Coupled Package-Device Modeling for MEMS

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ABSTRACT

Microelectromechanical Systems (MEMS), by their nature as sensors and actuators, require application specific packaging. The package is the near environment of the MEMS device and hence has a direct effect on its thermal behavior, on mechanical effects, and on environmental compatibility and contamination. Therefore, understanding the influence of the packaging on MEMS device performance is critical to a successful coupled package-device co-design. Here, an automated package-device interaction simulator has been developed. The simulator uses separate Finite Element Method (FEM) models for both the package and the device analysis and ties the results together through parametric behavioral package models. This technique allows the generation of package model libraries and supports the co-design of application specific packaging and MEMS devices. Experimental verification of the technique is demonstrated by comparison of simulation results to measured package strain data.

Keywords: Electronic Packaging, Microsystems, MEMS, Simulation, FEM

INTRODUCTION

MEMS, by their very nature as sensors or actuators, must interact with their environment. This need for interaction often generates package requirements that are fundamentally different from typical integrated circuit (IC) package requirements. These requirements create packaging challenges that are far more complex than in typical IC packaging. Areas of interaction that are common to both MEMS and IC packaging include: electro-magnetic interference, heat generation, shock survivability, etc. Areas where MEMS are often much more sensitive are: package and thermal induced stresses, optical energy flux, shock and vibration transmission, hermeticity, material out-gassing, environmental compatibility, contamination, etc. Package modeling, in this context, is the attempt to simulate these interacting effects so that the overall system behavior can be predicted and optimized.

Because of the complex MEMS package-device interactions described above, the package can often require significant design effort and cost more than the MEMS component (the device) itself. Indeed, if the package-device interactions are not well understood, the device performance can be compromised or even fail completely. Therefore, it is very important that MEMS devices and their packages be co-designed in an environment where the package-device interactions can be simulated and understood [1]. In addition, a single MEMS device can potentially be repackaged for multiple applications. In this case, a way to quickly analyze the affects of different packages on the device is important.

In addition to the complex physical domains that are required to simulate package-device interactions, there are also modeling challenges. One fundamental problem is the large difference in the size scale between a MEMS device and its package. Any combined device-package Finite Element Method (FEM) model with resolution appropriate to accurately model the device will easily exceed practical computational resources. Even when such a "brute force" solution can be computed, the need for numerous simulations to explore the design space makes such combined models of limited use.

To overcome these problems, a modeling technique was developed which allows extraction of parameterized behavioral package models [1]. This approach allows for a separate analysis of the package and device and was motivated by McNeil's work [2]. An appropriately meshed package model is simulated and a parametric compact model is extracted. Figure 1 shows the results of such a package simulation. The package-induced effects on a device can then be simulated through the application of the package compact model to the device simulation. Not only does this method allow coupled simulations with appropriately scaled FEM models; it allows the creation of package model libraries that can be used in combination with new or existing device models. This can facilitate the increased use of off-the-shelf packages and the cost effective re-packaging of devices for multiple applications.

PACKAGE-DEVICE MODELING METHOD

The package model extraction method is based on the use of independent package and device 3-D FEM models. It is described here as implemented in the Memcad analysis system [3]. The first stage of the analysis is the creation of a package model. The package solid model is simulated under the external influence of interest. Most often that simulation would be a mechanical solution of temperature induced deformation, as exemplified in Figure 1. The external influence of interest, represented by the package boundary conditions, is varied over the desired range of the design space. The resulting strain/stress fields of the package model form the basis for the compact model extraction. The extraction begins with the user's choice of a package-device interfacial surface (for example, the surface of the die on which the MEMS device is fabricated). The package model extraction tool then calculates the displacement fields for all nodes within this surface for each value of the changing external parameters (i.e., for each package simulation step). Next, a 4-th order polynomial fit of the extracted displacement fields is performed based on a Linear Least-Squares SVD algorithm. This fit is a function of the normalized local coordinates on the die surface. Such a polynomial fit is generated for each simulation point in the external-influence parameter space. This set of polynomials constitutes the package parametric compact model for the given range of external parameters. Since this part of the analysis is independent of the MEMS device, these package models can be generated independently to form a pre-computed package library.

