A Thermal-Stress FEM to Predict Aging in Packaged MEMS Resonators

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***Summary*—This manuscript introduces a 3D Finite Element Model (FEM) to predict aging in packaged MEMS resonators which encounter stress relaxation as the primary source of frequency drift. Currently, the 10-year instability is estimated by fitting a logarithmic function to a shorter range of measured data (usually 1,000 hours). However, this standard approach is not based on a physical phenomenon and cannot be used to predict aging due to stress relaxation. The developed model considers the encapsulation and mount epoxies as linear viscoelastic materials and relates the resultant transient deformation to the MEMS frequency shift. Under these conditions, the 3D FEM can describe any complex package structure, as we verify experimentally for a piezoelectric MEMS resonator encapsulated by two types of Land Grid Array (LGA) package: full-glob and cap-glob.**

Keywords—MEMS resonators; aging; plastic package; stress relaxation; thermal-stress FEM.

I. Introduction

Aging in resonators is defined as the continuous change in frequency over time when external factors, such as temperature and input power, are maintained constant. This magnitude is usually expressed in parts-per-million (ppm) and extrapolated to 10 years, corresponding to the expected product lifetime. In quartz crystals, researchers have pointed to two main sources of aging: mass transfer and stress relaxation [1]. Mass transfer links to the absorption and desorption of contaminants causing change in the resonator equivalent mass while stress relaxation comes from the variation of stress generated either extrinsically (package, mounts, and bonds) or intrinsically (electrodes, interfaces, and quartz).

Recent improvements in MEMS fabrication have led this technology to replace quartz crystals in system-on-chip (SoC) timing products [2]. For example, a piezoelectric Dual-Bragg Acoustic Resonator (DBAR) integrated with a fractional-N Digital Phase-Locked Loop (DPLL) divider can form a low-power 48 MHz reference clock that exhibits ±30 ppm long-term stability over a temperature range of -40 to 85 °C and aging [3]. Understanding the main contributors to aging in packaged MEMS is key to develop accurate models that can guide the design and target high precision applications (e.g., space and military communications). In this regard, previous experiments on the DBAR of study proved that, when this was attached to an epoxy layer and suspended by the wirebonds, its frequency drift was due to stress relaxation of the viscoelastic material [4].

In this work, we introduce a 3D FEM to predict the aging of packaged MEMS resonators by correlating stress relaxation from the plastic encapsulation to the shift of the MEMS resonance frequency (f_r). To validate the 3D FEM, we measure the long-term drift of a DBAR encapsulated by two types of LGA package: full-glob and cap-glob and subjected to 50 °C for 1,200 hours.

II. 3D FEM Model

The developed thermal-stress FEM can simulate any package geometry and aging temperature. Plastic packages are formed by several viscoelastic materials (an intermediate state between solid and liquid), such as die attach (DA), glob (or stress buffer material), and mold compound. These time-dependent materials are subjected to different thermo-mechanical conditions due to assembly and molding steps. During assembly, the MEMS and IC dies are stacked up, attached, and wirebonded to the package substrate. During molding, the assembled structure is covered with mold compound and cured at high temperature. Consequently, the reference temperature of mold compound is set at $T_{molding}$ while the rest of materials are set at $T_{assembly}$ in order to compute their respective thermal expansions. In the case of study, $T_{molding}$=150 °C and $T_{assembly}$ is equal to room temperature. The FEM departs from these two initial conditions for stress (σ_0) and strain (ε_0) and simulates, in transient domain, the stress relaxation that occurs along shelf (or storage) and aging steps (Fig. 1).

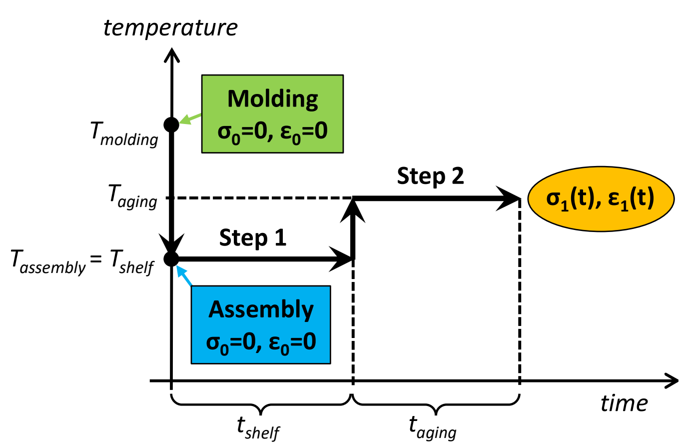

Fig. 1: Diagram of temperatures and time steps used to set up the FEM. The initial stress-strain conditions are due to assembly and molding.

