A COMBINED SIMULATIVE AND EXPERIMENTAL APPROACH TO RELIABILITY OPTIMIZATION OF MEMS

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ABSTRACT

Today CAD (computer aided design) simulation methods play a major role in the dimensioning of mechanical structures. It can be observed that a pure CAD approach becomes difficult during the reliability assessment of mechanical-electrical microsystems, because of the complexity of these systems, which originates from the large variety of integrated materials and thus a diversity of the resulting failure mechanisms. Nevertheless a design for reliability is vital for the successful production of MEMS (Micro Electro Mechanical Systems). Therefore strategies dealing with these uncertainties in reliability estimates need to be incorporated in the design process. The approach presented in this paper is based on the application of simulation and advanced deformation measurement methods named microDAC and nanoDAC, which are based on grey scale digital image correlation. It is exemplified on different detail levels of the reliability assessment, with an emphasis on fracture. The first stage consists of a parametric simulation approach, which helps to develop design guidelines for the geometry. For a more absolute quantitative analysis and for material selection in a new design the mechanical properties need to be specified and evaluated with respect to reliability. As the described approach of reliability assessment needs a profound knowledge of the failure behaviour, an analysis is undertaken based on the application of microDAC/nanoDAC techniques. In the prescribed way, it becomes possible to tackle reliability problems in early design phases.

1 INTRODUCTION

The development of a microsystem (sensors, actuators, …) involves several design iterations, which lead from the first idea to the final product. In this respect it is the goal of every design team to keep the number of iterations low in order to reduce development costs and time to market. Therefore reliability concerns have to be considered from the beginning, to avoid cost extensive redesigns in later development stages. The problem is, that in early design stages little is known about the exact nature of the final product, while specifications become more and more precise with every design iteration. Depending on the stage of the development phase different requirements on the modelling methods have to be met. The first models on the design draft have to give an understanding of the dependencies in the system. Currently detailed fracture models and experiments would be far to expensive and may even become useless when major design changes are being undertaken in later phases. Whereas in the final development phase quantitative estimates on the expected lifetime are of interest, but for such estimates a variety of experiments needs to be undertaken to calibrate the corresponding reliability models.

Therefore a methodology leading to solutions for a reliable product, should include different modelling and experimental testing approaches. As a complete overview of possible alternatives can not be given here, we concentrate in this paper on three examples and discuss their integration into the design process with a specific reference to fracture analysis and digital image correlation methods. At the end this approach may be incorporated into a more holistic system design approach, that involves the technological and functional boundaries as well as cost issues.

2 GEOMETRY ANALYSIS

To assess possible failure risks in the beginning of the design of a new MEMS device the following steps can be worked through:

1. Identification of loads and potential failure risks and modes
2. Identification of design variables and design space
3. Identification of dependencies

Before a simulation can be started the possible loads, failure risks and modes, which are of interest, have to be identified (step 1). This can be done either by engineering experience, literature research or analysis of similar products (i.e. deformation analysis as illustrated in section 4). As the system is too undefined to give a specific quantitative reliability estimate, the influence of design variations can only be analysed. Therefore the range of possible designs needs to be specified (design space). The identified failure modes are influenced by certain design variables (geometry, material, …). To assess their effect, in some cases analytical correlations can be used. But generally structures are too complex and in this case finite element analyses give the possibility to check the influences of the design. This is shown on different examples ranging from the analysis of the influence of copper layout on temperature [1], geometry of solder interconnects on solder creep strain [2] and via geometry on plastic straining of the copper layer [3]. The last example is illustrated in Figure 1, showing the parameter space of the geometry of a via at the edge of a silicon chip. The result of such an analysis is a design guideline with respect to the geometry of the resulting system, where it has to be kept in mind that the occurrence of failure can be predicted only in a very limited set of cases. A more general approach is shown in section 3.

