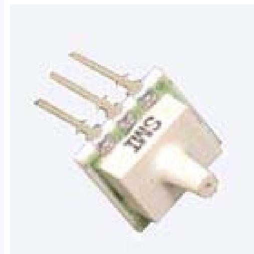
Compensation Approaches for Model SM5300 and SM5400 Series

INTRODUCTION

The following is a brief discussion of approaches applicable to the SM5300 and SM5400 series, uncompensated pressure sensors. The SM5300 and SM5400 parts are pressure die mounted in either surface mountable packages or in simple dual-in-line packages. These package styles are meant for customers who want to avoid the issues of die attach, wirebond, and pressure porting but do not want the cost associated with buying a fully temperature compensated and calibrated part, such as the SM5500 and SM5600 series.



SM5310, SM5410, and SM5455 Packages

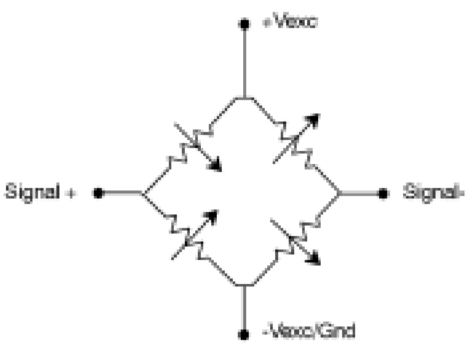


Figure 1 - 5310, 5415, and 5455 Equivalent Circuit

The SM5310 is a small closed-bridge device as diagrammed in Figure 1 below. This part has 4 leads – positive excitation, signal +, signal -, and ground. The SM5415 and SM5455 are also 4 lead devices and as such, the notes on the 5310 are applicable also for the SM5415 and SM5455.

The SM5350, SM5410, and SM5450 have a 5 lead configuration – positive excitation, signal +, signal -, and two leads from the bottom of the bridge for zero trim resistors. This is shown in Figure 2.

NEED FOR COMPENSATION

All sensor die need to be compensated for four parameters in order to get reasonable precision out of them. These parameters are:

- *Zero*
- *Temperature Coefficient of Zero*
- *Sensitivity, and*
- *Temperature Coefficient of Sensitivity*

In addition, the standard piezoresistive pressure sensor has some nonlinearity as a function of pressure and, further, the temperature coefficients of both zero and sensitivity tend to have a second-order temperature dependence.

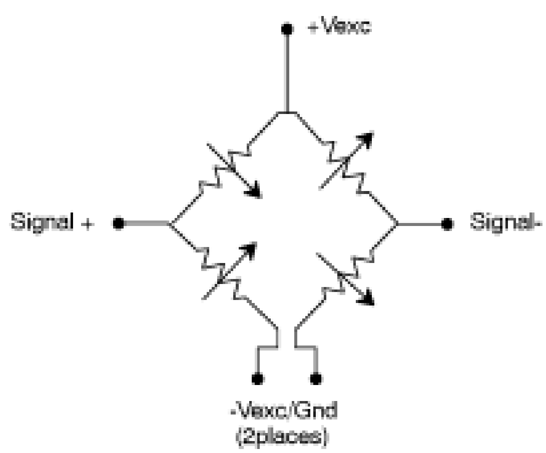


Figure 2 - 5350, 5410, 5450 Equivalent Circuit

In the vast majority of cases, the pressure nonlinearity can be ignored as can the second order effects.

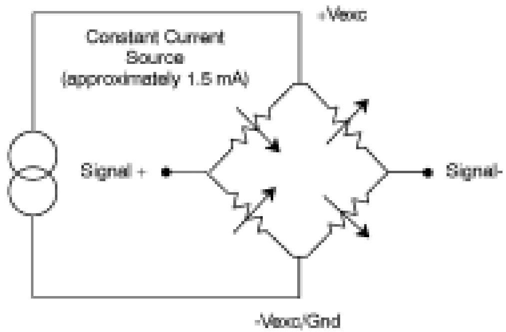


Figure 3. Constant Current Drive

For the purposes of the application note, we will ignore the second-order TC errors (typically resulting in less than a 1% error over the extended range of –20 to +85°C).

