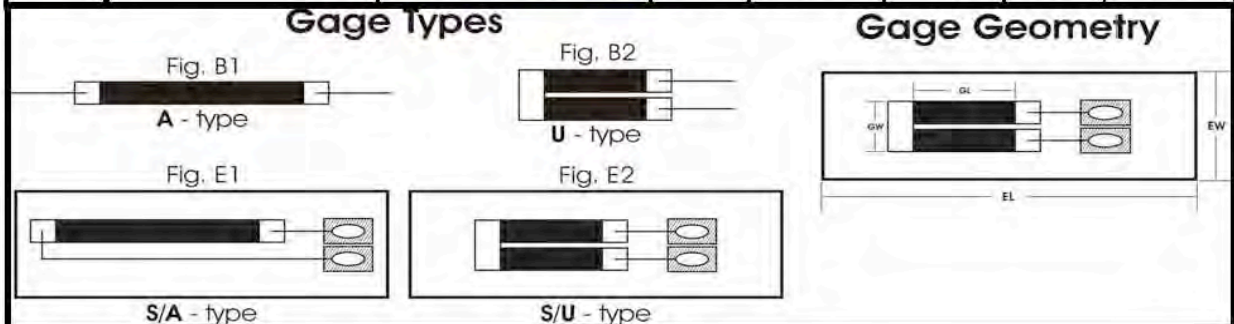
Part IV – Mounting Solder Tabs and Gage Application (For bare gages only)

1. Pre-tin tabs with solder.
2. After 4 hour cure, remove beams from curing oven. Allow to cool, and apply a thin layer of 8121 epoxy with a brush (000) to the back of the tab and place in appropriate locations on beam.
3. Cure at (250°F) for 1 hour.
4. Remove from oven and allow cooling. Solder gage leads to solder tabs.
5. Measure and record gage resistances, and check isolation at 200vdc.
6. Cure at (250°F) for 4 hours.

Part V- Apply Moisture Protection if Needed

STRAIN GAGE CHARACTERISTICS AND SELECTION TABLE

GAGE DOPING CODE	GAGE CHARACTERISTICS	PART NUMBER	FIGURE	EFFECTIVE LENGTH (GL)	GAGE WIDTH (GW)	ENCAPSULATION	
						LENGTH	WIDTH
						±10% (EL)	±10% (EW)
C	GF + 100	ACP - 15 - 150	B1	.100	.020		
	TCR + 4	ACP - 30 - 150	B1	.100	.010		
	TCGF - 6	ACP - 120 - 300	B1	.250	.009		
	Linearity ± 0.2	UCP - 120 - 090	B2	.060	.020		
		S/ACP - 120 - 300	E1	.250	.009	.500	.210
		S/UCP - 120 - 090	E2	.060	.020	.280	.140
D	GF + 115	ADP - 250 - 220	B1	.186	.09		
	TCR + 3	ADP - 350 - 300	B1	.250	.010		
	TCGF - 8	UDP - 350 - 175	B2	.140	.016		
	Linearity ± 0.2	S/ADP - 350 - 300	E1	.250	.010	.500	.210
		S/UDP - 350 - 175	E2	.140	.020	.350	.140
E	GF + 130	UEP - 350 - 090	B2	.060	.020		
	TCR + 6	AEP - 350 - 220	B1	.170	.009		
	TCGF - 10	AEP - 500 - 300	B1	.250	.010		
	Linearity ± 0.2	UEP - 350 - 060	B2	.030	.020		
		S/AEP - 500 - 300	E1	.250	.010	.500	.210
		S/UEP - 350 - 090	E2	.060	.020	.280	.140
F	GF + 140	AFP - 500 - 090	B1	.060	.010		
	TCR + 10	AFP - 350 - 090	B1	.060	.010		
	TCGF - 11	UFP - 750 - 090	B2	.060	.020		
	Linearity ± 0.2	S/AFP - 500 - 090	E1	.060	.010	.280	.140
		S/UFP - 750 - 090	E2	.060	.020	.280	.140
G	GF + 155	AGP - 350 - 090	B1	.060	.010		
	TCR + 18	AGP - 500 - 090	B1	.060	.010		
	TCGF - 13	AGP - 1000 - 300	B1	.250	.010		
	Linearity ± 0.2	UGP - 1000 - 090	B2	.065	.020		
		UGP - 1000 - 060	B2	.030	.020		
		S/AGP - 1000 - 300	E1	.250	.010	.500	.210
	S/UGP - 1000 - 090	E2	.060	.020	.280	.140	
H	GF + 175	AHP - 10000 - 220	B1	.170	.009		
	TCR + 45	AHP - 10000 - 300	B1	.250	.009		
	TCGF - 23	UHP - 5000 - 060	B2	.030	.020		
	Linearity ± 0.2	S/AHP - 10000 - 220	E1	.170	.009	.250	.150
		S/AHP - 10000 - 300	E1	.250	.009	.500	.210
		S/UHP - 5000 - 060	E2	.030	.020	.250	.140





KULITE SEMICONDUCTOR PRODUCTS, INC.

One Willow Tree Road • Leonia, New Jersey 07605 USA

Tel: 201 461-0900 • Fax: 201 461-0990

Email: info-kulite@kulite.com • <http://www.kulite.com>

Kulite holds 3rd party approval for AS9100 and ISO9001 as well as SIRA and CSA certifications.
Kulite is an approved FAA/EASA/CAAC repair station.
Please visit our web site for details.



Continuous development and refinement of our products may result in specification changes without notice.