

Effects of Thermo-compression Die Bond Residual Stress on MEMS Inertial Sensors

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Abstract

In inertial sensor applications a thermocompression bond is often used for die attachment in hermetic, vacuum packages. These bonds are made by heating the ceramic chip carrier and the MEMS sensor die to ~325°C, bonding the components, and cooling to ambient conditions. Due to mismatch in thermal expansion coefficients between the ceramic package and the sensor die, there is a residual stress that results in deformation of the die. In applications where a capacitive sensor between a structure and the substrate is used for measurements this bowing may be a source of error, as in tuning fork gyroscopes. Additionally, as the temperature of the component changes the curvature in the die also changes, decreasing while approaching the bonding temperature. It has also been observed that over time there may be a relaxation effect, alleviating residual stresses and reducing surface curvature at ambient temperature.

The changes in the shape topography of the MEMS die may adversely affect performance. By using several methodologies these effects are closely studied. Finite element analysis of a die bonded in a package is performed to determine the expected deformation. The degree of deformation (as a function of temperature) of components is measured using interferometric techniques to corroborate FEA findings. The performance of MEMS gyroscopes is measured using a Wuilfert EVO-10 rate table with custom thermal loading apparatus, allowing for investigation of the relation between sensing voltage with temperature and die curvature.

Keywords: MEMS, relaxation, gyroscope, rate table, thermal

1. Introduction

Microelectromechanical Systems (MEMS) inertial sensors have traditionally been one of the most successful concepts adapted to the microscale. Such sensors have high response time, high quality factor, small footprint, low power consumption, and low cost of fabrications [1].

There are a variety of error sources in these inertial sensors, resulting in both mechanical and electrical noise. These errors are currently the limiting factor in applying MEMS technology for complete inertial navigation.

One potential error stems from the die bond attachment during packaging. In order to maximize the Q-factor a high vacuum environment is required [2]. Such a vacuum is not compatible with an epoxy die attach method, requiring braze or thermo-compression bonding (TCB). In these bonding applications the complete system (die and package) are heated to approximately 325°C for bonding and cooled to ambient temperature [3]. Braze die attachment using eutectic AuSn has been investigated for time dependant relaxation [4], however there has been little work examining the behavior of gold TCB. Different coefficients of thermal expansion between the glass die and ceramic package introduce residual stresses that distort the chip.

The residual thermo-mechanical stress may directly affect the performance of a gyroscope by making a non-uniform plate in the capacitor sense element. The curvature of the stressed substrate may change due to thermal loading or relaxation of the gold TCB over extended periods of time [5-8].

2. MEMS Gyroscope operation

One form of a MEMS gyroscope is the tuning fork gyroscope (TFG), an example of which is shown in Figure 1. Such gyroscopes are reliant on a Coriolis force acting on vibrating proof masses when a rotation is introduced [9]. A gap between the proof mass and the MEMS substrate acts as a capacitor. The measured capacitance is inversely proportional to the gap distance. Any curvature in the substrate may adversely affect the gap distance, particularly if the curvature is not constant with time or temperature.

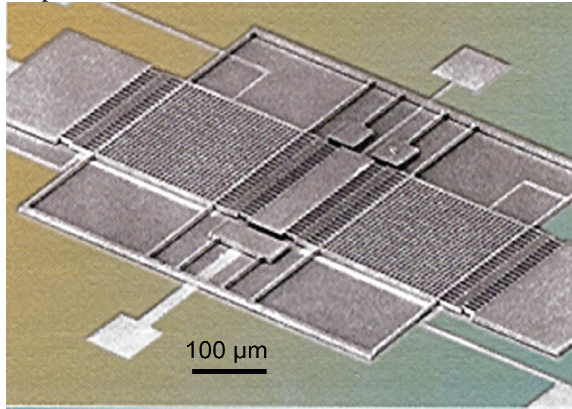


Figure 1. MEMS tuning fork gyroscope.

The gyroscopes in this study are fabricated using silicon on insulator (SOI) for the MEMS components, which are anodically bonded to a Hoya SD-2 glass. The material properties of the MEMS chip are those of the glass.