Pressure sensors can be compensated in several different ways. There are advantages and disadvantages to each. For the sake of simplicity, a "Constant Current" compensation approach is discussed below. There is also a constant voltage approach, and a diode compensation approach, as well as approaches that use thermistors.

GENERAL CHARACTERISTICS OF PIEZORESISTIVE SILICON PRESSURE SENSORS

To understand the compensation approach, it is necessary to understand what is physically happening in a typical pressure sensor. As stated above, there are four unknowns in the typical sensor.

Zero Error: The zero error is due to several parameters but the simplest explanation is that we have four resistors each with some variability

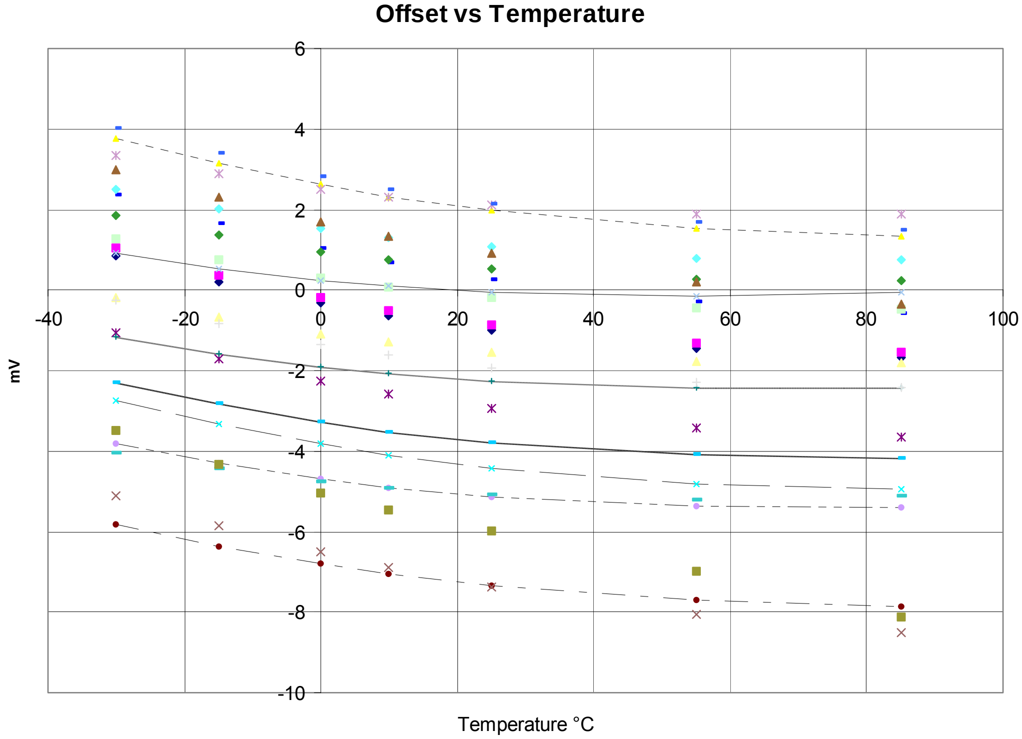


Figure 4. Offset as a function of Sensitivity for Typical Die Used in the SM5310 and SM5410 Packages
Note: 23 different parts have been plotted in this figure from 4 different lots over a 9 month period.

in resistance. While the resistors are processed at the same time, there are some variations. The nominal specification for most offsets are ±25mV bridge offset with 5 volt drive. This maps into a combined worst-case uncertainty of ±0.25% resistor matching on any bridge. For many sensors, the resistor width is in the 15 μm range so slight variations in width, down in the 0.04μm range, can produce this type of error. More typically, the true variation in the resistor matching is better than 0.05%. Even with this precision, the resultant offset for a 5 volt drive is 5mV.