Once the stress and strain tensors have been computed, the MEMS f_r, which depends on the resonator's principal direction of vibration, can be determined. For a thickness-extensional MEMS resonator, such as DBAR [5], f_r is inversely proportional to the vertical strain displayed across the piezoelectric film: $1+\varepsilon_z(t,T)$. As a result, the relative frequency drift can be expressed as:

$$\frac{f_r(t,T)-f_{r0}}{f_{r0}}[ppm]=\left(\frac{1+\varepsilon_{z0}}{1+\varepsilon_z(t,T)}-1\right)\cdot 10^6 \quad (1)$$

where the sub-index 0 represents initial values and $\varepsilon_z(t,T)$ is derived as an average of the DBAR volume.

III. Types of LGA Package

To validate the 3D FEM, we characterize the aging of DBAR as it is encapsulated by two types of LGA package: full-glob and cap-glob, whose only difference is the region covered by the stress buffer material. Fig. 2.a shows the full-glob version in which the stress buffer covers both MEMS and IC dies, and Fig.2.b shows the cap-glob version in which only the MEMS surface is covered by the soft glob. In both designs, a gap between the stress buffer and mold compound exists as a result of the large CTE mismatch. In terms of package dimensions and components, the chips are 3.2x2.5x0.9 mm^2 and contain a total of 6 copper pins embedded within an FR4 substrate to enable the surface-mount technology (SMT) for soldering. Although the MEMS die is wirebonded to the IC die and this is wirebonded to the substrate, no internal wires are included in the simulated 3D geometry in order to speed up numerical calculations.

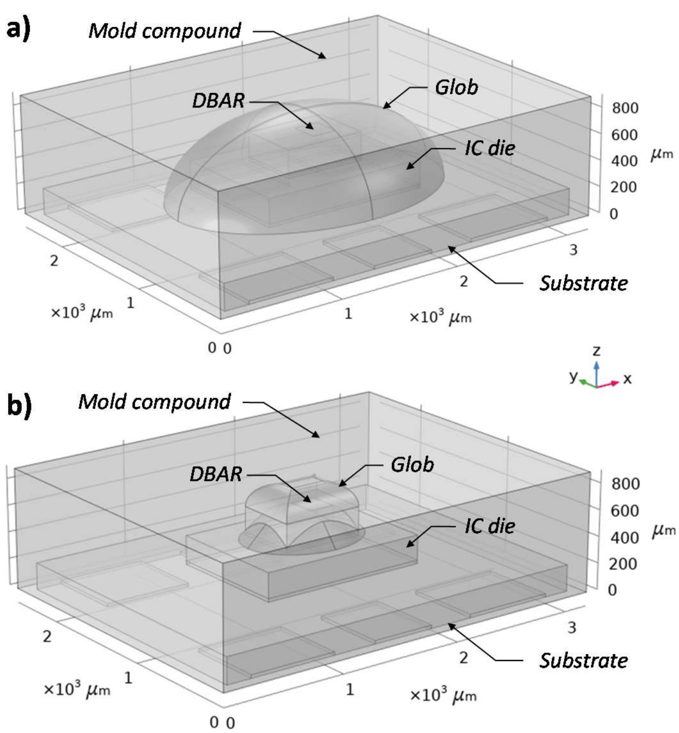

Fig. 2: FEM-simulated a) full-glob and b) cap-glob LGA packages containing the DBAR and IC dies.

