EFFECTS OF STRESS ON THE TEMPERATURE COEFFICIENT OF FREQUENCY IN DOUBLE CLAMPED RESONATORS

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ABSTRACT

This paper presents a theoretical framework for evaluating the temperature coefficient of frequency (TCf) of double clamped resonators due to stresses induced by the die and through die packaging. It is desirable to have a zero TCf such that the resonator frequency is stable over a broad temperature range. The TCf depends on how the resonator's material properties, dimensions, and stresses change with temperature. A passive method for using thin film induced stresses in an encapsulated resonator to compensate for material softening is explored. By using a combination of finite element and analytical models it is possible to predict the TCf and improve thermal frequency stability of micromachined resonators.

Keywords: resonator, Temperature Coefficient of Frequency, hermetic packaging

INTRODUCTION

Micromechanical resonators have shown promise to replace current quartz reference oscillator technology in wireless communication and other timing devices. The motivation for development of micromechanical resonators stems from their potential to reduce the size, power consumption, and manufacturing costs through high volume production and CMOS integration. However, one of the hurdles to commercialization is achieving frequency insensitivity to changes in temperature.

The Temperature Coefficient of Frequency (TCf) characterizes the thermal frequency stability of resonators. TCf is the rate of change of frequency with temperature relative to a reference frequency. Uncompensated silicon resonators typically exhibit a TCf of approximately –30 ppm/ºC, which is primarily due to the material softening of silicon. Methods for compensating the effect of material softening are necessary to achieve zero TCf.

Compensation techniques for reducing the TCf of resonators have been explored [1-3] and can be categorized as either passive or active. Passive techniques use a mismatch of coefficients of thermal expansion (α) of different materials to induce stress in the resonator [2]. Active techniques include ovenization (joule heating) [1] and electrostatic tuning (Ref).

This paper presents a theoretical framework for analyzing the TCf of flexure resonators and designing for zero TCf. Changes in TCf due to the electronic packaging of the die are explored. A method of using thin films to compensate material softening and achieve zero TCf in double clamped encapsulated resonators is presented.

TCF OF DOUBLE CLAMPED RESONATORS

Double clamped tuning fork resonators [1], whose frequency can be approximated by a single clamped-clamped (CC) beam, will exhibit stress sensitivity by coupling to the die through the anchor points (Figure 1). The frequency of a CC beam is found by solving for the non-trivial solutions to the equations of motion [4]:

$$f_{CC} = \frac{\beta^2 w}{4\sqrt{3}\pi L^2}\sqrt{\frac{E}{\rho}} \tag{1}$$

where w is the width of the beam in the direction of vibration, L is length of the beam, E is the Young's Modulus, ρ is density, and β is the mode constant. The mode constant for the first mode of unstressed CC beams is 4.73.

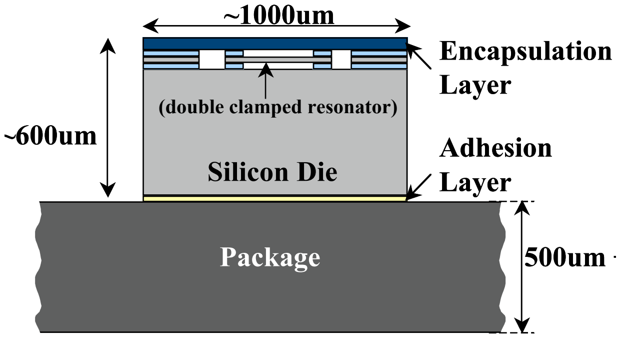

Figure 1: Device Schematic: A double clamped resonator in an encapsulated die is mounted on to a package handle using an adhesive. The resonator experiences stresses by coupling to the die and package through the anchors.

Finding the TCf of CC beams requires knowledge of how the parameters in equation (1) change with temperature:

$$\begin{aligned} \mathrm{TCf} &= \frac{1}{f_{ref}}\frac{\partial f}{\partial T} \\ &= \frac{1}{\beta}\frac{\partial \beta}{\partial \sigma}\frac{\partial \sigma}{\partial T} + \frac{\mathrm{TCE}}{2} + \frac{\alpha}{2} \end{aligned} \tag{2a}$$

$$\mathrm{TCf} \cong 0.121\xi\frac{\partial\sigma}{\partial T}+\frac{\mathrm{TCE}}{2}+\frac{\alpha}{2} \qquad \xi=\frac{12L^2}{\pi E w^2} \qquad \text{(2b)}$$

In the equation above, TCE is the Temperature Coefficient of Young's Modulus of the resonator and α is the Coefficient of Thermal Expansion of the resonator material. TCE accounts for the decrease in frequency due to material softening. TCE for silicon depends on crystal orientation in the resonator and is reported to be between –46 ppm/°C to –80 ppm/°C [5]. To find the temperature dependence of β, consider how β changes with axial stress, σ, and how σ changes with temperature.