Temperature Coefficient of Zero: The TC Zero (TCZ) errors originate from several sources including die attach, residual stress in the thin-films coating the silicon diaphragm, the registration of the resistors with respect to the diaphragm, and the resistor shapes. For a particular design on a high performance die, the TC Zero is consistent. This is shown in **Figure 4**. In this case, the zero changes by about 2mV from –25 to +85 for a 5V drive. At 150mV output for full-scale pressure, this represents less than a 1.3% total error for TCZ, or approximately +0.65%.

Sensitivity: Sensitivity is primarily set by diaphragm thickness. Sensitivity is normally given in units of mV/V/pressure unit and, to first order, sensitivity is proportional to the average stress in the resistors. Using classical mechanical models, stress is proportional to the square of 1/diaphragm thickness. For a 10% uncertainty in diaphragm thickness, there is a 20% variation in sensitivity. Sensor companies in general specify the sensitivity to +33% of the nominal value. This represents the ability to achieve better than a 15% total accuracy in diaphragm control both between wafers and across wafers.

For the case of constant current compensation, there is also the issue of the absolute resistance. This will impact the apparent sensitivity when computed in mV/mA/psi. The SM5310 and SM5410 series parts are specified to have resistance nominally of 3.3kΩ with an absolute limit of ±18%. This allows for some absolute

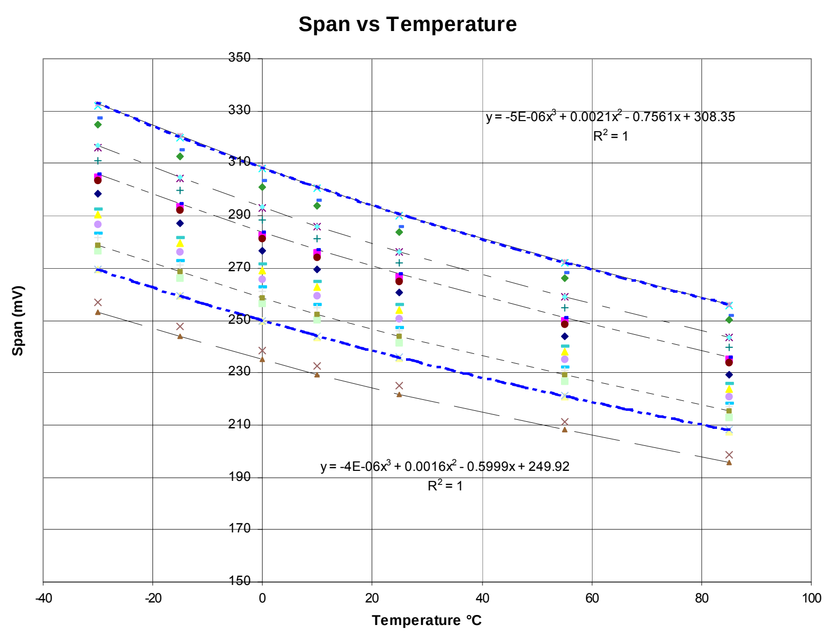


Figure 5. Span vs Temperature
Note: Span is equal to drive voltage times Full-scale pressure times sensitivity.

variations in linewidth control for the resistors, as well as some normal bias in the actual mean resistor target value. Typically, the resistance is held to better than ±10% on any lot. Total sensitivity variation that can be observed for parts used in constant current applications is the sum of these variations (±33% for sensitivity and ±10% for resistance).

Temperature Coefficient of Sensitivity (TCS): This particular parameter is most effected by the compensation approach used as will be seen below. For a sensor driven from a constant voltage source, sensitivity (mV/V/pressure unit) decreases with temperature. This is directly dependent on the mobility of electrons in the piezoresistors. **Figure 5** shows a typical set of plots for the die used in the 5310 and 5410 packages.

