JOURNAL OF MATERIALS SCIENCE 38 (2003) 4163 – 4167

Reliability assessment of polysilicon MEMS structures under mechanical fatigue loading

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This paper examines the current status and methodologies of study of material and system reliability in Microelectromechanical Systems (MEMS). This includes: a review of the current literature in the area of MEMS regarding failure analysis experimental investigations; testing methods and philosophies for material characterization and possible mechanistic analytical solutions for estimating material properties. The paper proposes a reliability framework that encompasses all the available information. This statistical platform will enable the MEMS design engineer to distill all the available information in the literature into a stand-alone semi-empirical material reliability model, and a holistic system-level model for a complete system.

1. Introduction

One of the major hurdles in the large-scale commercialization of Micro Electro Mechanical Systems (MEMS) is the development of a detailed study of failure mechanisms under various kinds of loadings [1–4]. MEMS may be classified in two broad categories, sensors and actuators. Within actuators, there is an emerging area of micro-motors and micro-engines that have shown promise of application in areas such as microfluidic systems, and are currently applied in devices such as optical switches on a commercial scale. However, a survey of the literature indicates that there is no mechanism based design tool that can aid in the reliable design of MEMS. The focus of this paper is to suggest a possible framework for the same.

The failure analysis approaches in MEMS can be broadly classified into three major categories:

1. Micro-mechanical material property testing.
2. System level failure tests to determine the relative frequency of device component failure in a complete working device.
3. Material failure mechanisms to determine the corrosive effects of mechanical and environmental stresses.

1.1. Micro-mechanical material property testing

A popular approach to studying the effect of mechanical fatigue loading on MEMS structures, chiefly in actuators, has been to electrostatically operate the MEMS device at its resonant frequency and observe either the degradation in resonant frequency, and/or its life until failure [1–4].

One of the earlier works by Connally and Brown [1] investigated the time dependent crack growth on single crystal silicon cantilevers excited at resonance. They suggested that stable crack growth occurs in single crystal silicon, and it can be related to the degradation of the resonant frequency of the specimen. With the advances in microfabrication and the development of the comb-actuator polysilicon specimens, Brown *et al.* [2, 3] were able to demonstrate the hitherto unknown effects of environmental conditions, especially humidity, on the fatigue life of the devices. The exact nature of the relationship between fatigue life, stress intensity and humidity was not established although a suggestion regarding the formation and subsequent cracking of the amorphous silica layer formed at the surface of the devices has been made. They were also able to show that the crack growth period of the fatigue life is often a very small part of the total life of the device as compared to the fatigue crack initiation life, and is often disregarded in the life estimate analyses. Similar conclusions have been drawn by Kahn *et al.* [4] and this information has been presented in the form of Stress versus Number of cycles (S-N) curves for a specific geometry of test specimens. Several others [4, 5] have performed material tests on microfabricated silicon structures in order to determine the fracture toughness values for polysilicon as a basis for investigating material properties from a fracture mechanics point of view.

The information for fatigue failure in this literature [1–4] comes in the form of S-N curves, which is the traditional way of representing fatigue data in absence of a fatigue mechanism based model. The difficulty with using S-N curves lies in the fact that each life test yields one point on the S-N curve. Due to the nature of this experiment, it is reasonable to assume that the data from the S-N curve also captures the device-to-device variability, which causes a large scatter in the observed data. The merit of this type of testing, thus, lies in the fact that it gives an estimate of the variability inherent in the materials used for the fabrication of the devices, as well as the fabrication process itself.

1.2. System level failure tests

Another approach to studying failures in MEMS structures is by studying the failure analysis patterns in the components of the devices. Two broad categories are seen in this case. In the first, a system level failure model examines the propensity for various types of failure modes in the devices. Tanner *et al*. [6] have investigated several complicated micro-engine and gear train assemblies. They conclude that the wear and tear may not be as large a problem as compared to debris-caused electrical short-circuits or vibration induced adhesion.

In similar tests, Tanner *et al*. [7] also investigated the failure modes of the devices under shock loading up to 40,000 g acceleration levels. This paper makes a significant contribution in analyzing reliability of the system by attempting to compute critical shock levels corresponding to several different modes of failure. Experiments have shown that the computed 'worst-case' limits for shock levels were safe due to damping effects. The information from these papers can be used to establish a limit state for design of systems subjected to shocks based on simple Newtonian mechanics solutions.