IV. Viscoelastic Materials

To simulate the stress relaxation of LGA package, we treat the DBAR DA, glob, and mold compound as linear viscoelastic materials (we assume that the IC DA does not have any impact on aging). Both DA and glob are made of the same PDMS-silica composite (datasheet: E=3.4 MPa, CTE=250 ppm/K) while the mold compound is made of an epoxy molding resin (datasheet: E=18 GPa, CTE=10 ppm/K). The viscoelastic response of the former material is extracted directly from the full-glob aging experiment, as we will explain in the following section. To determine the dynamic response of mold compound, we run Dynamic Mechanical Analysis (DMA) for which we apply a sinusoidal load perpendicular to a two-point clamped sample while the frequency and temperature are swept from 0.05 to 50 Hz and from 30 to 200 °C, respectively. The relaxation modulus resulted from DMA at the temperature of study, $E(t,50°C)$, is fitted through a Generalized Maxwell model (Fig. 3).

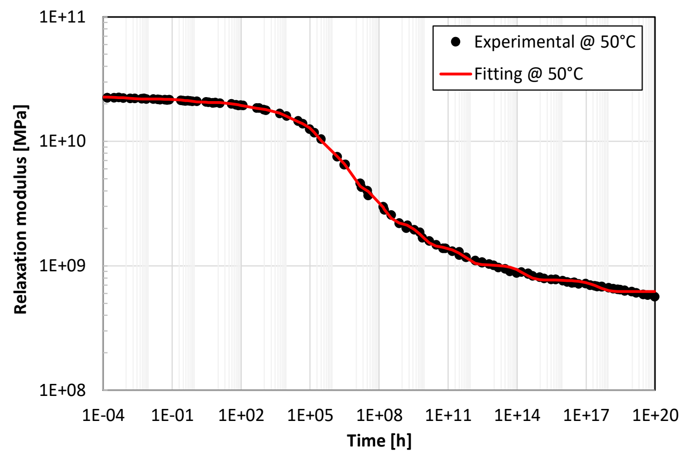

Fig. 3: Measured and fitted relaxation modulus of mold compound at 50 °C.

The multiple relaxation constants that arise from the $E(t,T)$ fitting (each one representing a parallel spring-dashpot branch of the Generalized Maxwell model) can be expressed in the form of a Prony series. The Prony series consists of N exponentially decaying stiffness functions with associated relaxation times, $\tau_i(T)$, and an equilibrium stiffness E_∞ ((2) shows this expression in time domain). For the case of study, we use 12 relaxation constants, which results in a good compromise between curve fitting (see Fig. 3) and computational complexity, as we input them into our 3D FEM. Table I summarizes the moduli and time constants derived for our mold compound at 50 °C.

$$E(t,T)=E_\infty+\sum_{i=1}^{N}E_i\exp-(t/\tau_i(T)) \quad (2)$$

TABLE I: MOLD COMPOUND RELAXATION CONSTANTS AT 50 °C. E_∞=621 MPa

	i=1	i=2	i=3	i=4	i=5	i=6	i=7	i=8	i=9	i=10	i=11	i=12
τ_i (50°C) [h]	1.26e-6	1.35e-3	6.18e-1	1.22e2	7.28e3	2.06e5	4.16e6	1.26e8	6.68e9	5.3e11	2.13e14	3.52e17
E_i [MPa]	735	878	1224	2073	3329	6258	4498	2173	847	430	253	148

V. Experiments vs Simulations

The experimental data were collected from one evaluation board containing 4 full-glob devices and 7 cap-glob devices. To eliminate the impact of solder reflow and creep, the devices under test (DUT) were not soldered to the evaluation board, but flipped upside down and wirebonded (or floating) (Fig. 4). The evaluation board was placed in a convention oven running at a constant temperature (T_{aging}) and the measured frequency was referred to f_{r0}, which was recorded 30 min after the oven had reached T_{aging} to account for the LGA package thermal time constant. The DUTs were stored at room temperature for about 1,000 hours prior to aging experiment (both shelf temperature and time parameters are used in our 3D FEM to properly compute f_{r0}).