Over the –30 to +85 °C range, the typical variation in slope on this particular parameter is very small (-2280 ppm/°C±16 ppm/°C, mean ± standard deviation). This is strictly for constant voltage excitation.

When the part is driven from a constant current source, the sensitivity out is then:

Vout = I X R(temperature)
X Sensitivity (temperature)

Thus, the effective output is proportional to the bridge resistance over temperature times the sensitivity over temperature. The temperature effect on resistance is shown in **Figure 6**.

The Temperature Coefficient of Resistance (TCR) tends to change based on the exact process schedule for the fabrication of the piezoresistor. This is shown in the figure based on the curve fit for device 23 and device 11. Device 11 was fabricated with a slightly different thermal cycle than was device 23. The equation on the top corresponds to device 23 while the equation on the bottom maps to device 11. Typically, the TCR variation is limited to ± 10% of the nominal resistance.

The effect of the sensitivity resistance product is shown in **Figure 7**. This is what one would expect to see for sensitivity changes on parts

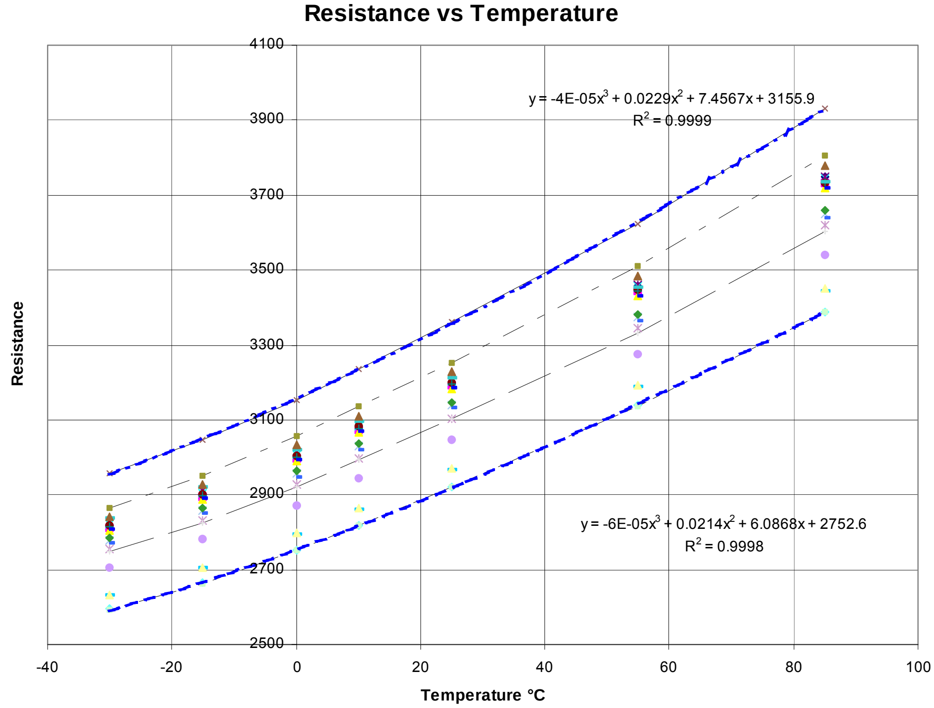


Figure 6. Resistance vs Temperature

under constant current excitation.

COMPENSATION OF THE 5310 AND 5410 PARTS

The principle concern in many applications is with the temperature performance of the part. Part-to-part temperature independent zero errors and sensitivity errors can be handled in many cases with a microprocessor controlled A/D system to obtain the zero and full-scale readings once. In other cases, the application requires significant accuracy and the zero error has to be eliminated as quickly as possible in the signal path. In this case, the circuitry can become rather complex as shown in **Figure 8** for the SM5310 and a little simpler for the SM5410. The two resistors used for trim offset are computed after the RTZ resistor has been added in the circuit.