1.3. Material failure mechanisms

Research at the level of material structures and environmental interaction has been fundamental in leading to better understanding of the actual failure processes of polysilicon. Failure at this level has been attributed to the combined effects of an active atmosphere and surface forces. The action of oxygen on an exposed polysilicon surface results in the formation of a native oxide layer of amorphous silica [8]. This superficial layer shows stress corrosion cracking [9]. The work by Allameh *et al*. [10] showed clearly that surface topology evolves due to the application of the stress, however it is well established if this topology evolution gives rise to microcracks initiating from flaws in the crystal structure that lead to the ultimate failure of the test specimen. They have established a critical voltage at which failure takes place, and thus potentially a critical surface stress level, which exacerbates the surface evolution rates leading to quicker failures in the specimens. In a paper on cracking mechanisms proposed by Liu *et al*. a framework for formulating design rules for better structural design has been proposed, [11] thus advancing the understanding of the physical mechanisms associated with failure of polysilicon devices.

The wide range of approaches presented above [1–11] is likely to overwhelm the MEMS design engineer when making assumptions for system design. The motivation of this paper is, therefore, to develop a platform that will allow the integration of information from different testing procedures and mechanism-based theories into a reliability prediction framework.

2. The performance hierarchy of a micro electro-mechanical system

From an applications standpoint, the performance of a MEMS would have to integrate the following four levels of reliability assessment:

TOP LEVEL

1. User application compliance reliability
2. System level reliability
3. Device component level reliability
4. Material reliability.

BOTTOM LEVEL

If performance is defined as the compliance with standards, then a satisfactory performance of a device from the user application standpoint would logically have to comply with ALL the specified standards at all the different tiers of the model.

The scope of this paper is limited to assessing the reliability of a device under mechanical fatigue. As such, the development of performance standards will only be demonstrated for mechanical fatigue, however, the performance hierarchy presented above may be used for developing a complete systems approach to MEMS design.

3. Performance of MEMS under mechanical fatigue

Consider a hypothetical device, such as an optical encoder, which uses a microengine similar to the one developed by Sandia National Labs [6, 7]. At the topmost application level, the performance requirement would be in the form of a numerical standard such as encoding speed and useful life to failure as a product requirement. This performance standard has various implications at the component level and the level of reliability of any sub-assembly of the device, requires a detailed knowledge of the interactions of the sub-assembly.

At the system level, the established standard translates into frequency and number of cycles to failure. Compliance at this level requires the reliable performance of every component of this system, that is crucial to its working, for the life requirement at the given frequency. This sets the standard for the device component reliability.

Material reliability functions are often set for physical parameters of the system such as stress, surface roughness, flaw size and defect distribution etc. However, in order to express system performance in terms of the standards imposed for frequency and life to failure, one must be able to establish a relationship between material reliability functions and performance criteria.

In the absence of a well-established mechanistic understanding of failure processes in polysilicon due to fatigue, and in accordance with the available information from the literature, semi-empirical models must be developed using probability theory. Due to its simplicity, the best approach for development of such a model is by regression.

4. A statistical expression of reliability

The reliability of a system can be readily described as the probability of survival. In general terms, a device will survive if the load applied to the system can be sufficiently resisted by the strength of the system. In case of fatigue, the load applied to the system is in terms of stress, while the strength of the system may depend upon physical parameters such as material strength properties (such as tensile and compressive strengths, fracture toughness, modulus of elasticity, etc.), flaw size distribution, surface roughness values and ambient environment.

4.1. Material level reliability

The strength of a system can be modeled as a probability distribution [12]. In this review paper, it has been shown that life of an actuator component can be modeled as a stochastic multiplicative function of applied stress and thickness of the specimen for several data sets in the literature. This function has been represented as [12]:

$$\eta = f(S, t)$$
$$\eta = \alpha_0 S^{\alpha_1} t^{\alpha_2} \quad (1)$$

Equation 1 can be linearized to give

$$\ln(\eta) = \ln \alpha_0 + \alpha_1 \ln(S) + \alpha_2 \ln(t) \quad (2)$$

In Equations 1 and 2, η is the number of cycles, S is the stress level of the test, and t is the thickness of the specimen. $\alpha_0, \alpha_1, \alpha_2$ are the model constants.

The fundamental unit of reliability models using a statistical platform has been explained by Haugen [13] and also by Ang and Tang [14]. This is shown in Fig. 1:

4.2. Component level reliability

Several devices or components of MEMS structures may be connected in series, where the failure of one device will cause the failure of the entire system.

