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A survey of Mechanical failure and design for Reliability of MEMS

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Abstract. In this paper, several experimental mechanical investigation techniques are presented to evaluate the reliability of micro-electro-mechanical systems (MEMS). Microsystems in recent years have spread in many everyday devices. We find micro-scale sensors and actuators in automotive, biomedical and aerospace applications where are demanded very strict performance requirements. Electromechanical non-linear coupling is often a crucial problem both in design and also for the reliability of the system. Mechanism of failure and failure modes has to be taken into account in order to evaluate the reliability of the final system. Focusing on device failure, it emerges that mechanical damage is the most significant source. In this paper a survey of recent advance in mechanical testing of MEMS is presented including: mechanical fatigue, mechanical strength and plasticity, surface and contact failure and creep. Different design of testing specimens is discussed to identify the material properties and failure modes behavior in order to obtain design rules and strategies.

1. Introduction

MEMS technology allows the advantage, first of all, to considerably reduce the size and weight of the devices and consequently allow an actuation using a lower electric power. In literature are mainly described aspects of micro-fabrication and technological realization of MEMS. Recently, with the significant diffusion in different application fields of MEMS sensors and actuators, several researchers concentrated to the attention to the problems of reliability and durability [1,2].

MEMS reliability is challenging but a survey of the literature pointed to a lack of experience in systematic approach. Several papers pointed out on a specific failure mode or concentrated the attention on a particular device behavior [3-5].

Wide are the applications of MEMS. Main reasons for choosing MEMS device, instead of a more mature technology, are the reduction in dimensions and weight. These are then accompanied by a more advantageous integration in an electronic system that also includes in the final device a microchip of signal processing. For example, in the telecommunications and satellite communications sector oscillators or MEMS switches have been introduced for radio frequency applications, in automotive and aerospace vehicle applications accelerometer sensors and MEMS gyroscopes have been introduced, in biomedical applications have been developed MEMS micro chambers for microfluidic analysis techniques (LAB-on a-chip).

However, MEMS has to be categorized in order to derive effective design rules. MEMS devices can be categorized based ability to interact with their environment and on their actuation sources into four main groups: electrostatic, electromagnetic, piezoelectric, and electro thermal actuators [6-9].

Unlike macro structures in micro devices and in particular in MEMS structures the study of reliability becomes more complicated due to the difficulty in generating and replicating fault events.

The following list can help to address their possible failure depending on the dynamic behavior, schematically devices with:

- deformable parts of the micro-structure that can move but without impacting on the substrate such as for example in the case of gyroscopes, accelerometers and RF oscillators;
- deformable parts with impacting surfaces including micro-mirror arrays and RF switches.

About structural reliability, it is necessary to evaluate the effects of the process parameters and load working conditions. Among main loads the electromechanical non-linear coupling is crucial for design and represents a potential source that can lead to device collapse. Mechanical damage represents the most significant source of failure usually generated by localized material deterioration. The technology realization of a micro-device is strongly influenced by the process and therefore also the final properties of the material will be due to the process. With regard to the most frequent type of localized damage in the MEMS we find the wear of moving parts due to the electromechanical adhesion of the sliding contacts. Over time the contact surfaces can change their shape due to the wear of the surfaces and therefore determine strong variations in the electromechanical coupling force with consequent failure.

Some of the most common techniques used for MEMS have been firstly developed for integrated circuits and derived from microelectronic process industry. In the present paper a survey of recent advance in mechanical testing of MEMS is presented including: mechanical fatigue, mechanical strength and plasticity, surface and contact failure and creep. Specimen design and failure modes have been listed related to a specific fabrication process in order to derive design rules strategies focusing on reliability.

2. Failure modes

A failure occurs when "*a device or a system no longer performs the required functions under the stated conditions within the stated period of time*" [10]. Due to the nature of coupling, the performance of a MEMS device depends on the mechanical and electrical characteristics of the entire system. Two main types of faults can be highlighted:

- catastrophic (or irreversible) failures, which leads the device to be completely inoperable
- degradation failure, that affects a local part of the device changing functions and parameters outside then normal range of operation.