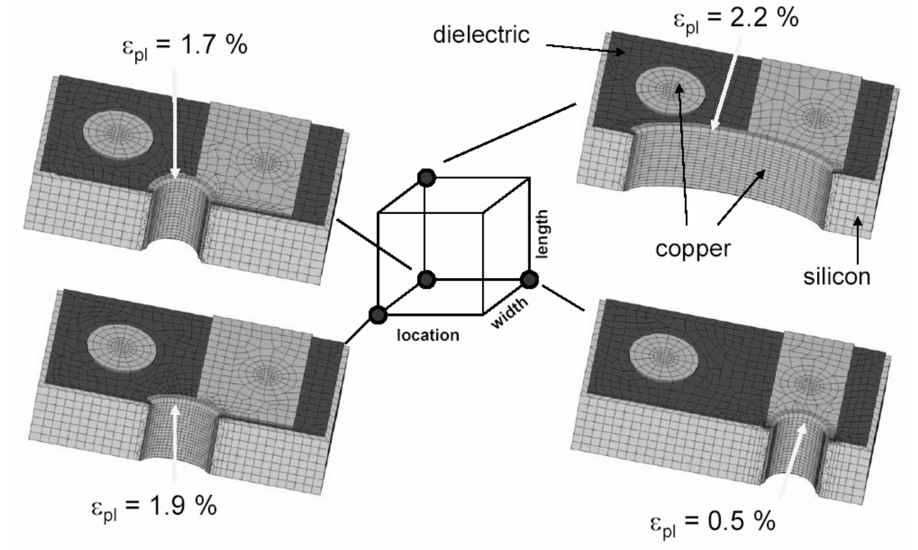

Figure 1: Investigated copper layouts and via geometries on one half of the device and indication of plastic strains after thermomechanical loading (printed wiring board, solder balls and solder resist are present in the model but not shown in the image.) [3]

3 MATERIAL EVALUATION

The material data for the models described in section 2 can either be taken from literature or being measured, depending on the quantitative accuracy that is required. When it comes to the mechanical evaluation of different materials, that are involved in a MEMS structure, the approach of section 2 needs to be extended, where some of the indicated tasks can run in parallel.

1. Identification of loads and potential failure risks and modes
2. Identification of important material parameters
3. Selection of materials of interest
4. Measurement of missing material data
5. Parametric modelling with respect to specified and characterised failure modes

The identification of important material parameters (step 2) needs to take into account the possibly important failure modes determined before (step 1). For example for a brittle fracture problem these material characteristics include the fracture toughness and the deformation behaviour, that includes Young's modulus and Poisson's ratio for elastic materials. More complex material behaviours need to be investigated with respect to the suitable material model (elastic-plastic, viscoelastic, …) [4]. When the load is induced due to thermal mismatch also the CTE (coefficient of thermal expansion) is of relevance.

In the next step (step 3) and based on the boundaries (i.e. technology, availability, cost, …) materials can be selected, which are of interest for further investigation. As often not all relevant material data is given by the manufacturers or in literature, the missing data needs to be determined experimentally (step 4). One problem in characterisation of MEMS materials is sometimes the small size of the structures of interest. Therefore miniature specimen are being introduced for stress strain measurement and fracture toughness determination [5]. In this respect deformation measurement by grey scale correlation is an option to measure strains on various specimen sizes, as they can be applied on different imaging methods for various scales, which can be based on optical microscopy, electron microscopy as well as atomic force microscopy. It has been demonstrated to enable the determination of CTE on thin films and Poisson's ratio of polymers [6]. Even concepts to determine fracture toughness on small geometries have been presented [7].

To evaluate the influence of the different materials on reliability, a simple comparison of fracture toughness does not give the relation describing the reliability in the MEMS structure. Also the influence of modulus or CTE stays often unclear, when only the material data is being compared. Therefore modelling gives the possibility to evaluate the dependency of reliability on different materials [8] or to detect critical situations for a catastrophic failure [4]. The complexity of these tasks shows that modelling of such failures needs profound knowledge of the failure modes and models.