The mode constant, β, has a nonlinear dependence on the axial stresses in the resonator and can be solved for numerically [6]. The resulting approximation in equation (2) was found by considering the rate of change of β about the zero stress stage (Figure 2). This approximation is valid for small changes in stress.

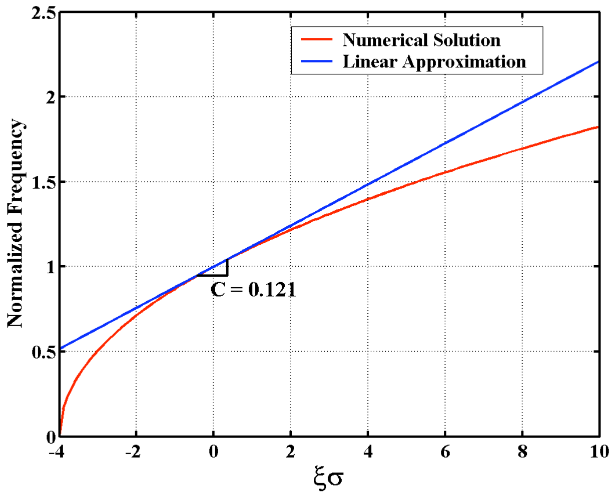

Figure 2: Normalized frequency vs. non-dimensional axial stress parameter in a double clamped resonator. The approximation tends to under predict in compression and over predict in tension. The effect of material softening is not included.

Changes in axial stress with temperature depend on the geometry, die and packaging materials and must be considered on a case-by-case basis. The finite element method can be used to determine the changes in stress with temperature due to α mismatch or other applied forces. In the following section, finite element analysis will be conducted to determine the thermal stresses induced in the resonator due to a α mismatch in the materials in the die and IC packaging. To capture the biaxial stress state in the die due to thermal stresses, a 2D axisymmetric model is created using the cross-section of the die.

EFFECTS OF IC PACKAGING

After dicing, the die are attached to a standard IC package using a die-attach adhesive and mounted on a printed circuit board. In previous experiments [1], Epotek H2OE epoxy was used as the adhesive and a TCf of –178 ppm/°C was observed. Finite element modeling revealed that the IC packages, which have a copper lead inside the plastic package, were inducing thermal stresses in the resonator through the epoxy. The copper, which has a higher coefficient of thermal expansion than silicon, induces tensile stresses in the die at the interface with the epoxy. The resultant moment created by the forces at the interface generates a compressive stress at the top of the die where the resonator is located. The compressive stress further reduces the TCf of the resonator (Figure 3).

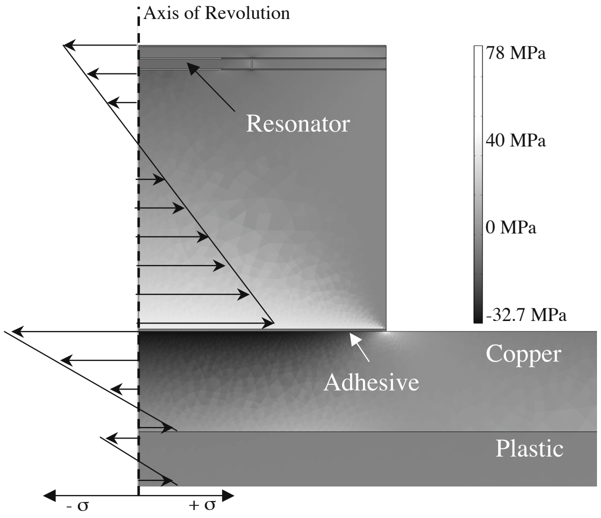

Figure 3: 2D axisymmetric finite element simulation of double clamped resonator in an encapsulated die mounted on a copper lead package with a hard epoxy. Stresses are calculated for a 35°C temperature increase from a 25°C zero stress state. Since copper has a higher CTE than silicon, the bottom of the die is in tension and the top of the die is in compression. The compressive stress in the resonator causes a decrease in the TCf.