It is possible to define failure modes and failure mechanism describing observable effects (broken structure, cracked surface, plasticity mechanism, etc.) or directly measurable degradation exceeding prescribed limits. The study of mechanical reliability strictly depends on the understanding the failure modes and mechanisms in different operational conditions. These study output could be design rules that including fabrication processes parameters allow reliable operation of the device during its operating life. In this paper main failure modes and mechanisms that occur in MEMS devices have been identified. The following sections provide a description of the primary failure modes, together with a discussion of the techniques proposed in literature to evaluate and determine them.

2.1. Material and residual stress

The failure of a device and its reliability are strongly influenced by the type of materials used and their structural compatibility. In the technological MEMS process a large number of different materials are used. Metal materials or often silicon are used to make the moving parts of the devices. For electrical and thermal isolation both silicon dioxide and silicon nitride have traditionally been used. For electrical isolation also other materials are used as aluminum oxide and polyimide.

In the realization of MEMS devices technological processes derived from micro-electronics are used. Different materials are integrated, some with structural functions and others with electrical functions, which lead to having failure mechanisms that must be interpreted before they can be traced back to the most known failure mechanisms in the traditional field of electronics or mechanics. RF MEMS technology widely uses gold membrane and beam with different layers that behave like a composite material. In recent years the studies available in literature conducted on the stability of MEMS devices in the long term and on the maintenance of properties over time are still few in number.

The mechanical properties of micro-size material used in MEMS technology could be strictly influenced by the process parameters and process recipes [11-13]. For example the presence of the residual stress generated in the materials during fabrication process could lead to unwanted behavior of membrane, beam, or cantilever structures realized with metal or dielectric thin films within the material [14-16].

In different applications and for different micro-fabrication process experimental testing of MEMS mechanical failure mechanism have been presented in literature such as: buckling [17]; fatigue [18-22]; thermal effect and creep [23-27]; wear and tribology [28,29].

3. Testing procedures, specimen and results

In the last two decades extensive modeling and experimental activities of MEMS have been done by the research group of Politecnico di Torino - Mechanical Department. The deformable elements in MEMS are usually relatively simple and analytical techniques have often been used in the design procedures. The complexity of mathematical calculations can grow due to the non-linearity of the electrostatic coupling computer models and finite element analyses are necessary to fully understand the device characteristics. Finite element can be used, before the expensive and time-consuming fabrication and testing, to evaluate the static, dynamic and thermal behavior of the system. In the case of MEMS it is preferable to use multi-physics finite element models to take into account the couplings of the different physical domains.

The coupling mechanical electrostatic behavior has been studied taking into account the non-linear effect of material [30] and large displacement in different device configuration [31]. Both for MEMS realized in poly-silicon material and in gold material for RF MEMS switch application [32]. Non-linear and linearized simulation method is developed for the static analysis, pull-in and frequency shift dynamic simulation [33,34]. The coupling problem of fluid-structure interaction has been widely studied, simulated and defined in order to evaluate the fluidic damping parameter respect the dimension structural parameters [35,36]. Modeling simulation approach has been also derived to study the termo-structural coupling behavior of MEMS [27]. Main results of these studies were to develop simulator to enable a better understanding of MEMS behaviors, suitable to assist first the design and then the fabrication process. A key feature of this method was the iterative approach involving simulation, sensitivity analysis that leads to optimal MEMS structures [37].

In order to efficiently realized a design procedures firstly modeling approach can be performed decoupling different failure modes effect.

