Development and Verification of a Standard Packaging Library for Advanced MEMS Design


(1) Coventor Sarl, COVENTOR Sarl, 3 Avenue du Quebec, 91140 Villebon sur Yvette, France
Tel: +33 (0)1 69 29 84 85, Fax: +33 (0)1 69 29 84 88, gerold.schropfer@coventor.com
(2) Coventor Inc., 625 Mt. Auburn St., Cambridge, MA 02138, USA
(3) Kyocera Corporation, 6 Tobadono-Cho, Takeda,Fushimi-Ku, Kyoto, 612-8501, Japan
(4) Kyocera Corporation, Yamashita-cho, Kokubu, Kagoshima, 899-4396 Japan

Abstract

A Standard Package Library (SPL) for MEMS was developed that facilitates the selection process by providing ready-made package models, which can in turn be used to analyze the effects of the packages on MEMS devices. With access to package geometry and materials data, designers can choose specific package concepts from a variety of package types, initiate performance-based design (such as thermo-mechanical effects), and modify package data to specific microsystem requirements. The use of the package library helps shorten the design cycle, reduce risk and decrease time-to-market. Emphasis is put on coupled device/package macro model extraction, which provides the ability to include package stress effects at the system level.

Key words: MEMS, Package, Library, MEMS Package Co-Design, Simulation, Modeling

1. INTRODUCTION

A well recognized commercialisation barrier for MEMS enabled products has been and continues to be packaging. The various different technical problems resulted in custom packaging development for each application, leading to higher overall package cost, which may be as high as 80% of the product cost [1, 2]. Packaging of MEMS components differs significantly from the packaging of microelectronics, which is well established, primarily because unlike microelectronics, the functional specification of the MEMS chip is critical to the design of the package.

2. MEMS PACKAGING CHALLENGES

Microsystem packaging involves multiple levels of interfaces enabling connectivity from the chip to the outside world. It is well established that any unforeseen effects of a package on a MEMS device can ultimately inflate product development cycles, time-to-market and production costs. For standard off-the-shelf packaging to be viable in the MEMS industry, multiple effects must be considered at all levels, starting with the MEMS device, chip, module, card, board and finally frame gate. MEMS typically contain moving parts that are very sensitive to package effects, and often need to interact with the outside world in some way depending on the application. In the working environment, packages need to provide a controlled environment that is often hermetically sealed to protect against environmental factors and corrosion, as well as mechanical and electrical isolation to improve device robustness. For all these reasons, the complexity of MEMS packaging becomes highly dependent on the specific application, forcing designers to either consider these effects seriously and come up with unique solutions or go back to the drawing board. Additionally, MEMS devices are fragile mechanical devices that need to be protected from damage during wafer level processes such as dicing and cleaning. Wafer Level Encapsulation (WLE) technologies as a post-processing step in a manufacturing flow is a low cost technique for increasing yield and is more widely used today in the MEMS industry. In certain applications, WLE is sufficient as final packaging of the device prior to use.

In microelectronics, open tool packages may be used for several chip designs as long as they meet size and connectivity requirements, which is quite unlike MEMS packaging. However, open tool packages serve as very useful starting points for MEMS packaging concepts and combined with wafer level or die level packaging or encapsulation solutions,
could offer a low cost path to MEMS product commercialisation.

3. CO-DESIGN OF MEMS & PACKAGING

Currently, MEMS design is typically focused on the component level using specific MEMS CAD tools that address the inherently complex device design. Although techniques exist that allow for package-device co-design [2], they assume that decisions about the kind of package, size, materials etc. have already been made, which is typically not that straightforward a task in the first place, given the diversity of applications. Product design groups rely heavily on the expertise of package designers to choose the package based on a variety of factors like cost, availability, customisation, etc., and then to design the package based on specifications of the MEMS device. This has typically resulted in product developers postponing package selection until after the initial device design has been completed, when design modifications are time-consuming, complex, and costly to rectify. This has also led to inefficiencies in the design process due to the time involved per design iteration. Although the industry is recognizing the specific differences between MEMS & IC packaging, and the need to protect the MEMS during fabrication, addressing these challenges often requires access to industry specific tools and know-how that often resides with package suppliers. It is important for suppliers to share enough data with designers to overcome these barriers.

It is possible to capture package models for reuse. There are the options of reuse in physical models, device models or system models. Here the latter two can be considered simultaneously since they will be implemented in system models. In any case it will be advantageous to build up a library of known models of packages for reuse. The options are to store complete physical field simulations on packages, extracted compact models of these simulations, or Reduced Order models. All this data can be reused in a MEMS-device or component design study on either the physical field solver level or the system level. For both, we will give examples in paragraph 5.