3. Computational model

Finite element analysis of the system is performed using Elmer FEA solver [10], in conjunction with Gmsh pre-processor [11]. A model of a glass MEMS die, compression bonded into an alumina chip carrier at a temperature of 325°C, and then cooled to room temperature has been made. The thermo mechanical deformations are extracted, as well as shear stresses in the gold bump bonds.

The geometry of the system is defined using Gmsh, with the meshed volume shown in Figure 2. The model is based on a square die of length 4000 μm and thickness of 500 μm. Nine bump bonds are

used for attachment, distributed in a uniform array about the center of the die, lateral spacing of 1500 μm between bump bonds.

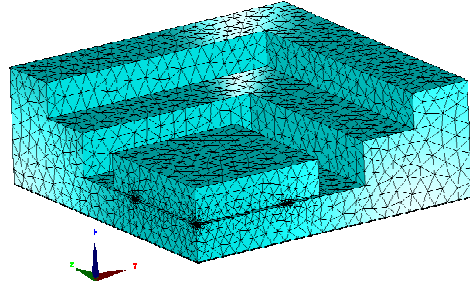


Figure 2. Mesh of MEMS die bump bonded to alumina package: quarter model.

This packaged system is comprised of three materials, with pertinent properties listed in Table 1.

Table 1. Material properties of TCB components.

	$\rho, \left[\frac{kg}{\mu m^3} \right]$	$E, \left[\frac{kg}{m s^2} \right]$	$\alpha, \left[\frac{ppm}{^\circ C} \right]$
Al ₂ O ₃	3.89e-15	375.0e03	8.4
Au	19.3e-15	78.0e03	14.2
Hoya SD-2	2.6e-15	86.9e03	3.2

The locations of the bump bonds are as shown in Figure 3. The height of the bumps is 35 μm. A quarter model is used, with appropriate boundary conditions applied to the sectioned surfaces, to reduce the number of elements.

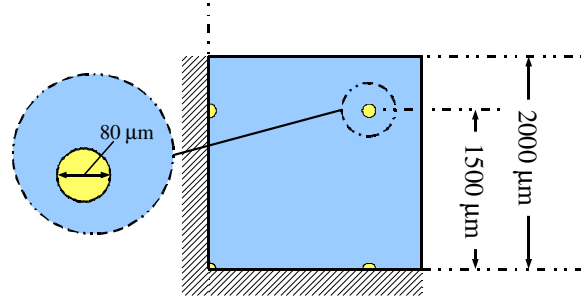


Figure 3. Geometry of bumps in MEMS die: quarter model.

4. Analytical model

A schematic of the bonded assembly, after cooling to ambient temperature, appears in Figure 4. The chip carrier has a larger coefficient of thermal expansion (CTE) than the chip, applying a shear force, F , to the bottom surface of the chip, which is transmitted through the gold bumps. The chip and chip carrier are both ideal elastic materials, in contrast to the gold bumps, which exhibit visco-

elastic behavior, so their state of stress is time dependant.

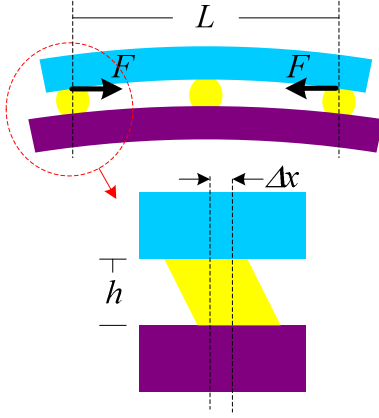


Figure 4. Schematic cross section of bonded assembly after cooling to ambient temperature.