Table 1: Parameters Used for FEM Simulation:

Property	Value	Units
α, Silicon	3	ppm/°C
α, Polysilicon	2.33	ppm/°C
α, Hard Epoxy	31	ppm/°C
α, Copper	17	ppm/°C
α, Plastic	25	ppm/°C
E, Silicon	168	GPa
E, Polysilicon	160	GPa
E, Copper	110	GPa
E, Plastic	5	GPa
L	220	μm
w	8	μm

To decouple the thermal stresses in the resonator from the IC package, a softer epoxy is necessary to isolate the die from the package. Table 1 shows a comparison of TCf for three mounting options. Type 1 is a mount to the IC package using a hard epoxy. Type 2 is a mount to the IC package using a soft epoxy. Type 3 is a floating mount in which the epoxy under the die was dissolved and the die is floating by wirebonds. The table also shows predictions of the TCf found by using the numerical solution and approximation given in equation (2). Differences in experimental data and predicted values can be accounted for by uncertainty in the material properties in the materials used.

Package Type	TCf_{EXP} (ppm/ºC)	TCf_{NUM} (ppm/ºC)	TCf_{LIN} (ppm/ºC)
1	-176	-199	-195.3
2	-38	-43.3	-40.7
3	-31	-41	-38.9

Table 1: Comparison of obtained TCf from experiments, using a numerical solution, and the linear approximation introduced in equation (2). Type 1 page is a mount using hard epoxy. Type 2 is a mount using soft epoxy. Type 3 is a floating die mount.

Finding an appropriate epoxy that doesn't transmit stresses from the package is essential to maintaining frequency stability. It is also important to note that the IC packaging and adhesive properties have not been fully characterized and could introduce hysteresis in the frequency measurements.

THIN FILM COMPENSATION TECHNIQUE

The IC packaging experiments have shown the negative effect on TCf of compressive stresses in the resonator. Conversely, if an appropriate tensile stress were created in the resonator, it would act to alleviate the effect of material softening. By setting equation (2) to zero, it is possible to determine the exact tensile stresses that will result in zero TCf. As a reference, a 1.3 MHz resonator whose length, *L*, is 220 μm and width, *w*, is 8 μm, requires approximately 50 kPa/ºC to exactly counteract material softening.

One method of inducing tensile stresses in the resonator is to include an additional layer in the die which has a larger coefficient of thermal expansion than the resonator. With increasing temperature, this layer would create tensile stresses in the die to counteract material softening. The magnitude of the stresses induced depends on the biaxial modulus, coefficient of thermal expansion, and thickness of the layer. For a given material, whose material properties are known, it is only necessary to determine the ideal thickness that would correspond to the appropriate stresses and achieve zero TCf.

Two methods for determining the ideal thickness of the layer are discussed. The first is an approximation that will provide a rule of thumb for designing the layer. The second method is a more accurate finite element optimization. In both methods, the compensation layer is the last layer deposited in the manufacturing process on top of the encapsulation and assumes the effects of IC packaging have been mitigated.

To derive the ideal thickness approximation, several assumptions are made. The first is that the materials in the die, excluding the compensation layer, have similar coefficients of thermal expansion such that the stresses induced by the die materials are much smaller than then the stresses induced by the compensation layer. Second, the stresses induced in the die are comparable to the wafer level stresses prior to dicing. Third, the thickness of the compensation layer is much smaller than the thickness of the substrate. Forth, since the resonator is located near the encapsulation, and thus near the compensation layer, the stresses in the resonator are approximately equal to the stresses at the interface of the encapsulation and compensation layer.

By considering the compensation layer as a thin film covering the substrate, the stresses in the compensation layer are found by using strain compatibility at the interface of the film and the substrate:

$$\begin{aligned} &\varepsilon^{f} = \varepsilon^{s} \\ &\varepsilon^{f}_{\text{elastic}} + \varepsilon^{f}_{\text{thermal}} = \varepsilon^{s}_{\text{elastic,at interface}} + \varepsilon^{s}_{\text{thermal}} \end{aligned} \tag{3}$$

Using the compatibility equations the gives the stresses induced in the film due to coefficient of thermal expansion mismatch:

$$\sigma_f = \frac{(\alpha_s - \alpha_f)\Delta T}{\left(\frac{1}{B_f}\right) + \left(\frac{1}{B_s}\right)\left(\frac{4t_f}{t_s}\right)} \tag{4}$$

Where the subscripts 'f' and 's' refer to the film and substrate respectively. B is the biaxial modulus, ΔT is the change in temperature, t is the thickness where t_s includes all of the layers in the die except the compensation layer.