4. PACKAGING LIBRARY

4.1 Standard Open Tool Packages

Recent availability of a set of standard open tool IC packages within an existing MEMS CAD tool environment will deliver to designers detailed package design data in a easy-to-use, accessible environment [3]. The package CAD data is supported by the package supplier (Kyocera) directly and will be available in the form of a library of different packages of various sizes and type, and which are easily modified to custom designs. Through the availability of open tooled packaging solutions from Kyocera, designers now have significantly more choices for initial package selection i.e. in terms of chip size, number of electrical connection, etc., and to consider the effects of packaging early in the design phase. With access to the package geometry and materials data in a MEMS design environment, both package and MEMS designers could communicate design information more effectively.

4.2 Content of Package Library

For MEMS design, packaging data is best introduced in the form of 3D models. The library allows designers to create the 3D geometry from supplied data, modify the existing provided geometry or import it in standard format. A complete description of the materials used in each package type is also available. Since a variety of views exist for the package it is possible for the designer to modify the package geometry and material properties completely, thereby enabling some customisation of the available packages.

![Figure 1: Four examples of package models, which are part of Kyocera standard package library available within CoventorWare™.](image-url)
mechanical or thermo-fluidic performance or coupled RLC analysis. In the working environment, packages experience a variety of loads such as high-g-loads, shock impact, electrical currents or fields, operational temperature ranges, ESD, etc. and it is of critical importance to be able to understand the effects of these loads on the operation of the MEMS device. Additionally, the designer needs to quantify the effects of other external stimuli such as noise, and vibration. It is also important for designers to be able to directly observe the coupling between the various sub-systems - MEMS, IC, and packaging. System level modelling (through standard tools from Synopsys® or Cadence®) is a very powerful technique to allow the MEMS product group to couple the various sub-systems in a single environment. Standard packages from the library could also be converted directly into macro-models that are available to system level descriptions of the product, thereby allowing for a higher level of optimisation of the product.

5. CASE STUDY: PACKAGED MEMS GYRO

In the following case study we examine the interaction of device and package behavior. More specifically, we study the effects of the ambient temperature of a package on the performance of a packaged MEMS gyro sensor.

5.1 Description of MEMS Device

The MEMS device is a gyroscope, which is an electro-mechanical device that measures angular rotation rate. The device modeled in this paper is not a “real” device in that it has never been fabricated or tested, but is a demonstration example intended to validate the package MEMS co-design approach. It consists of a single proof mass suspended by four silicon springs. The proof mass is driven in the “motor” (horizontal) direction by electrostatic forces from a pair of inter-digital comb structure. The proof mass moves perpendicularly to the motor direction under the influence of the angular rate caused by the Coriolis effect. The important frequencies of this gyro are the motor frequency at 7.2 kHz and the sense frequency at 7.5 kHz [4].

5.2 MEMS Gyro Behaviour Model

The MEMS device model has been created using Coventor’s ARCHITECT™ that incorporates a MEMS component library, a schematic editor and a mixed-signal behavioral simulator [5]. The MEMS designer first assembles a schematic of the device by selecting “components” from the MEMS library and wiring them together, in much the same way an electronics engineer composes a schematic of an IC. Underlying each component, whether mechanical or electrical, is a mathematical behavioral model that is implemented in a hardware description language (HDL). Because these components rely on analytical models that accurately describe the component’s behavior, simulations of the complete device take much less computer time (by an order of magnitude or more) than equivalent FEM/BEM simulations, allowing the designer to explore design variations in a fraction of time enabling designers to explore the design space more effectively. Designers can perform many types of analysis in ARCHITECT, including steady state, time domain, frequency domain, sensitivity, reliability, and control system analysis. Furthermore, because both mechanical and electrical systems can be modeled in the same system-modeling environment, ARCHITECT enables designers to perform co-simulations of a MEMS device, the surrounding electronic control circuits and package. The latter one is described in paragraph 5.5. In addition Designers can supplement the supplied components by creating new models in either MAST or VHDL-AMS.

A schematic model of the gyro is shown in Figure 3. The schematic model can be converted into a 3D solid model automatically, which can then be meshed for FEM /BEM simulations.

5.3 Package Selection and Simulation

The user starts by selecting a package model from the Kyocera package library, in this case we choose

![Figure 2: Generic MEMS Tuning Fork Gyro.](image)

![Figure 3: Schematic of a MEMS Gyro including anchor-models for connectivity to the substrate.](image)
package type SMD KD-V99902-A based on the cavity size, 3.6x2.6mm, and the number of pins required 8 leads – see Figure 4. First, we use the FEM solver to analyze the package deformations due to temperature. It is then possible to use these results to compute the effects of the package on the MEMS sensor. This approach assumes that the package influence on the device dominates because of the size of the package compared to the MEMS.

In the presented case we applied an ambient temperature variation ranging from 223K to 423K. The reference or zero stress temperature in this case is assumed at 273.15K. Figure 5 shows the simulated deformation at various temperatures for a lid-less package. A comparison of maximum and minimum displacement between package with and without a lid showed a difference of less then 10%.