4 FAILURE ASSESSMENT

As stated above the identification of failure modes is a crucial task for a reliable design. When prototypes or demonstrators are at hand, grey scale correlation methods (i.e. microDAC, nanoDAC) may give the possibility to identify cracks and delaminations as being demonstrated in [7] and summarised in the following paragraphs. With such information the methodology illustrated above could be supported by profound knowledge on the occurring failure modes.

In-situ non-contact SFM scans on top of a gas sensor membrane have been carried out at room temperature and at 100 °C. The area which was observed is illustrated in Figure 2 as location 2. At this area an overlap of the SiO_2 membrane by the platinum electrodes should result in a thermally induced stress/strain field. The temperature was achieved by applying a defined voltage to the microheater of the gas sensor.

The determined thermally induced displacement field shows that the platinum layer with its higher CTE value reveals an inherent expansion towards the edge of the layer (Figure 3). In supplementary tests with heating cycles with maximum temperatures in the range of 450 °C severe delaminations of the platinum layer at the edges to the SiO_2 substrate layer were observed (Figure 3). Details of this testing cycle are described in more detail in [9].

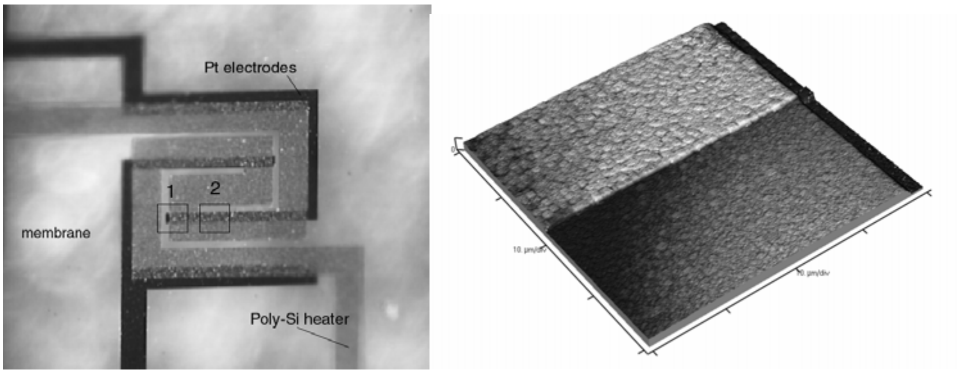

Figure 2: (left) Microscopic image of flow and gas sensor membrane, overall membrane thickness: approx. 2 µm, field of view: approx. 500 µm; (right) SFM topography scan of gas sensor depicting the Pt layer on top of the SiO_2 membrane and part of the Poly-Si heater embedded, (detail 2 of Fig.6 (left)), Source: [9], joint project with the Dept. of Electronics, University Barcelona)

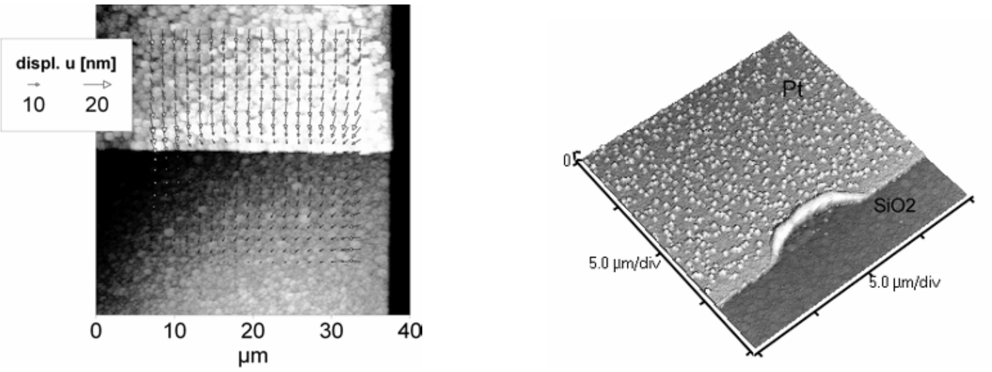

Figure 3: (left) SFM topography image of platinum and SiO_2 layers; vector plot of displacements u measured by nanoDAC; (right) SFM topography scan of membrane layers after tempering at 450 °C, Pt electrode destruction (compare to Figure 2)

5 SUMMARY

The integration of specific simulative and experimental methods in the design process of MEMS is exemplified on three methods, which help to analyse reliability issues. It is shown what input needs to be defined for these methods as well as the possible results, which can be obtained.