The compact package model is now used in the simulation of the device by applying the package model as a boundary condition to the device. One could think of this step as attaching the device inside the package. The device is now subject to the direct environmental influences (temperature, etc.), the package-induced effects, and history dependent effects (such as built-in residual stresses). Before the device analysis can be run, a translation is needed from the package model to the device boundary conditions. The package model extraction tool projects the package displacements onto the interfacial nodes of the device model based on user-defined placement of the device on the chosen package surface. This means that the user is able to place the device anywhere on the package surface that was used to generate the package model. Note that the device placement is independent of the FEM mesh of the package solid model. Since the package models are parametric, the user is also able to simulate the device anywhere in the external parameter space. The device can be simulated at any parameter value between the maximum and minimum parameter values that were used in the original package simulation. In fact, the device can be simulated outside this region if the extrapolation inherent to the polynomial fit is acceptable.

Several assumptions are made in order to simplify calculations. It is assumed that only the mechanical effect of the package on the device is important. In other words, the existence of the device does not contribute to the stress/strain field of the package. This is not a fundamental limitation as there are several techniques available to include the device-induced effects in the analysis of the package. For example, boundary conditions on the package analysis can include device effects such as thermal sources.

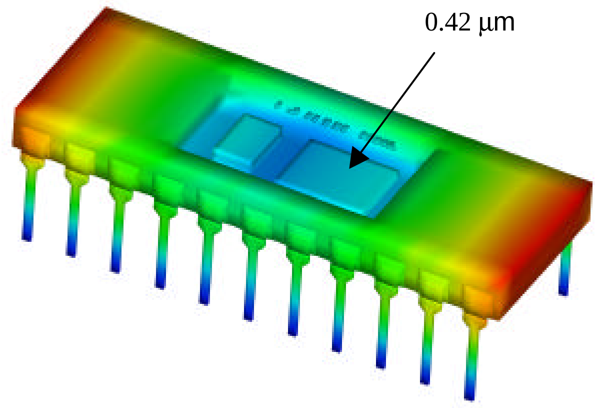

Figure 1. A 3-D visualization of a thermo-mechanical package simulation done in the MEMCAD coupled package-device simulator. The color scale shows the displacement magnitude at 125 ^{o}C. The probe shows the displacement magnitude at the center of the die surface.

EXPERIMENTAL VERIFICATION

In order to confirm the usefulness of this simulation approach, we compare the results of experimental measurements to package strain predictions. The experimental characterization of packages involves the measurement of strain or displacement fields from which stress can be inferred [4]. It is possible to purchase silicon test die to measure package deformations. However, similar test die are not available for glass substrates, which are also widely used for MEMS device substrates. Here we use off-the-shelf metal-film strain gauges to measure the displacement field on the surface of a glass substrate (die). To obtain accurate simulation results, we wish to have a full mapping of the package strain onto the strain gauge. This is accomplished by treating the strain gauge as the "device" in our package modeling method.

The experimental measurements were conducted on a 22-pin ceramic DIP package that contains a silicon die and a glass die. It represents a two-chip solution for a MEMs device. In Figure 2, the ceramic package is shown with an ASIC and a silicon micromachined accelerometer (on the glass die). By contrast, the same package and similarly sized die are shown with strain gauges attached. The strain gauges are used to extract die strain and resistance changes that will be compared to the simulation results. The strain gauges are connected to the package pins by wire bonding, so that electrical connection can be made. An optical micrograph of a metal-foil strain gauge is shown in Figure 3. For comparison, the model of this strain gauge is shown with displacement and electric potential fields in Figure 4.

The gauges were connected to a strain indicator, using a quarter-bridge, three-wire approach. The strain indicator provided the constant voltage power and output amplification. It also enabled the system to be balanced (zero microstrain output at room temperature) and to perform an internal shunt calibration (a precision resistor is shunted across the strain gauge to provide an equivalent resistance change of a mechanical strain of 4906 microstrain).

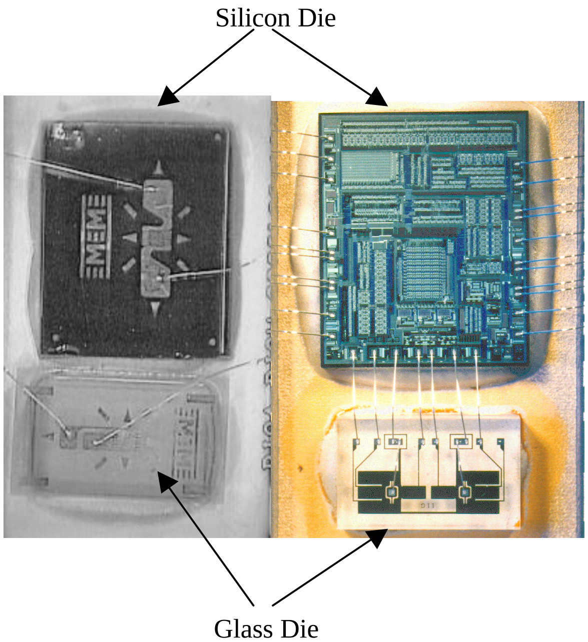

Figure 2. On the right, the ceramic package cavity is shown with the silicon ASIC die and the glass MEMS die. The same type of package is shown on the left with strain gauges on the silicon die and the glass die. The instrumented die, on the left, have the same dimensions as the actual device die.