Note that the absolute precision needed for the application will determine if each part needs to be characterized independently. For total accuracy's less than 1% over extended temperature ranges, detailed calibration for each sensor is required. Choosing fixed resistors without measuring the individual part should provide for accuracy in the 2 to 5% range; slightly better performance can be achieved by recentering the fixed resistors based on the bridge impedance and TCR for the given lot.

For the case where zero trimming is dealt with in other electronics and the objective is to provide a simple temperature compensated part, the circuit in **Figure 9** is useful. In this case, only the TC of Sensitivity and the TC of Zero are actually being trimmed. The zero and the sensitivity are trimmed through other electronics.

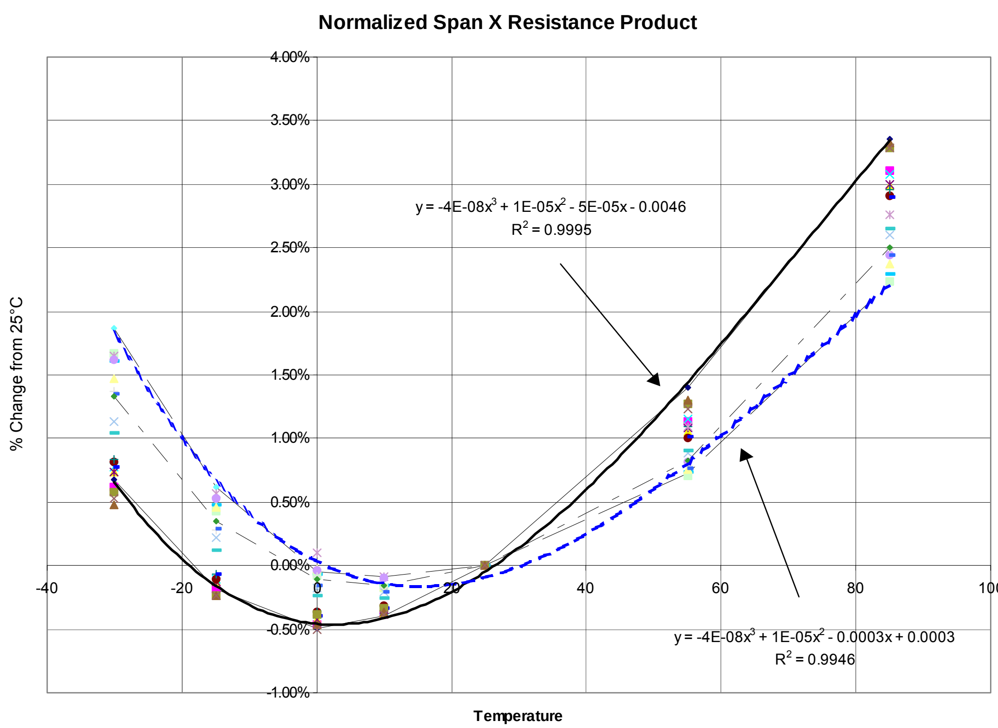


Figure 7. Span-Resistance Product vs. Temperature
Note: This is equivalent to the temperature behavior of the sensor when driven in a constant current mode.

