Designing MEMS for Reliability (DFR)

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Abstract

In recent years, the topic of reliability of MEMS has become an increasingly important priority for an industry focused on delivering low-cost products to the market in the shortest possible time. This paper will focus on the Design for Reliability (DfR) of MEMS by discussing CAD Methodologies and how they impact DfR, feature based design and system level architectural improvements, and functional yield modeling. As with any other manufacturing technology process development and material property characterization, and an understanding of the physics of failure (POF), impact design strategies for improving yield, design for reliability (DFR), packaging and test.

Keywords: *Reliability, DfR, Design, MEMS*

1 Introduction

According to recent industry figures [1], the MEMS industry (for silicon and quartz based devices) is expected to double in 5 years (to approximately $10B US) by the year 2010. While most of this growth is expected from a larger than expected embedding of more conventional MEMS devices (Figure 1) such as pressure sensors, accelerometers and gyros in the consumer electronic products such as laptops, athletic shoes etc., a significant increase is expected from newer devices such as RF MEMS, Fuel Cells, and MEMS microphones. This expansion of the MEMS market is good news for an industry that has had to overcome significant barriers in terms product development times for almost every new product introduced, but the signs of change are evident.

Over the past five decades, the time to market for MEMS enabled products such as pressure sensors or inertial devices or RF devices, from initial concept through to market introduction, has fallen [2] but is still on the order of a decade; implying that it takes a lot of effort to commercialize a successful MEMS enabled product. The reasons for the decline in time (while certainly product dependent) are arguably because of significant improvements in Design Automation (CAD) that has made implementation of DfM strategies increasingly more efficient. As in the semiconductor industry, the interdependency between the design and the process (often referred to as Design for Manufacturability – DfM) is of critical importance [4]. Designing manufacturable MEMS devices requires a clear strategy that links the design and process effort through a common CAD framework. Toward this end, MEMS design tools that enhance automation and incorporate a top-down design methodology with reusable parametric libraries of MEMS components, standard MEMS package libraries and relevant system components are critical and are now part of the MEMS industry infrastructure [5].

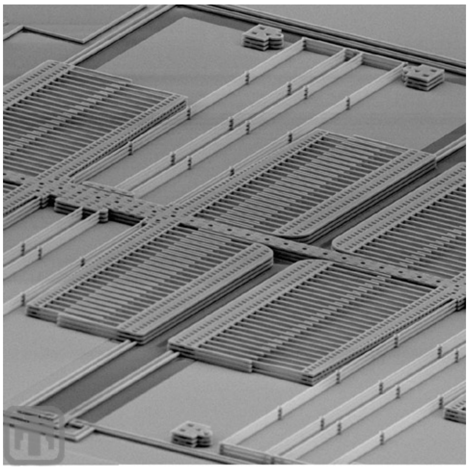

Figure 1: A comb drive - Courtesy of Sandia National Laboratories, SUMMiT^{TM} Technologies, http://www.mems.sandia.gov/

A significant portion of the time involved in the commercialization of MEMS enabled products is however devoted to improving the reliability [6]. It is interesting that a decade ago the challenge was to produce designs that were manufacturable (by adopting a concurrent engineering approach as opposed to a build-and-test approach) in a minimal number of fabrication starts. Today the challenge is to produce reliable MEMS, which perform to specification with minimal number of fabrication starts. In this article we will address some of the issues, complications and solutions regarding designing MEMS enabled products to meet their reliability specifications.

2 What is Reliability in MEMS?

Reliability is simply defined as quality as a function of time or more accurately as probability that a product will perform its intended function for a specified interval of time under specified conditions. It is usually measured with an index such as MTTF or MTBF or as a Failure Rate and is one of the eight dimensions of quality that include durability, performance, conformance, etc. [7]. The bathtub curve, which is obtained by plotting the failure rate vs time, has 3 distinct regions of interest (infant mortality, constant failure rate, and wear out) and these have been fairly well studied in the semiconductor and more recently in the MEMS industries. Further modeling of the failure rate, based on probability theory is routine in the form of either uniform distribution, Weibull distribution, and/or lognormal models, but these models must be appropriately utilized with testing data for them to be able to predict reliability (i.e. failure rate) with any accuracy.

In MEMS, the root cause of reliability, i.e. the failure mechanisms, are highly product dependent, and not much data has been made available on how specific failure mechanisms were overcome for specific products, primarily because of competitive advantage, but significant fundamental research is available on generic failure modes. The most common of such mechanisms are mechanical failure (fatigue, creep etc.), wear, electrical failure (charging, electromigration etc.), surface failure (stiction), delamination, contamination (in-use) and others. Several recent publications have attempted to categorize [3,6 & 7] these modes of failure but during the product development process FMEA (both design and process) is the dominant methodology for reducing the effects of failure, and maximizing reliability. FMEA encompasses a systematic and comprehensive approach to identifying failure modes, their cause & effect, their severity, and more importantly provide corrective action.