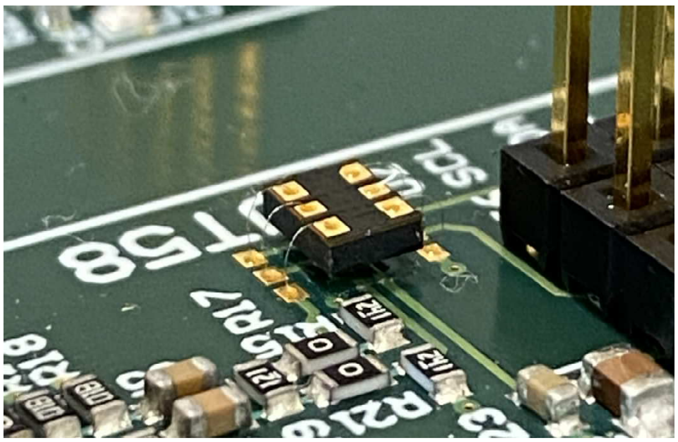

Fig. 4: Snapshot of flipped chip wirebonded to evaluation board for aging experiments.

Fig. 5 plots the full-glob and cap-glob experimental data and compare them with the 3D FEM model. For each package design, we plot the average data, which was collected with a measurement resolution of 2 min. During test, the lab computer was automatically rebooted several times to install software updates and some intermediate data points were not recorded (from 135 to 263 hours, from 420 to 840 hours, and from 862 to 962 hours). Fortunately, the oven was still operative and the measurement trend did not change, validating our hypothesis that aging comes from a thermo-mechanical process. To model aging, we assume bulk material properties for Si (DBAR and IC dies), input the datasheet properties for IC DA (E=3.4 GPa, CTE=156 ppm/K), and create a viscoelastic function with the Prony series extracted via DMA for mold compound (Table I). Then, we set the stress buffer as a linear viscoelastic material and construct a Prony series with one exponential component where E_{∞}=3.4 MPa (based on datasheet). By fitting the full-glob aging data, we determine that E_1=200 MPa and $\tau_1=1\cdot10^6$ s. These values are comparable to cured material properties found in literature for similar epoxies [6].

The plotted data show that cap-glob exhibits larger aging than full-glob over the measurement range. In particular, cap-glob shows an unusual trend that reaches a peak around 200 hours while full-glob shows a closer trend to a logarithmic function. Finally, we conclude that, by using the same material properties, we are able to fit both full-glob and cap-glob data trends simultaneously, which validates the accuracy of our 3D FEM model to predict the DBAR long-term drift.

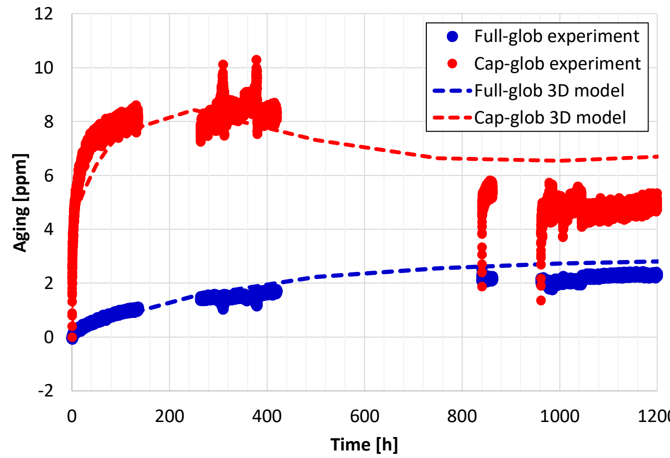

Fig. 5: Experimental and 3D FEM data extracted from two types of LGA package: Full-glob and cap glob.

VI. Conclusions

This manuscript confirms that aging in an encapsulated DBAR resonator primarily comes from package stress relaxation and introduces a 3D FEM model based on thermal-stress analysis and linear viscoelastic treatment of the constituent epoxies to model complex package geometries. By using the actual mold compound DMA data and fitting the glob and DBAR DA relaxation modulus to the experimental data, we are able to simultaneously predict the aging observed in two LGA packages (full-glob and cap-glob) at 50 °C, which validates our 3D FEM model. As a result, this tool can be used by package engineers to identify how much ppm variation can be attributed to each plastic component and decide on what materials and packaging technologies are more adequate to meet the demanded application specs.

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