The total shear strain, ϵ_T , of the gold bumps, as illustrated in Figure 4, is comprised of elastic and plastic components, ϵ_E and ϵ_P respectively, such that

$$\epsilon_T = \epsilon_E + \epsilon_P = \frac{\Delta x}{h} \quad (1)$$

where Δx is the displacement between the midpoints of the top and bottom surfaces of the bump, which is of height h . The magnitude of this total strain is the product of $\Delta\alpha$, the difference in coefficients of thermal expansion, $L/2$, the distance between the gold bump and the neutral axis of the assembly, and ΔT , the difference between the bond and ambient temperatures, thus

$$\epsilon_T = \frac{\Delta\alpha \Delta T L}{2 h}. \quad (2)$$

The elastic strain is proportional to the shear force, F , which is applied to the chip and can be written as

$$\epsilon_E = \frac{1}{G} \frac{F}{A} = \frac{\sigma}{G}, \quad (3)$$

in which A is the cross sectional area of the bump, and G is the shear modulus of gold. The chip can be modeled as a simple beam with applied bending moments, as shown in Figure 5.

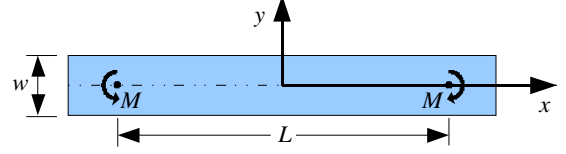


Figure 5. Bending moments applied to the chip at the locations of the gold bumps.

The chip's curvature, κ , which is approximated by the second derivative of displacement, can be written in terms of the applied bending moment, M , the chip's modulus of elasticity, E_C , and the bending moment of inertia, I_C ,

$$\kappa = \frac{\partial^2 y}{\partial x^2} = \frac{M}{E_C I_C} = \frac{F w}{2 E_C I_C}. \quad (4)$$

Since the applied force is the product of the bump's shear stress, σ , and its cross sectional area, A , Eq. 4 can be rewritten as

$$\kappa = \frac{\sigma A w}{2 E_C I_C}. \quad (5)$$

The plastic strain behavior of gold is described by the equation

$$\frac{d\epsilon_P}{dt} = S \exp\left(\frac{-\Delta H}{RT}\right) \sigma^n, \quad (6)$$

in which S is a constant, ΔH is the activation energy, R is the gas constant, T is the absolute temperature and n is a constant. By combining Eqs 1 and 3, the stress can be written as

$$\sigma = G \epsilon_E = G (\epsilon_T - \epsilon_P). \quad (7)$$

Substitution of Eq. 7 into Eq. 6 yields

$$\frac{d\epsilon_P}{(\epsilon_T - \epsilon_P)^n} = S \exp\left(\frac{-\Delta H}{RT}\right) G^n dt. \quad (8)$$

Upon integration of Eq. 8 we obtain

$$\frac{(\epsilon_T - \epsilon_P)^{(1-n)}}{1-n} = S \exp\left(\frac{-\Delta H}{RT}\right) G^n t + C, \quad (9)$$

in which C is a constant of integration. At time $t = 0$ it is assumed that all strain is elastic ($\epsilon_P = 0$), thus

$$C = \frac{(\epsilon_T)^{1-n}}{1-n}, \quad (10)$$

which upon substitution of Eq. 2 for the total strain becomes

$$C = \frac{\left(\Delta\alpha \Delta T L \frac{1}{2h}\right)^{1-n}}{1-n}. \quad (11)$$

The shear stress acting on the gold bumps as a function of time is obtained by first substituting ϵ_E for the difference between the total and plastic strains in Eq. 9, i.e.,

$$\frac{(\epsilon_E)^{(1-n)}}{1-n} = S \exp\left(\frac{-\Delta H}{RT}\right) G^n t + C, \quad (12)$$

and then substituting Eq. 11 for C and rearranging terms to obtain

$$(\epsilon_E)^{1-n} = (1-n) S \exp\left(\frac{-\Delta H}{RT}\right) G^n t + \left(\Delta\alpha \Delta T L \frac{1}{2h}\right)^{1-n} \quad (13)$$

Substitution of Eq. 7 for the elastic strain may be performed, giving

$$\sigma = \left[(1-n) S \exp\left(\frac{-\Delta H}{RT}\right) G t + \left(G \Delta\alpha \Delta T L \frac{1}{2h}\right)^{\frac{1}{1-n}} \right] \quad (14)$$