In this case, the probability of survival of the entire system, denoted by $P(S)$ is provisional to the condition that all the components survive, and if they can be considered as failing independently of one another. If $P(S_1)$, $P(S_2)$, $P(S_3)$, ... $P(S_k)$ are the probabilities of survival of the different components connected in series, i.e., the survival of each device is crucial to the survival of the system, then the probability of survival of the system becomes

$$P(S) = \prod_{i=1}^{k} P(S_i) \quad (3)$$

If several component are linked in parallel, where the failure of one component does not necessarily hamper the output of the device. In this case, the probability of survival can be expressed as:

$$P(S) = 1 - \prod_{i=1}^{k} (1 - P(S_i)) \quad (4)$$

In reality, every system will be a mixed system, with some components in series, some in parallel. The computation of the overall probability of survival of such a system will follow the rules of probability mentioned in Equations 3 and 4 above.

For example, if a structure consists of the mixed system of components shown in Fig. 2, then the reliability of the MEMS Structure can be expressed as:

If $P(S_1)$ and $P(S_2)$ are the reliabilities or the probabilities of survival *f* components (1) and (2) in series, then the combined probability of survival of these two components is $P(S_1) \cdot P(S_2)$. If the reliabilities or the probabilities of survival of components (3), (4) and (5) are given as $P(S_3)$, $P(S_4)$ and $P(S_5)$, then the overall system reliability of components (3), (4) and (5) can be expressed as $1 - [1 - P(S_3)][1 - P(S_4)][1 - P(S_5)]$.

From the above results, the combined probability of survival $P(S)$ of all the components (1), (2), (3), (4) and (5) can be expressed as:

$$P(S_1) \cdot P(S_2) \cdot [1 - [1 - P(S_3)][1 - P(S_4)][1 - P(S_5)]] \quad (5)$$

4.3. System level reliability

System level failure tests can be used to generate information as the relative frequency of the different failure mode that will be seen in a system.

The several possible types of failure that have been observed in references [6, 7], which looks at a system level reliability, have been listed below:

1. Electrical short circuits caused by debris movement
2. Structural damage (fracture of components)
3. Packaging and electrical connection problems

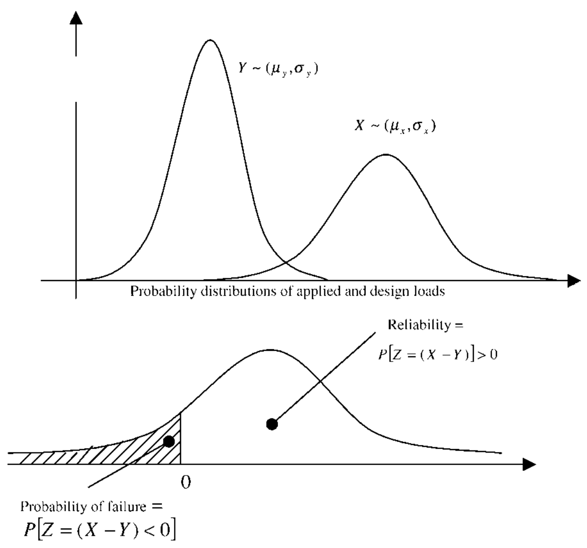

Figure 1 Modeling reliability and probability of failure.

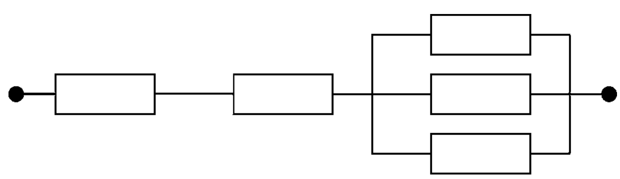

Figure 2 A mixed MEMS structure consisting of components (1) and (2) in series and components (3), (4) and (5) in parallel.

4. Misalignment
5. Stiction and adhesion

The determination of reliability at this scale can come only after manufacturing several devices and rigorously testing them, and would encapsulate all the reliability information at a level that would allow a designer to ensure a well-balanced design of a system.

5. Designing against fatigue

Performance criteria will establish a suitable standard for a device based upon the required function of the device. This could be in terms of service life on a time scale, or it could be in terms of total number of cycles. These are equivalent measures related with the native device frequency.