A significant step towards creating more reliable designs is to include reliability in the design phase more actively – Design for Reliability (DfR). This is possible with current advances in system level (or behavioral) modeling e.g. Architect^{TM} tool (from Coventor), where it is now possible to include modeling of failure modes.

3 Design for Reliability (DfR)

Design for Reliability (DfR) considers reliability very early on in the development phase of the product and takes a holistic approach [8], with five different areas of focus at the center of which are the design tools, but include metrology, physics of failure, methodology and validation, as shown in Figure 2.

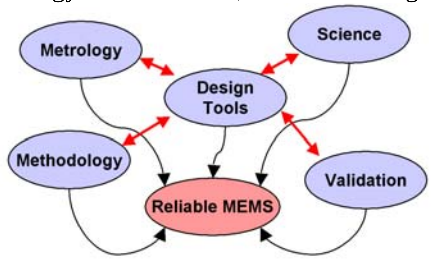

Figure 2: Focus areas for DfR approach

In a previous article [9], the central approach to linking the process and design areas (DfM) has been outlined and even demonstrated with examples of MEMS-CMOS integrated accelerometer devices.

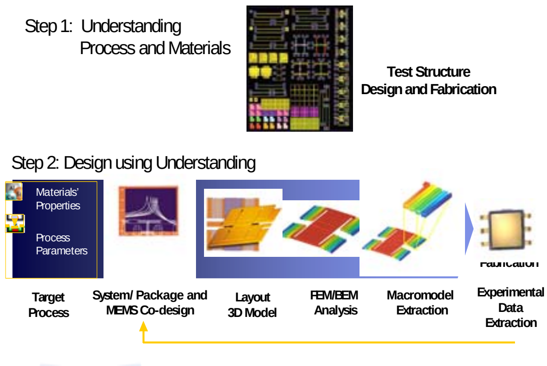

Figure 3: DfM Design Methodology

The CAD methodology essential to such automation is typically called a "top-down" methodology implying that for MEMS devices (as with IC's) starting from a system level description of the product implemented within a schematic tool, as shown in Figure 3.

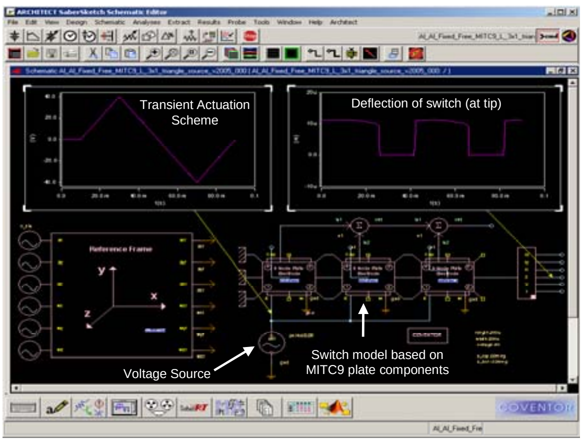

Figure 4: System level model of an RF switch

The methodology relies on accurate system level description of the product (or device) in a schematic environment (see Figure 4) and process description

The schematic model is then capable of not only predicting behavior of the system including the MEMS device, control electronics and packaging but also enables the designer to make trade-offs based on the constraints of the process. Further, it is possible to use the same environment to perform virtual manufacturing studies where the effects of process variability are quantified and bounded as shown below in Figure 5.

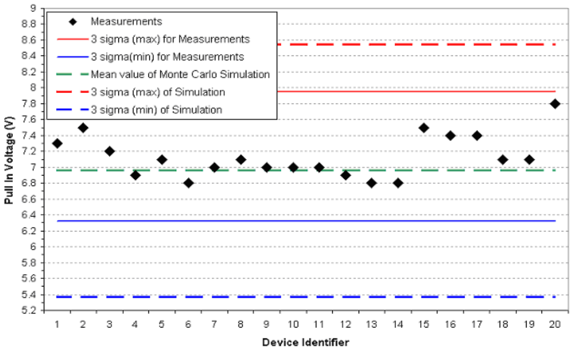

Figure 5: Virtual Manufacturing Analysis of MEMS plate-tether device [9] – Measurement & Prediction of Pull-in Voltage

Design for Reliability however requires the ability to incorporate the fundamental physics of failure into the design. Modes of failure described above such as stiction or fracture or contact wear or dissipation (gas damping) and others are easily incorporated in such a system level description (using tools such as Architect™). The fundamental failure mechanism (empirical or theoretical model) is programmed into the tool and added to the particular system level model at the appropriate stage of the design process. This makes it very convenient and an order of magnitude faster than other approaches in providing real insight into the potential failure of the system.