The curvature as a function of time may be found by substitution of Eq. 14 into Eq. 5, yielding

$$\kappa = \frac{A w}{2 E_c J_c} \left[(1-n) S \exp\left(\frac{-\Delta H}{RT}\right) G t + \left(G \Delta\alpha \Delta T L \frac{1}{2h}\right)^{\frac{1}{1-n}} \right] \quad (15)$$

5. Experimental analysis

To complete the experimental analysis of MEMS gyroscopes with curvature caused by residual thermo mechanical stresses two methods are utilized, interferometric shape measurements to compare with FEA and analytical results, as well as characterization of MEMS gyroscopes using a precision rate table with a custom thermo electric cooler (TEC) system used for thermal loading.

5.1. OELIM system

To measure the curvature in a MEMS die an optoelectronic laser interferometric microscope

(OELIM) system is utilized. The interferometer is based on a Twyman-Green phase shifting interferometer (PSI). Such systems are often adopted for the study of MEMS topography due to the high accuracy out of plane and compatibility with relatively flat, highly reflective surface, such as MEMS.

Although using interferometers is common in MEMS measurement, there has been little work done in measuring a substrate under a component. To quantitatively analyze a measurement a continuous surface is required for phase unwrapping. Generally a MEM structure covers a significant portion of the area, such is the case with the TFG.

In this application however the substrate is extremely flat, such that there is maximum deviation of less than one fringe (320 nm for the LED used) over the surface. It is possible to artificially link the regions by connecting the 12 areas in each of the phase steps prior to analysis, as shown in Figure 6.

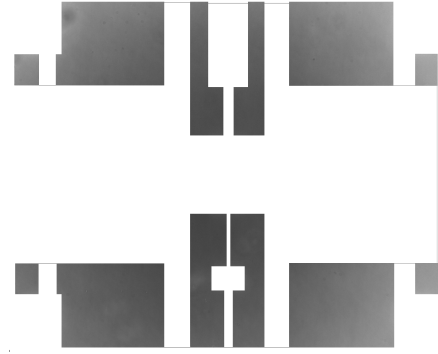


Figure 6. Substrate regions of MEMS gyroscope.

A second order surface may be fit by least squares method to the analyzed surface to obtain a mathematical representation of the form

$$Z(x, y) = A + Bx + Cy^2 + Dx + \dots + Exy + Fx^2 \quad (16)$$

where $A, B, \dots, F$ are constants to be determined. Again the principal curvature may be approximated by the second derivative of the surface.

Measurements are also made on a gyroscope that has been bump bonded into a package, of the form shown in Figure 7.

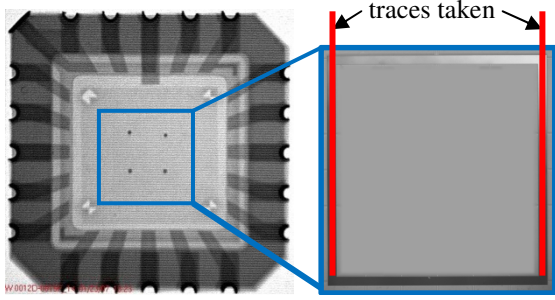


Figure 7. Xray image of packaged gyroscope, metalized frame on the component.

The MEMS component has been masked out of the image; the frame, which is directly on the substrate glass, is measured for curvature values.

Initial measurements were made shortly after die bonding, a second set of measurements were made approximately 18 months later, after some bond relaxation occurred. The differences in curvature over this time aide in the development of the analytical model of the system.

5.2. Gyroscope characterization

Although in the past there has been a discussion as to the presence of curvature in the die, and potential relaxation of the gold bump bonds, there has been little investigation into the effects that changes in curvature may have on the performance of a gyroscope.

Characterization of the MEMS TFG is performed herein with a precision rate table with custom thermal loading capabilities. In particular, the Wuilfert EVO-10 rate table, shown in Figure 8, is outfitted with a TEC heating/cooling element, capable of temperature ranges between 5 and 85°C.