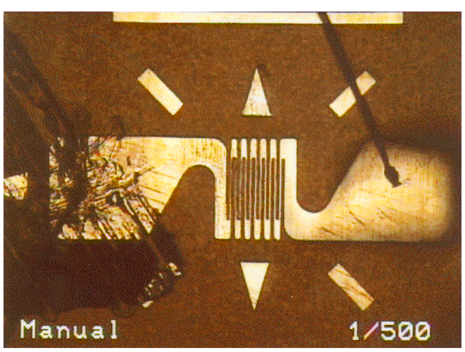

Figure 3. An optical micrograph of one of the metal foil strain gauges used for experimental calibration of the package model.

The experiments were performed in a Tenney environmental chamber between the temperatures of –40 and 100 °C. The ramp time to reach –40 °C was 20 minutes with a 5 minute soak time. In the subsequent steps, the temperature was increased by 20 °C, in 10 minutes, with a 5 minute soak time. At the end of the 5 minute soak time, the strain on the silicon die and pyrex die were recorded. While in the chamber, the packages were unconstrained except for the lead wires that provide the electrical connection from the package to the strain indicator.

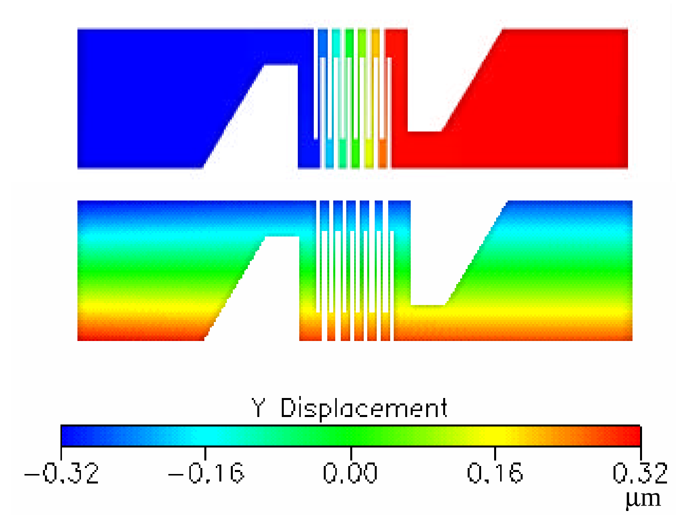

Figure 4. These figures show 3-D FEM simulation results of the metal film strain gauge. The upper figure shows the electric potential distribution in the metal foil. The left-hand edge is set to zero volts and the right-hand edge is set to 1 volt. In the lower figure, the color scale shows the displacement along the sensitive axis of the resistor element (vertical direction).

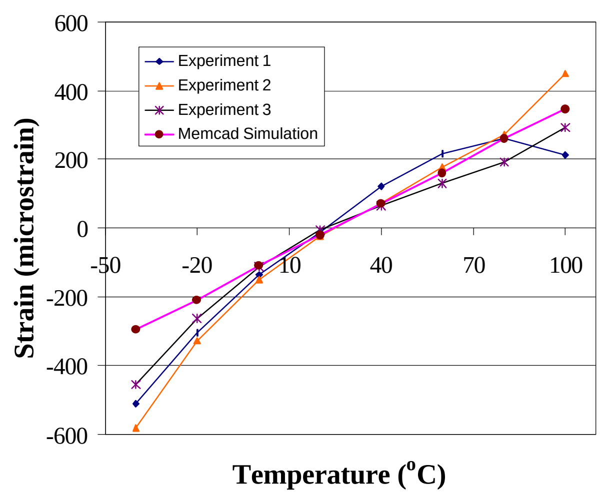

Figure 5. The relative strain in the Pyrex die as a function of temperature. All results are normalized to room temperature.