5.4 MEMS Package Co-Simulation by FEM
It is possible to use the results of the previous analyses to quantify the device performance due to this temperature change. CoventorWare™ offers the user two complementary methods to analyze the MEMS device in the package. The package deformation data can either be loaded back into another FEM solver run using ANALYZER or it can be used directly on the system level with ARCHITECT. In both cases package effects are captured as temperature depending die curvatures.

In the FEM based ANALYZER approach, the extracted package deformation is applied to the MEMS substrate of the FE device model as a displacement boundary condition. This allows a set of FEM simulations considering the package effects on the MEMS gyro, such as modal mechanical stress analysis, electro-mechanical etc.

![Figure 6: Meshed 3D solid model of the MEMS gyro.](image)

![Figure 7: Comparison of X,Y, and Z displacement (in µm) between temperature at 223K (a) and 423K (b) - for package without lid.](image)
The displacements of the MEMS sensor as a function of temperatures using a package with and without lid have been simulated. Figure 7 shows that the maximum deflection occurs in the direction normal to the substrate. In the same way a comparison of Mises Stress between temperature at 223K and 423K was conducted indicating that the maximum stress occurring in the suspension beams is more than three times higher at the higher temperature.

The deformation of package and gyro at a temperature of 223K results in a die substrate contraction where the gyro beams bend upwards relative to the top surface of the substrate. At a temperature of 423K, we do get an expansion of the substrate making the beams bending down relative to the substrate top surface.

One would expect that the resonance frequencies of the MEMS gyro are influenced by the package induced stress on the suspension anchors and connected beams. A quantitative verification with a modal analysis is shown in Figure 8. However, not only do the nominal values of the frequencies differ between the packaged and unpackaged device, also the mode shape of the 1st and 2nd mode show a reversal (see Figure 9).

5.5 MEMS Package Co-Simulation using Behaviour Models

In comparison with a traditional FEA approach, the behavioural models from the Architect libraries allows for quick design iterations, especially with full transients where FEA simulations might be quite time-consuming, and for statistical analyses to study the effects of manufacturing tolerances.

The Architect MEMS design libraries have been upgraded to supported package deformation data directly. The post and anchor models can read in displacement and rotation offsets from a FE package analysis based on their position in the local device coordinate system. The substrate temperature is thereby defined by a global variable that can be altered in variation loops to analyse the effects on the design performance.

The ACHITECT comb models account for substrate deformation due to packaging effects by giving vertical and horizontal displacements to the fixed fingers based on their location on the substrate, see Figure 10.

The electrode model as used for the gyro example on Figure 3 account for substrate deformation by splitting the electrode into segments with individual horizontal and vertical offsets, which is graphically explained in Figure 11.
The individual modelling approach used in ARCHITECT’s behavioural models have been verified in detail by comparing ARCHITECT results with results from pure FE analysis. Figure 12 for example, shows the comparison of the gyro’s electrode capacitance as a function of the temperature depending substrate deformation. The two lines in the graph show a perfect match between the results from ANALYZER and ARCHITECT.

Device schematics built with the Architect libraries allow a fast simulation of packaging effects requiring a minimum of user setting. Existing device schematics can be used immediately by simply specifying the name of the underlying FE package analysis. All relevant data is extracted automatically be the individual components.

Figure 13 shows the results of a DC vary analysis for the complete gyroscope as an example. The DC output capacitance as a function of the substrate temperature was simulated. Our test case gave an offset drift of 10F/100K. Another example is the frequency shift of the gyro’s driving mode that can be analysed for a wide range of different gyro designs.

The advantage of incorporating the package effects on at behaviour model level is not only to save simulation time, but more important, it allows one to explore a variety of MEMS design inter-dependencies of the packaging and furthermore permits more sophisticated simulations, such as Monte Carlo analysis or virtual testing. Regarding the last point, the response of the packaged device to external stimuli such as noise sources, vibrations, shock loads, etc. needs to be well understood for optimal device performance, which can be now simulated using a complementary approach of FEA and schematic (system-level) design.

6. CONCLUSION

For the first time, a standard package library available in a MEMS CAD tool, that may be used to select and analyse the effects of a package on a MEMS device in a single environment. A simulation case study has been presented that demonstrates the co-simulation approach of a MEMS gyro embedded into a standard Kyocera package. The ability to successfully import, build, analyse and troubleshoot packaging effects on MEMS devices early in the design cycle enables designers to limit product risk and reduce cost. Further it offers package designers a path to start with an available package and make changes with the microsystem in mind, and further to feed those changes directly back to the supplier for custom development if necessary. This new capability would ultimately help bring MEMS enabled products to market faster and at a lower cost.

7. REFERENCES