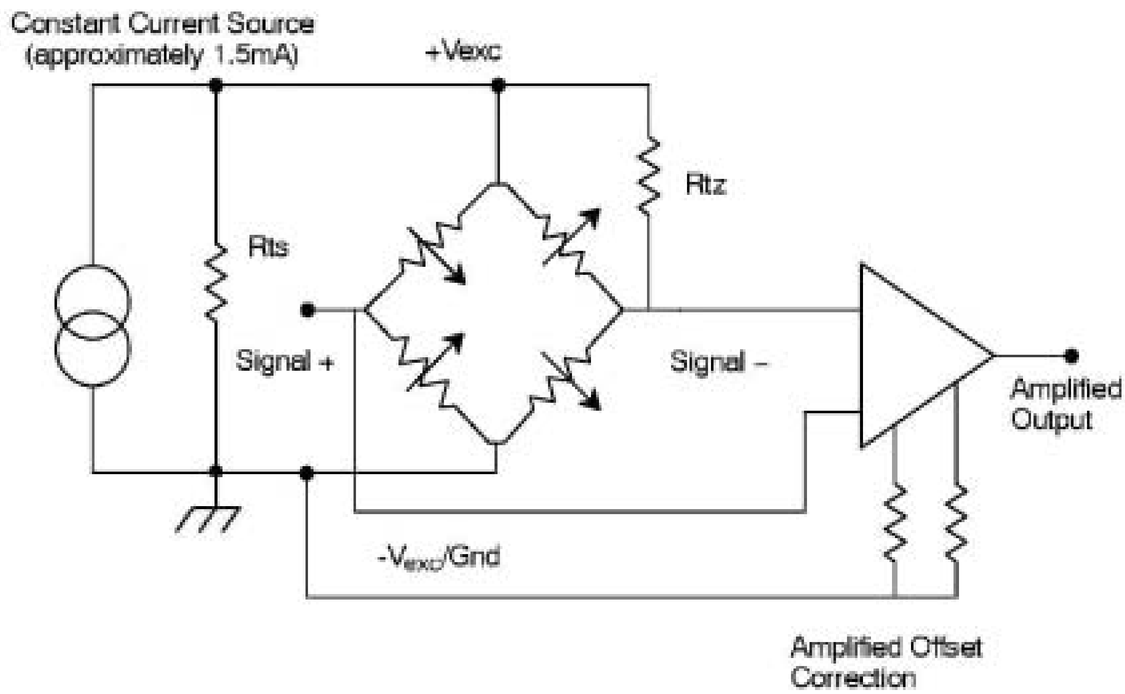


Figure 8A. Offset Correction Approach for SM5310, SM5415, and SM5455

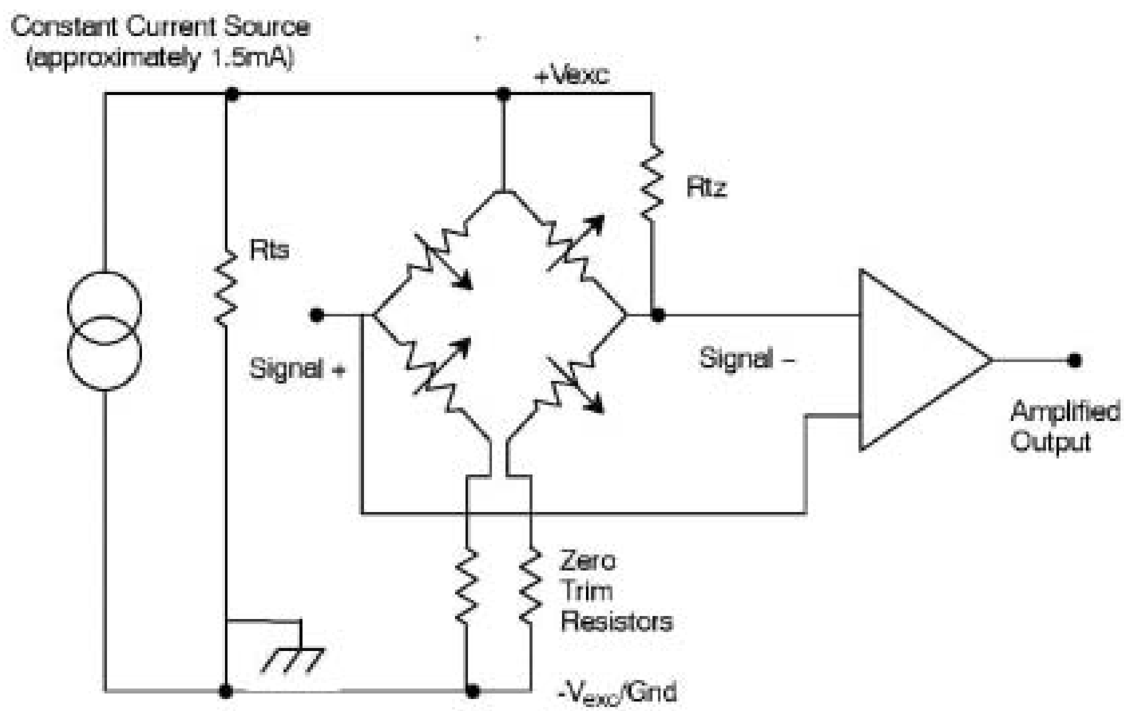


Figure 8B. Offset Correction approach for SM5410, SM5350, and SM5450

The exact order of trimming is not important in this case. Either the TCZ or the TCS can be determined, without significantly impacting the other.

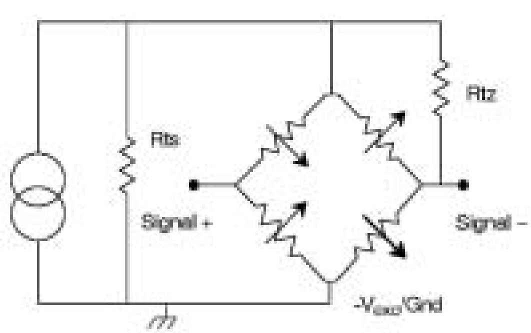


Figure 9. Simplified Compensation Circuit for TCZ and TCS Correction

Temperature Coefficient of Zero:

The Rtz resistor is used to correct for the TC of zero. Effectively what is being done is artificially lowering the TC of the resistor across which the Rtz resistor is shunted. In the perfectly balanced bridge, the four resistors are identical and as the temperature is increased all four resistors track and the output does not change. By shunting one leg of the bridge as shown, the bridge is intentionally imbalanced.

The output is given as:

$$Vout = Vexc\left(0.5 - \left(\frac{Rb}{Rb + (Rb \parallel \mathrm{Rtz})}\right)\right)$$

$$Vout = Vexc\left(0.5 - \left(\frac{1}{1 + \left(1 + \left(\frac{1}{1 + \left(\frac{1}{Kz}\right)}\right)\right)}\right)\right)$$

Where:

Vexc	=	the drive across the sensor
Rb	=	the bridge impedance
Rtz	=	the zero compensation resistor
Kz	=	Rtz/Rb

As shown in **Figure 4**, the nominal change in offset is –2.0 mV/100°C. For nominal 3.3kΩ bridge, the output will change by –2.2 mV given a TCR of 2700 ppm/°C if Rtz is set at 0.5MΩ.

Thus, one algorithm to allow a reduction in offset error without measuring each individual part would be to put a 0.5 MΩ Rtz resistor as shown in the circuit. This will produce a TC offset error in the range of ± 0.5 mV over the range of –20 to +85°C, without need for actually measuring the individual parts. Note that the addition of this resistor will create an offset of about –8mV, over and above any residual offset already resident in the sensor. This is summarized in **Table 1**.

This result can be optimized based on the bridge impedance and also based on the TCR reported for the wafer lot. However, as shown in the table, the nominal change of –2.0mV is obtained for TCR's of 2600 to 2800 ppm/°C and for a ±10% variation in resistance. Note that for limited temperature ranges, for instance, 5 to 85°C, the slope of the offset change is lower and R_{TZ} may be 2 to 4 times higher.