Experimental Results

The primary goal of these measurements was to measure and predict the temperature-induced strain on the die in the package. Figure 5 shows the measured strain plotted versus temperature for three different packages. Each package has similar die and strain gauges, but they were tested at different times. One package was tested alone. The other two packages were tested simultaneously. It is evident in Figure 5 that the results are consistent between the three packages. Figure 6 shows the strain gauge resistance change as a function of temperature for the same three experiments. Note that the results in Figures 5 and 6 are zero at room temperature. This is because the strain indicator was adjusted to read zero at this temperature. Relative to room temperature, the glass die-stress is compressive below room temperature and tensile above room temperature.

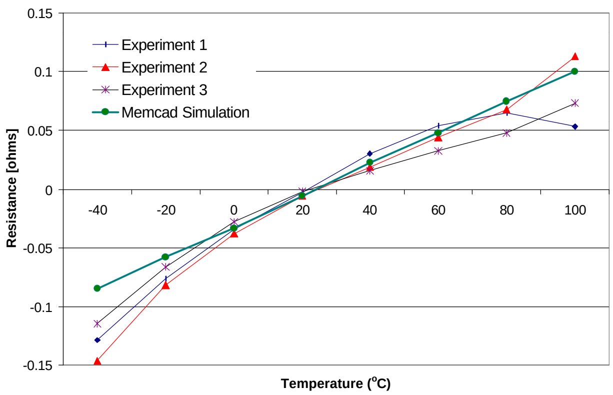

Figure 6. The change in resistance in the metal foil strain gauge as a function of temperature. All results are normalized to room temperature.

The ceramic package used in these experiments was simulated using the MemPackage software tool. Figure 1 shows the displacement in the center of the die top at 125°C. Figure 5 shows a curve of the simulated strain on the surface of the Pyrex substrate. In this case, computational results were obtained directly from the package simulation; no device (i. e. strain gauge) was attached. The simulation and experimental results show good agreement. Both the simulation and experimental data are normalized to the strain at room temperature (24°C).

Once the package model has been simulated, it can be applied to a device, which can subsequently be simulated with any of the simulation engines in the Memcad tool suite. The Memcad tool suite has a piezoresistance computation module that allows the electrical characteristics of a strain sensitive material to be simulated directly. In this case, the strain gauge becomes the "device" and the package strains are applied to it. The change in the metal foil resistance is then computed directly.

A strain gauge was located in the center of the Pyrex die top (see Fig. 2). A coupled package-device model was simulated to account for temperature-induced strain/stress and the corresponding geometry change. The Memcad piezoresistive module was then used to calculate the resistance change generated by both the geometrical effect and the change in resistivity due to the strain. The piezoresistive coefficient was obtained by matching the manufacturer's gauge sensitivity factor of 2.09 to the experimentally obtained change in resistance:

$$dR/R = S_g \varepsilon,$$

where R is resistance, S_g is the gauge factor, and ε is the axial strain. The above procedure was iterated with respect to changing temperature. Figure 6 shows the results of this simulation compared to the measured values of resistance change. Again, the data shows good agreement between the experimental and numerical data.

DISCUSSION

The current implementation of the package model extraction tool assumes that the die surface is a planar simply-connected region. It also assumes that the deformed shape of the chosen surface can be accurately approximated by a 4-th order polynomial (higher orders or other fitting functions can be easily implemented). Another important underlying assumption is that the device behavior does not influence the package. This assumption is valid for a wide variety of materials and dimension combinations since MEMS devices tend to be much smaller than the package. In addition, the device materials are not much stiffer than die materials in general. However, for relatively stiff devices, the difference between the actual strains and the strains calculated for the case where the influence of the device on the package is ignored can be as high as 10% [5]. A stiff device in this context is the case where the device Young's modulus to package Young's modulus ratio is more than 10 and the device height-to-length ratio is more than 0.003. To remove this limitation a fully coupled package-device modeling scheme could be implemented. Alternatively, coupling could be done at the compact model level. A compact model of the reaction forces extracted from interfacial nodes in the device simulation could be sent back to the package simulation in the form of a reaction force on the relevant interfacial nodes. Several relaxation iterations between package and device simulations with coupling through displacements (package to device) and reaction forces (device to package) would lead to a solution with mutual package-device interaction effects accounted for.

CONCLUSIONS

The effect of the packaging on the behavior of a MEMS device cannot be ignored. An automated package-device interaction simulator has been demonstrated. The simulator uses 3-D simulation models for both the package and the device analysis and ties the results of the simulations together through parametric re-usable models. This methodology is confirmed with package measurements instrumented with metal-film strain gauges. This has demonstrated the power and universality of the modeling approach to allow designers to explore complex design questions that are not otherwise practical to simulate.

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