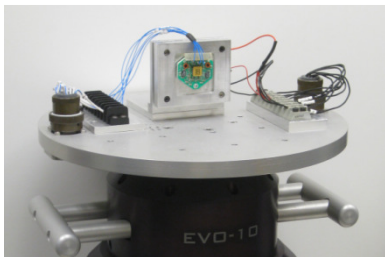


Figure 8. MEMS TFG mounted on EVO-10 rate table.

The table is used to maintain constant rates spanning the usable range of the gyroscope, with voltage outputs recorded from the TFG. This process is repeated at temperatures steps of 20°C. A linear

trend is observed, with the slope equal to the scale factor, and the intercept equal to the bias voltage.

6. Results

6.1. Computational

Solutions for the displacements normal to the chip are shown in Figure 9. Contour lines show levels in 0.1 μm increments from the die center.

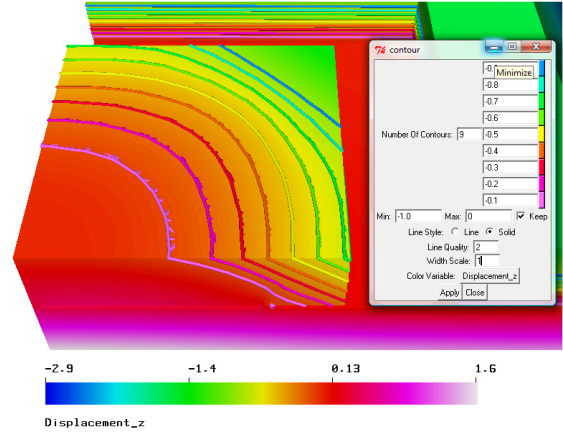


Figure 9. Out-of-plane displacements of MEMS die, Elmer simulation: quarter model.

It is assumed that the deformation follows a second order form until reaching the bumps, at which point a linear deformation occurs. This hypothesis is supported based on the output of the FEA solution. An approximation of the curvature of the die is made by the displacement of the MEMS die directly above the bump bond. Through the x-axis it is shown that the deformation, relative to the center of the die, is -0.4 μm . Fitting a second order polynomial through this point, with a linear coefficient of zero, result in the trace

$$y = -1.86 \times 10^{-7}(x^2), \quad (17)$$

which corresponds to a curvature of

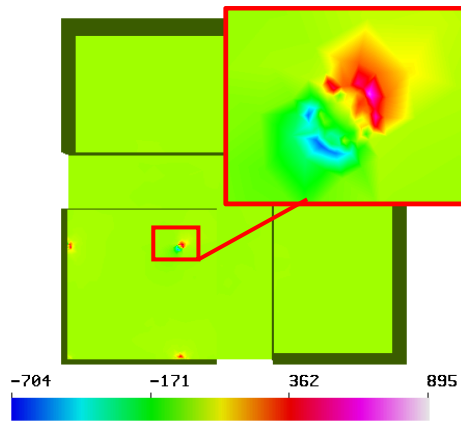
$$\kappa_{FEA} = \frac{\partial^2 x}{\partial y^2} = -3.72 \times 10^{-7} \mu\text{m}^{-1}. \quad (18)$$

This procedure of approximating the curvature is repeated for different temperature changes, simulating the steady state thermal condition of 5-85°C in 20°C increments. The curvatures, along with the percent reduction from the 5°C reference point, are summarized in Table 2

Table 2. Summary of Elmer simulations.

T, °C	κ_{FEA} , μm^{-1}	% reduction
5	-3.72E-07	0%
25	-3.47E-07	-7%
45	-3.26E-07	-12%
65	-3.02E-07	-19%
85	-2.81E-07	-24%

Solution of the finite element model also allows for investigation into the shear stress after cooling to ambient conditions. The shear in the x-y plane is shown in Figure 10, with units for the stress of $\text{kg}\cdot\mu\text{m}^{-1}\cdot\text{s}^{-2}$.