Table 1. Temperature Coefficient of Zero Reduction in Offset

TCR (ppm/°C)	Current	Rb	Rtz	$V_{out}(t_1)$ mV	$V_{out}(t_1 + 100\ °C)$ mV	$\Delta V_{out}/(100\ °C)$
2700	1.5mA	3.0k	1.0M	-3.744	-3.744	-1.1mV
2700	1.5mA	3.0k	0.5M	-7.478	-9.489	-2.0mV
2700	1.5mA	3.3k	0.5M	-8.223	-10.434	-2.2mV
2600	1.5mA	3.3k	0.5M	-8.223	-10.352	-2.1mV
2800	1.5mA	3.3k	0.5M	-8.223	-10.516	-2.3mV

Temperature Coefficient of Sensitivity

The TC of Sensitivity can similarly be estimated with reasonable accuracy as well.

$$Vout = Sensitivity \times I \times (Rb \,\|\, \mathrm{Rts})$$

$$Vout = Sens\left((1 + TCS \times temperature) \times I \times \left(\frac{(1 + TCR \times temperature)}{1 + (1 + TCR \times temperature)\dfrac{Rbo}{Rts}} \right) \right)$$

Where:

I	=	the drive current across the sensor
Rb	=	bridge resistance
TCR	=	the fractional change in resistance for a given temperature increment
TCS	=	the fractional change in sensitivity for a given temperature increment
Temperature	=	the temperature increment
Rts	=	the sensitivity compensation resistor
Rbo	=	Rb @ reference temperature

In this case, what the algorithm effectively is doing is decreasing the effective TCR; this makes the increase in drive voltage (I X Rb) (equivalent to the increase in resistance shown in **Figure 6**) be equal and opposite to the decrease in sensitivity (as shown in **Figure 5**). With no Rts resistor, the equivalent transfer curve looks like that shown in **Figure 7**.

Current SMI products exhibit a sensitivity resistance product as shown in the upper curve. In this case, to produce the optimum performance from –20 to +85°C, the lower end of the curve needs to be raised while the upper end of the curve is lowered. With the total error from 25 to 85°C, reduced to about 1.25%, the cold error will also be in the range of 1.25%. Thus, the design target, over the extended range is to intentionally set the above equation to give about a 1.25% increase, compared to the current 3% increase as indicated in **Figure 7**. If the equations are solved and Rts is made a multiple of Rb, then for perfect matching (assuming a perfectly linear transfer), Rts should nominally be 4 times Rb, for a TCR of 2700 ppm/°C and 4.6 times Rb for a TCR of 2600 ppm/°C. This was based on a 50°C temperature increase (approximately representing the change from 25°C to 75°C). This is solved explicitly in the equation below.

To achieve a slight increase in transfer, Rts can be intentionally made higher than the perfect target. In this case, if Rts is chosen to be 8.4 times Rb, the composite sensitivity will increase by about 1.25% going hot, and due to second order effects in both TCR and TCS, the performance cold will also be about 1.25% above the sensitivity at 25°C. As with the RTZ, the RTS resistor value will depend on the intended temperature range of the part.

$$k = -1 - \frac{TCR \times temperature}{1 - (1 - \partial)(1 + TCS \times temperature)(1 + TCR \times temperature)}$$

Where:

k	=	ratio of Rts/Rb
TCR	=	the fractional change in resistance for a given temperature increment
TCS	=	the fractional changes in sensitivity for a given temperature increment
∂	=	intentional residual error desired
Temperature	=	the temperature increment
Rts	=	the sensitivity compensation resistor

SUMMARY

The design equations and examples of typical values for the SM5310 and SM5410 products has been presented. The TCZ is small (less than -2mV/100°C) and may not need an RTZ resistor in many applications. However, if it is desirable to reduce this to zero, on average, a 0.5 MΩ resistor can be added between the negative output and the supply. This result is close to a ±0.5 mV error over the –20 to +85°C range.

The sensitivity shows an uncompensated increase over temperature of about 3% from 25 to 85°C. This can be corrected by adding a shunt resistor across the excitation applied to the sensor, if the sensor is driven from a constant current source. For near ideal compensation from 25 to 85°C, some under compensation is needed to make up for the non-ideal behavior below 0°C. In this case, an Rts resistor 8.4 times the bridge resistance is recommended.