The stress in the substrate is found by considering equivalent forces and moments due to forces transmitted at the substrate and film interface. The stress in the substrate at the interface will be approximately the stresses in the resonator by the assumptions previously mentioned:

$$\sigma_{\text{resonator}} = \sigma_{\text{s, at interface}} = -\frac{4\sigma_f t_f}{t_s} \tag{5}$$

Combining equations (4) and (5), an approximation of the stresses in the resonator is derived in terms of known parameters:

$$\sigma_{resonator} = -\frac{4t_f}{t_s}\sigma_f = -\frac{4t_f}{t_s}\frac{(\alpha_f - \alpha_s)\Delta T}{\left(\frac{1}{B_f}\right) + \left(\frac{1}{B_s}\right)\left(\frac{4t_f}{t_s}\right)} \qquad (6)$$

Having obtained the stresses in the resonator, equation (6) can be used in TCf approximation equation (2). By setting equation (2) to zero, solving for the zero TCf point, and solving for the compensating layer thickness, t_f, the ideal thickness is determined.

$$t_f = \frac{-\frac{t_s}{4}\left(\frac{1}{B_f}\right)\left(\frac{TCE}{2} + \frac{\alpha_{si}}{2}\right)}{\left(\frac{1}{B_s}\right)\left(\frac{TCE}{2} + \frac{\alpha_{si}}{2}\right) - 0.121\xi(\alpha_{si} - \alpha_f)} \qquad (7)$$

Since thinner films are desirable for feasible deposition, by observation of equation (7), the thickness of the film can be reduced by reducing the substrate thickness, reducing substrate biaxial modulus, increasing film biaxial modulus, or increasing mismatch of coefficient of thermal expansion.

To obtain a more accurate model of the ideal thickness of the film, a finite element simulation was performed in conjunction with an optimization algorithm. The model included all of the different layers in the die as well as the compensation layer. Since 3D finite element simulations are time intensive, a 2D axisymmetric model was used to model the biaxial stress state in the dies. The results of the optimization are displayed as contour plot in Figure 4. By knowing the Young's Modulus and coefficient of the thermal expansion the ideal thickness is found. For example, if aluminum (E = 70 GPa, α=16 ppm/°C) is the compensation layer, the ideal thickness is approximately 5 μm.

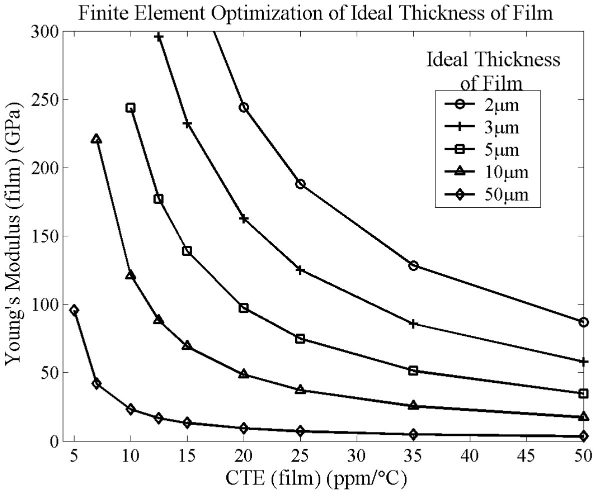

Figure 4: Contour plots of ideal compensation layer thickness obtained by Finite Element optimization.

The analytical approximation derived for the ideal thickness, equation (7), provides a contour plot similar to Figure 4. However, the analytical approximation under-predicts the ideal thickness.

Of particular interest is the class of materials for which the thickness is essentially irrelevant. Specifically, for materials with low Young's Modulus (< 0.5 GPa) and high coefficient of thermal expansion (> 25 ppm/°C), the effect of increasing the thickness of the compensation layer saturates. This is of interest because the fabrication of the compensation layer is simplified. Several plastics fall into this category.

CONCLUSIONS

The frequency of double clamped resonators are sensitive to stresses induced in the die. Compressive stresses in the resonator further exacerbate the decrease in frequency due to material softening. However, tensile stresses can alleviate the effects of material softening, and with careful design, zero TCf can be achieved. A passive method to achieve zero TCf using thin films has been presented. This technique does not require changes to the original design of the resonator or the manufacturing process. However it relies on strong coupling of stresses between the resonator and the die which may have adverse consequences.

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