For a parametric analysis of the geometry basic material data (i.e. from literature) and a basic idea of the structure is being needed. Thus the results will have a qualitative nature and will give a first idea on the influence of geometry variations and some material parameters.

To analyse the influence of materials an experimental analysis of the materials under investigation is needed. Especially for small specimen geometries grey scale correlation methods give the possibility to determine deformations under prescribed loads. Therefore parameters like CTE, Poisson's ratio or fracture toughness can be determined. With these results simulations can be undertaken, that give the possibility to compare different materials and detect critical situations.

The methods above are based on profound knowledge of the failure mode. When this is not at hand grey scale correlation methods (microDAC, nanoDAC) are shown to give information on specific failure modes.

6 REFERENCES

[1] Schindler-Saefkow F., Wittler O., Schacht R., Großer V. and Michel B., *Thermal Behaviour of 3D MATCH-X Packages*, 14th European Microelectronics Packaging Conference & Exhibition EMPC, Friedrichshafen, Germany, June 23-25, 2003, proceedings

[2] Wunderle B., Auersperg J., Großer V., Kaulfersch E., Wittler O. and Michel B., *Modular Parametric Finite Element Modelling for Reliability-Studies in Electronic and MEMS Packaging*, 5th Symposium on Design, Test, Integration and Packaging of MEMS/MOMEMS DTIP, Mandelieu - La Napoule, France, May 5-7, 2003, proceedings, pp. 335-340

[3] Wittler O., Manessis D., Sommer J.-P. and Michel B., *Thermo-Mechanical Design Analysis of Wafer Level Packages*, European Microelectronics and Packaging Symposium, Prague, June 16-18, 2004, proceedings

[4] Wittler O., Sprafke P., Auersperg J., Michel B. and Reichl H., *Fracture Mechanical Analysis of Cracks in Polymer Encapsulated Metal Structures*, Polytronic 2001, Potsdam, Germany, October 21-24, 2001, proceedings, pp. 203-208

[5] Walter H., Bierögel C., Grellmann W., Fedtke M. and Michel B., *Fracture Mechanics Characterisation of Epoxy Resins with Mini-Compact Tension (CT)-Specimens*, 3rd International Conference and Poster Exhibition Micro Materials, MicroMat 2000, Berlin, Germany, April 17-19, 2000, proceedings, pp. 537-540

[6] Vogel D., Luczack F., Wittler O., Gollhardt A., Walter H., Michel B., *Measurement of Material Properties by a Modified MicroDAC Approach*, , 3rd International Conference and Poster Exhibition Micro Materials, MicroMat 2000, Berlin, Germany, April 17-19, 2000, proceedings, pp. 829-832

[7] Keller J., Vogel. D., Bauer M., Michel B., *NanoDAC – A Powerful Method for Nanomechanical Analysis of Polymeric Materials*, Materialsweek 2002, München, Germany, September 30 – October 2, 2002, proceedings

[8] Wunderle B., Schacht R., Wittler O., Michel B. and Reichl H., *Thermal Performance, Mechanical Reliability and Technological Features of Different Cooling Concepts for High Power Chip Modules*, 9th International Workshop on Thermal Investigations of ICs and Systems Therminic, Aix-en-Provence, France, September 24-26, 2003, proceedings, pp. 59-64

[9] J. Puigcorbé, D. Vogel, B. Michel, A. Vilà, N. Sabaté, I. Gràcia, C. Cané, J.R. Morante: "AFM Analysis of High Temperature Degradation in MEMS Elements", MME'02, The 13th Micromechanics Europe Workshop, October 6-8, 2002, Sinaia, Romania