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Reliability modelling and analysis of thermal MEMS

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Abstract. This paper presents a MEMS reliability study methodology based on the novel concept of ‘virtual prototyping’. This methodology can be used for the development of reliable sensors or actuators and also to characterize their behaviour in specific use conditions and applications. The methodology is demonstrated on the U-shaped micro electro thermal actuator used as test vehicle. To demonstrate this approach, a ‘virtual prototype’ has been developed with the modeling tools MatLab and VHDL-AMS. A best practice FMEA (Failure Mode and Effect Analysis) is applied on the thermal MEMS to investigate and assess the failure mechanisms. Reliability study is performed by injecting the identified defaults into the ‘virtual prototype’. The reliability characterization methodology predicts the evolution of the behavior of these MEMS as a function of the number of cycles of operation and specific operational conditions.

Keywords: MEMS reliability; Virtual prototype; FMEA; thermal actuator.

1. Introduction

In contrast to microelectronics, MEMS reliability models and test structures used to understand operation failure modes are still in infancy. MEMS devices, by their very diverse nature, have different failure mechanisms from their macroscopic counterparts. The multiple domains of energy (electrical, mechanical, thermal, biological, optical, chemical, radiant, etc.) in which such systems work result in a multiplicity of potential failure modes lying very often at the boundaries of these domains. With the growing industrial relevance of microsystems, the assessment of their failure mechanisms and reliability characterization has become of critical importance in order to improve yield, reliability towards the commercialization of such devices in critical applications and accelerate the industrial take up of this technology. In this article we propose a new methodology to study the reliability and
behavior of MEMS in specific use conditions and applications. This methodology is employed to achieve an optimum design before manufacturing, resulting in savings of time and money.

2. Methodology to characterize MEMS reliability

The proposed reliability characterization methodology is based on the concept of ‘virtual prototyping’. The schematic of the methodology is shown in figure 1.

![Methodology for predictive analysis of MEMS reliability.](image)

Virtual prototyping is a behavioral model methodology that considers the possible failure mechanisms before the completion of the design and before their occurrence in the field. The first step of this methodology is the creation of the virtual prototype from the specifications using modelling tools and materials databases. The reliability study can then be carried out by injecting the already identified defaults in the developed model and optimizing the MEMS design before its fabrication. In this article U-shaped electro thermal actuator (Fig. 2) is used as a test vehicle, to present the steps involved in the development of the virtual prototype: analytical modelling, finite element modelling and validation with experimental data obtained with test structures. As shown in figure 2c, $l_h$, $l_c$ and $l_f$ are the lengths of the ‘hot arm’, ‘cold arm’ and ‘flexure arm’, respectively; $w_h$, $w_c$ and $w_f$ are the widths of the ‘hot arm’, ‘cold arm’ and ‘flexure arm’, respectively; and $g$ is the distance between the two arms. The current circulation in the structure results in unequal thermal expansion caused by ohmic heating of microstructures with variable cross sections. Higher current density in the hot beam causes it to heat and expand more than cold beam, thus produces lateral arcing motion towards the cold beam side (to the bottom in the Fig. 2).

3. The FMEA method

FMEA (Failure Mode and Effect Analysis) is a systematic and structured study of potential failures that might occur in any part of a system and is used to determine the probable effect of each on all other parts of the system to improve the design, product or manufacturing process. A best practice FMEA is applied on the thermal actuator to find the factors critical for reliability improvement [1, 2]. This analysis is proactive rather than reactive as potential problems can be investigated before completion of the design and before failures occur in the field. The FMEA outcomes are summarized below:

1. Design related issues: Stiction is one of major failure modes either during the manufacturing process due to capillary condense, residual stress induced deformation or during operation with ageing, due to humidity and thermomechanical stress induced bending. Increasing the elevation of
the actuator above the substrate is an ideal remedy to improve reliability. This solution can also reduce dramatically the device power consumption by increasing the thermal isolation to substrate. A trench under the hot arm further increases the power efficiency by decreasing the thermal loss to the substrate [3].

[ii]. Technology related issues: Geometric, electrical, thermal and mechanical parameters critically determine the performance of the actuator. Certain level of residual stress is also found in some structures. Excessive residual stress can warp and bind against substrate causing the actuator to fail. In this respect the fabrication process must be well controlled to achieve designed parameters, minimize residual stress and also avoid residues and capillary condense caused stiction after post releasing etch.

[iii]. Operation related issues: Overdriving the actuator causes back bending failure where the hot arm is heated sufficiently to become plastic, and buckles against the cold-arm flexure and the driven device [4]. At higher input power, the hot arm melts and begins to redistribute itself until the arm thins out enough to burn through. Both of these deformations make the hot arm shorter, causing the overall actuator to deflect further back from its initially position after the input power is removed. Back-bending is a non-reversible phenomenon, and continued operation in back-bending regime drastically shortens the lifetime of the actuator. The actuator design can be optimised by selectively increasing the hot arm width in the hottest region to increase maximum applicable input power and therefore overall deflection. For long term applications the actuators must be driven at safe levels and a decrease in force and deflection must be expected. The actuator performance, reliability and lifetime are directly influenced by the input excitation in terms of pulse shape, power level, duty cycle and frequency.

As the thermal actuator structure is heated to high temperatures (about 500K) during operation, the hottest region in the structure is also prone to oxide formation. This can detrimentally affect device functionality and reliability by altering thermo-physical, mechanical and electrical parameters of the structure. Hermetic package avoids such oxide formation.