**Figure 10. Shear stress on the top of a gold bump.**

The yield stress for gold wire used to make the gold bumps is $170 \text{ kg}\cdot\mu\text{m}^{-1}\cdot\text{s}^{-2}$, thus there is plastic deformation in the areas where the stress exceeds this value.

6.2. Analytical

The curvature of the bonded die based on the solution of Eq. 5 is performed for ΔT values ranging from -320 to -240°C. The bending moment, I_C , is defined for a width of $1 \mu\text{m}$, approximating a thin slice through the center of the chip. The curvatures for different temperature states are shown in Table 3.

Table 3. Summary of analytical calculations.

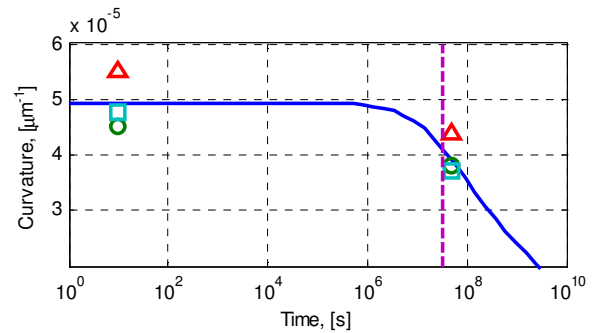
T, °C	$\kappa_{Analytical}$, μm^{-1}	% reduction
5	0.0690	0%
25	0.0647	-6%
45	0.0604	-12%
65	0.0561	-19%
85	0.0518	-25%

Additionally the creep model for curvature as a function of time (Eq. 15) is solved. The variables used for solution are as defined in Table 4.

Table 4. Values used for time-dependent model.

Variable	Value	Units
n	6.57	--
S	$6.1\text{e-}38$	$\text{Pa}^{-n}\cdot\text{s}^{-1}$
ΔH	132.9	$\text{kJ}\cdot\text{mol}^{-1}$
T	293	°K
R	$8.31\text{E-}03$	$\text{kJ}\cdot\text{mol}^{-1}\cdot\text{°K}^{-1}$
G	$2.70\text{E+}10$	$\text{N}\cdot\text{m}^{-2}$
Δa	$5.20\text{E-}06$	°K ⁻¹
ΔT	-305	°K
L	$4.24\text{E-}03$	m

The values of stress exponent, n , and the activation energy, ΔH , are provided by Puigcorbé, et al [12]. The geometric constant, S , is based on experimental measurements of a bump bonded MEMS gyroscope. The values in Table 4, used in conjunction with Eq. 15, result in the plot shown in Figure 11. The analytical calculations for the initial curvature differ substantially from experimental measurements, the initial condition for this plot (the value of C , is determined based on measured data rather than the analytical model. The data points on the plot are experimental measurements of three different MEMS die, of the configuration shown in Figure 7.

**Figure 11. Relaxation model of gold TCB die bonding.**

6.3. Experimental

Direct measurement of the substrate curvature is made with the OELIM system. The interferometer is aligned such that modulation is focused on the substrate. The gyroscope structure is masked off and traces are made between the areas of the substrate to allow for unwrapping. The shape of

the substrate is shown at approximately 5 and 85°C, Figure 12.

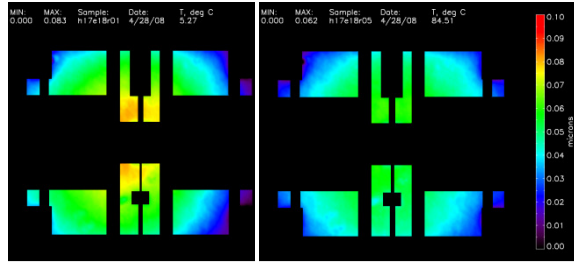


Figure 12. Gyroscope substrate at (left) 5°C and (right) 85°C.

A 2nd order surface is fitted to each temperature state. The average curvature over a lateral trace is approximated by taking the second derivative with respect to x of Eq. 16, summarized in Table 5

Table 5. Summary of experimental calculations.