3.1. Elastic-plastic tests of MEMS

Unlike the macro-scale domain, in micro-scale testing it generally is not possible to decouple the specimen of characterization of the material from the machine that solicits the specimen. The test micro-structures (Figure 1) are designed in such a way as to allow an actuation of the specimen in the range of behavior expected of the material. Using electrostatic actuation of the lateral plates the stress–strain behaviour and plastic strength of the microstructures is experimentally studied by measuring the static deflection of the central specimen. By means of non-linear finite element method (FEM) simulations the tensile stress behaviour in the test specimen is evaluated [38, 39].

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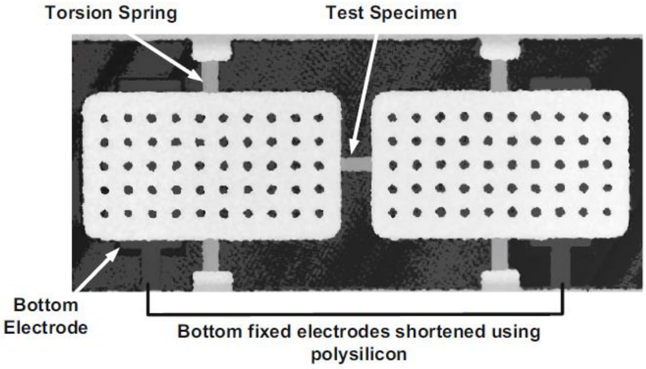

Figure 1. Test microstructure for elastic-plastic tests with the central specimen

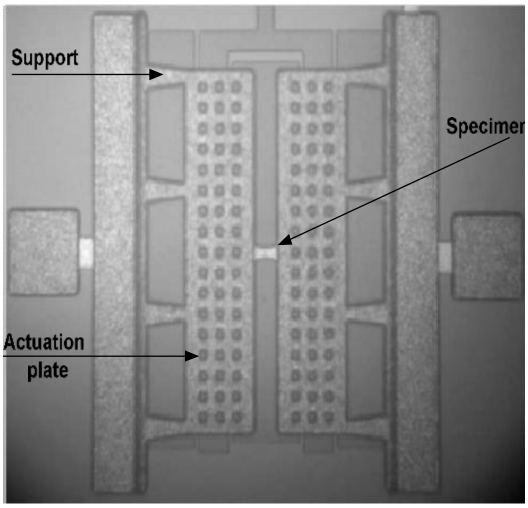

Figure 2. Fatigue testing device: actuator (perforated plates) and specimen (suspended beam).

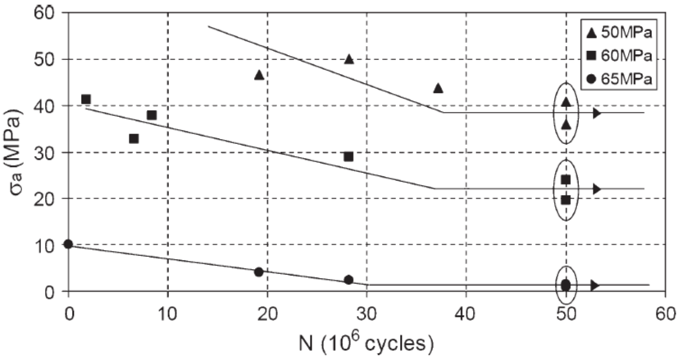

Figure 3. Experimental results of fatigue tests in the Wohler diagram for three values of mean stress. Specimens marked with an arrow did not fail.

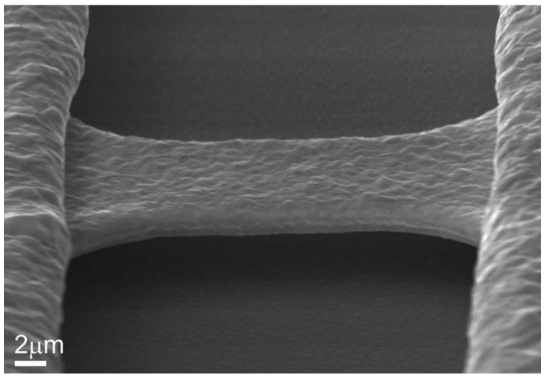

Figure 4. SEM detail of the specimen fabricated using gold electro-deposition technique.