[iv]. Environment related issues: The device is sensitive to environment, i.e. pressure, temperature and humidity, because the thermal loss is sensitive to those parameters. During our reliability tests, an increase of the displacement was measured at decreasing pressure. Conversely, an increase of the ambient temperature provoked a decrease of the displacement of the actuator arm due to the decrease of the differential thermal expansion between the cold and hot arms. Finally humidity levels in the operational environment also influence the actuator output through changing the thermal conductivity losses to the working ambient. Hermetic package improves performance and reliability by protecting the actuator from contamination, oxide formation, humidity and pressure variation. For a given requested displacement, hermetic packages permit the thermal actuator to work at very low power levels.

4. Electro-thermo-mechanical modelling

4.1. Electro-thermal model:
The electro-thermal modelling provides the repartition of temperature in the structure as a function of the electrical excitation. This result can be used to calculate the average temperatures in the actuator arms which are necessary for the mechanical study. The study is simplified as a one-dimensional problem which simplifies the structure to a series of three beams [5]. After having discretized the beams in small length elements, two methods have been used to find the temperature profile in the structure: the resolution of the heat equation with MatLab and the modelling of an equivalent electrical circuit with the VHDL-AMS language.
4.1.1. **Resolution of the heat equation with MatLab.**

The balance of the thermal exchanges in the finite element of length $\Delta x \to 0$, width $w$ and thickness $h$, provides the heat equation:

$$\frac{d^2 \theta(x)}{dx^2} - m^2 \theta(x) = 0,$$

(1)

With $\theta(x) = T(x) - T_0$, $T_0 = T_S + J^2 \rho/k_p m^2$ and $m^2 = F_S/k_p h R_f$, where $T(x)$ is the temperature in $x$, $T_S$ is the substrate temperature, $J$ is the current density, $\rho$ and $k_p$ are the resistivity and the thermal conductivity of polysilicon, respectively and $F_S$ is the shape factor used to assimilate the convection as a conduction through a thermal resistor $R_f$ [6]. The resolution of the differential equation gives the analytical expression of the temperatures in the arms.

4.1.2. **An equivalent electrical circuit and VHDL-AMS modelling.**

The second method used to obtain the temperature distribution is based on an equivalent electrical circuit to model the thermal exchanges in the element (Fig. 3). To model this electrical circuit, we used the VHDL-AMS language. The good correlation between VHDL-AMS model and the MatLab one is obtained with ten elements per arm as given in the Fig. 4[7].

Fig. 3. Equivalent electrical circuit for the finite element electrothermal representation.

Fig. 4. Temperature profiles obtained with the two analytical models (MatLab and VHDL-AMS).

4.2. **Thermomechanical model:**

The energy method is used to find the current-induced displacement. The free enthalpy $G = U - Fx - TS$, allows finding the deformation of the structure $x$ from the force $F$ and the thermal expansion coefficient $\alpha_T$ through the equation:

$$x = -\left( \frac{\partial G}{\partial F} \right)_{T,C} = \frac{F}{k} + \alpha_T L T$$

(2)

After having determined the complete free enthalpy of the actuator, we can solve the equations with MatLab or the VHDL-AMS language to obtain the variation of the displacement in function of the applied current. To validate this model, test structures have been fabricated and correlation between
the analytical data and test data is shown in Fig. 5. The complete VHDL-AMS model of the U-shaped actuator can then be used to make a parametric study.

5. Parametric study

To characterize the influence of the input parameters on the actuator displacement, the sensitivity factor is defined as

$$S = \frac{\Delta \delta}{\delta_0} / \frac{\Delta W}{W}$$

This variable characterizes the influence of the various parameters on the actuator function. $\delta_0$ is the displacement for the parameter $W_0$ and $\Delta \delta$ is the variation of the displacement for the variation $\Delta W$ of the parameter.

The influence of each parameter (technological, design and environmental) can then be characterized and analyzed with underlying physics (see example in the Fig. 6). The displacement is found to be very sensitive to geometrical dimensions of the actuator. By measuring the geometry of fabricated structures, we obtained a good correlation between the model and the experimental data as shown in the Fig. 5.

6. Ageing analysis

To obtain the virtual prototype of the U-shaped actuator, an ageing model of the structure is necessary. The failure mechanisms of the structure are still difficult to model. So we fabricated actuators and performed ageing tests.
The typical ageing test result is presented in the Fig. 7. The shape of this typical ageing curve can be given by the following transfer function:

$$\delta(n) = \delta_0 \sqrt{1 + \left(\frac{n}{n_c}\right)^\alpha}$$  \hspace{1cm} (4)

Where $n$ is the number of cycles, $n_c$ is the number of cycles where the displacement has decreased to 30% of the initial displacement and $\alpha$ is the gradient of the displacement decrease.

Complementary works have to be done to characterize the coefficients of the transfer function as a function of the input parameters of the U-shaped actuator model.

7. Conclusion
This paper presents the reliability analysis of the U-shaped thermal actuator through a virtual prototype. FMEA analysis has been performed to investigate the potential failures and reliability issues. By performing the reliability analysis, potential problems can be investigated before the design has been completed and before failures can occur in the field. A parametric study has been carried out to determine the influence of input parameters of the actuator with the aim of obtaining the correlation between tests and modelling. The ageing of the actuator is being modelled to predict its performance with respect to its lifetime.

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