T, °C	κ_{OELIM} , μm^{-1}	% reduction
5	-5.32E-08	0%
25	-4.96E-08	-7%
45	-4.50E-08	-15%
65	-4.14E-08	-22%
85	-3.66E-08	-31%

Gyroscopes have been measured with the OELIM system at different points in time. A comparison of trace plots at the initial time of bonding, and then again 18 months later, are shown in Figure 13.

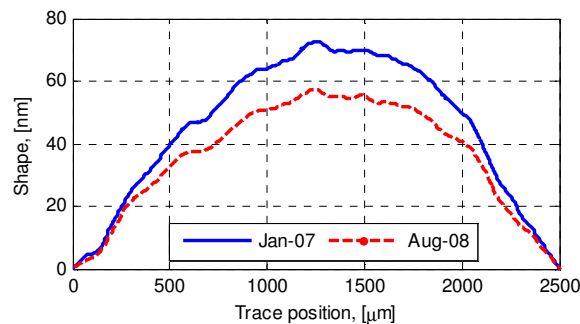


Figure 13. Comparison of traces made on MEMS over time.

A rate table has been used to characterize the TFG performance as a function of temperature, the scale factor and bias are recorded for a gyroscope at different steady state temperature conditions, with the results summarized in Figure 14.

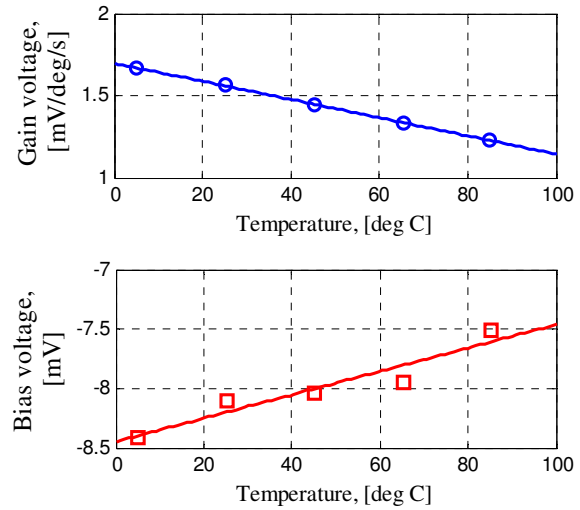


Figure 14. Changes in TFG performance over temperature.

7. Discussion

Comparison of all three solution methodologies shows a consistent decrease in the substrate curvature as a function of temperature, however the magnitudes differ substantially. Both the analytical and computational models are elastic systems, with no plastic deformation considered. The stresses produced are above the yield stress for gold, which would cause plastic deformation until the yield point is reached. There are further discrepancies in the analytical model as it assumes the shear acting on the gold bump is constant, and a maximum, across the entire surface. The maximum stress is only covering a small region of the gold bump, as shown in the FEA analysis. When this force acting on the chip is calculated, the over approximation of area greatly increases the force, F .

Gold bump bonds have been shown to exhibit a visco elastic behavior by measurements made separated by a period of 18 months. This behavior has been modeled, analytically, as shown in Figure 11.

Characterization of a MEMS TFG has been performed at various temperatures. The temperature is inversely related to the curvature of the MEMS die, as the temperature increases the curvature decreases. A similar decrease in curvature is seen as a function of time. It may be possible to predict the change in performance of a gyroscope over extended periods of time by correlating the steady state temperature that will cause a similar reduction in curvature. Other factors should also be considered in this model such

as the temperature dependence of material properties comprising the MEMS component. Influence of thermal dependence of material properties shall be investigated in subsequent studies.

Future work will consist of developing models, both analytical and computational, that will better approximate the stress acting on the gold bumps. Also, the FEA analysis should be expanded to model the relaxation in the gold bump following the form of the equation presented in this manuscript. Additionally, mechanical testing will be performed to better define creep properties used in the relaxation model. This testing will consist of creep testing on gold wire used to make thermo-compression bonds.

8. References

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