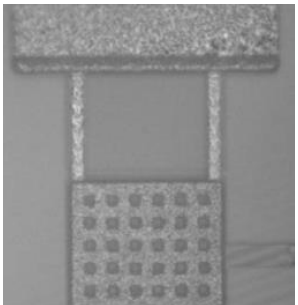

Figure 5. Electroplated gold sample for creep test

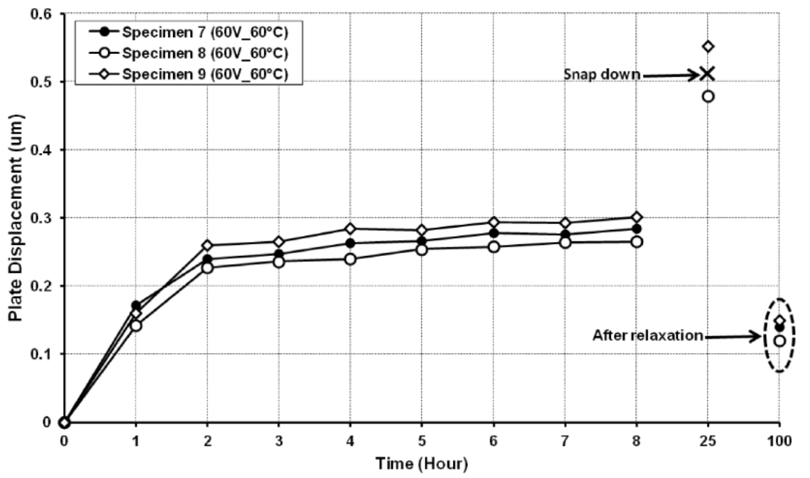

Figure 6. Experimental measurement of specimen displacement at 60 V and 60 °C and residual displacement after 100 hours

3.2. Fatigue tests

Specific specimen (schematically described in Figure 4) and extensive experimental tests have been conducted to study the fatigue behavior of MEMS [40, 41]. Dedicated fatigue test devices (Figure 2) are designed and fabricated with the aim of producing an alternate load on the embedded specimen. In the device is possible to fabricate an embedded beam specimen (Figure 3). Using electrostatic actuation as a driving force the central specimen could be loaded in tensile mode with different levels of mean and alternate stresses. By using FEM models, previously identified, is possible to evaluate the stress level produced in the specimen during the test phases. The Wohler diagrams of the experimental fatigue tests are presented in Figure 3.

3.3. Creep tests

Specific specimen (schematically described in Figure 5) and experimental test has been realized to study the thermo-mechanical behavior of MEMS in order to evaluate the material coefficient thermal expansion (CTE) and evaluate creep mechanism [42]. The evaluation of the amount of creep damage could be done, if reach a measurable magnitude, firstly through the detection of permanent deformation of specimens. In [42] was proposed also a novel indirect method associating the amount of creep damage to the variation of mechanical stiffness. This variation could be measured using electro-mechanical parameters such as resonance frequency shift, pull-in voltage. In Figure 6 results demonstrated the presence of a final plastic deformation after relaxation due to creep. Moreover the continuous curve displays reversible strain due to the viscoelastic behavior of the material.

4. Conclusion

The diffusion of MEMS devices in different advanced application depends largely on their reliability. MEMS technology is derived from micro-electronic process, but the presence of micro-movable parts determine that device level reliability is strictly influenced by mechanical behavior. In this paper, main mechanical failure modes of MEMS devices have been listed and described separately. Dedicated mechanical tests can be performed firstly to understand the associate failure mechanisms at the micro-scale and in presence of multi-physics coupled domain such as electro-mechanical coupling. It is evidenced that in MEMS specific fatigue, creep and plasticity tests are also useful to qualify the process technology and the process recipes. Final result of the combination of the test results could lead design rules suitable for a systematic modeling approach in MEMS focusing on reliability.

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