A typical example is stiction, which is a very common reliability problem in surface micromachined MEMS devices. The fundamental mechanisms of stiction under capillary forces in various environments have been well studied [10], but it has not been until very recently that the ability to include accurate predictive stiction models into the device level models has been possible. Traditional approaches using FEA based solvers are able (albeit with some challenge) to incorporate adhesive forces (equation 1 below) into existing models for contact but at significantly high simulation times which makes adding such sophisticated adhesion models at the system level much more efficient.

$$F_a = -\frac{\gamma_c L_c}{2\delta} w \qquad (1)$$

where γ_c is the interfacial adhesion energy.

The benefits are the obvious ability to predict the release of devices such as switches, the potential stiction failure of devices such as accelerometers and capacitors. In Figure 6, we see a typical example of a cantilever types switch simulated in Architect™. The plate models used to describe the coupled electro-mechanical behavior of the cantilever switch are quite sophisticated and include adhesion and contact forces, besides being able to model complex elasto-mechanics with residual stresses and stress gradients.

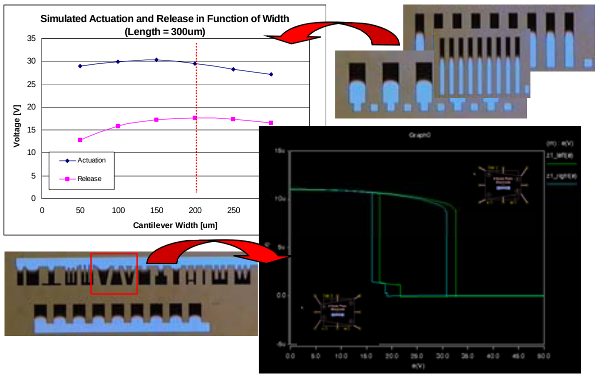

Figure 6: Plate Models applied to simulation of different switch geometries

This makes simulating the transient behavior of such devices even more efficient to the point where complex events such as the shock loading response (Figure 7) of an accelerometer with stiction and residual stress become feasible.

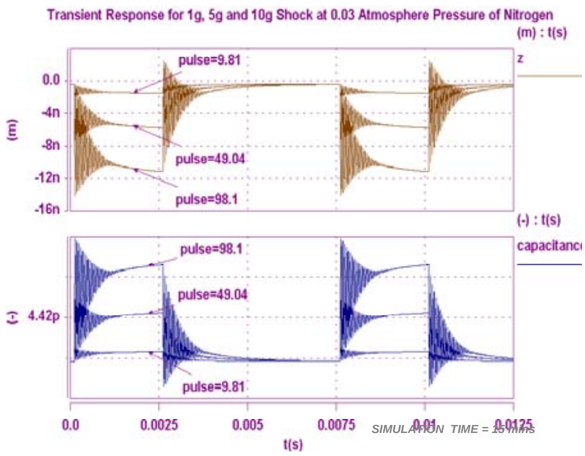

Figure 7: Transient Response to repeated 1g, 5g and 10g shock at 0.03 Atm. N_2.

These are precisely the class of predictive simulations that have challenged designers in the past and the ability to be able to accomplish these in the design phase in a short amount of time forms the basis of DfR automation.

Further, it is not unrealistic to expect that for a particular fabrication process, many more potential failure modes such as fracture, fatigue, creep, as well as electrical failure modes such as dielectric charging or breakdown could be added to existing electromechanical models thereby increasing the complexity of available models to designers, and more importantly, increasing the ability of designers to produce designs robust to such common failure modes. Although much work has to be done in building in time-dependencies (either from metrology based empirical data or from first principles) into these models to account for real-life time dependencies of actual parts the basic foundation for automating such design capabilities now already exists.

Finally, the schematic capture tools produced by the semiconductor industry (such as Saber® from Synopsys) already have certain reliability tools for FMEA or DOE built-in within their various tool-boxes and these have been used for many years in the IC industry. With the maturity of MEMS device behavioral model libraries [5] these tools can be now used for MEMS system level design in much the same way.

4 Conclusion

The enormous benefit and efficiency of using schematic driven tools such as Architect™ (Coventor) for simulating failure modes of MEMS devices and systems will help accelerate the ability of designers to produce more robust designs in shorter periods of time and at lower costs. Just as the semiconductor industry evolved to a point of producing reliable chips, so too will the MEMS industry gain in terms of time-to-market.

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