This performance standard will have its implications down to the material reliability level. These limits can be established for specific probabilities of failure using the methodology outlined above that would allow the designer to create a MEMS design by complying with the required specifications. Moreover the design of MEMS Structures must also consider the effective control of the related input variables that can affect performance. This is essential in order to maximize both the reliability of each component and the total system reliability of any MEMS structure. With models such as that shown in Equation 1, it will be possible to design a system with specific parameters (like stress expected on the system, and thickness of the component for example).

These parameters in turn can be used to estimate the material reliability, which is the probability of survival, which can be used as information input for device component reliability, which in turn will generate a reliability estimate for the system level in a manner similar to a fault tree analysis [14].

Thus, for a given set of performance criteria, the overall system reliability can be evaluated. The schematic diagram for this process is shown in Fig 3.

6. Conclusion

A systems level reliability assessment procedure has been established in this paper. The procedure can be used to establish theoretical reliability models as functions of related material parameters and specified performance parameters. The theoretical probabilistic models should be validated using appropriate experimental data. The methodology developed in this paper can also be used to control the major related material

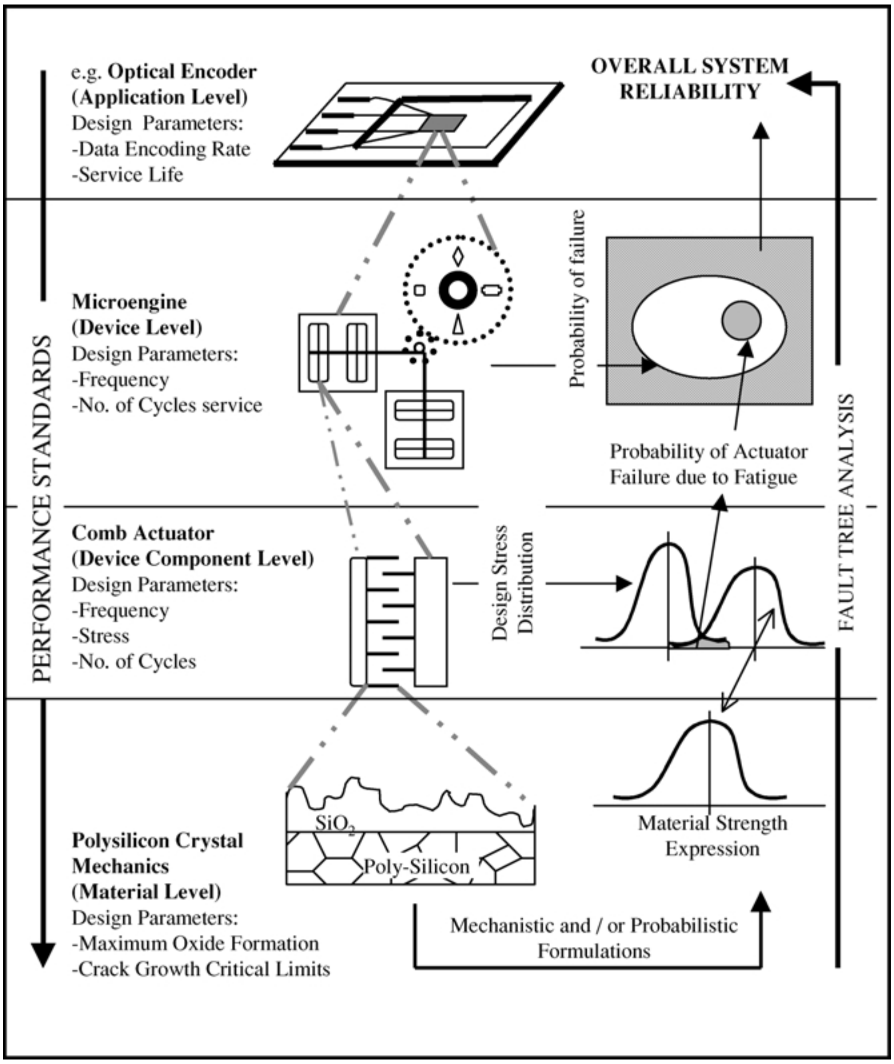

Figure 3 The performance and reliability assessment methodology.

variables which can affect performance. These are necessary in order to maximize the reliability and consequently minimize the maintainability of components and systems utilizing MEMS structures. The use of the model can be made as follows:

- In the downstream direction, one may use the model to establish performance standards on the design and function of the MEM System.
- In the upstream direction, one can use existing data to evaluate the reliability of the device.

The platform, in conjunction with experimental analysis has the potential to eventually grow into a complex system that can be utilized for the efficient design and optimum reliability of micro electro mechanical systems.

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