MONITORING MEMS SWITCH CLOSURE TIME AS A MEASURE OF RELIABILITY

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Abstract — In this paper we present a novel method for monitoring MEMS switch reliability during lifetime cycle testing. Switch degradation under repeated cycling is measured by monitoring changes in the switch closure time and analysing this data with an energy based dynamic model. The tested MEMS ohmic switches were made of electroplated Au. The results obtained offer the potential to gather data during the switch cycling and to eliminate the need for actuation voltage measurement at pre-defined intervals. The results may also provide data on the evolution of switching characteristics to understand the nature of ohmic MEMS switches failures.

Keywords: MEMS, reliability, bouncing, switch dynamics, modeling

I - Introduction

Microelectromechanical devices (MEMS) have been as the science – only devices for a long time. From the first constructions presented in the fall of 1960/1970s[1][2], MEMS have been something more of a curiosity then a useful solution to problems. But technology never stands still and what was once just a research material is today’s one of the most expected and prominent “newcomer” to the markets[3][4]. Microelectromechanical devices base their current rise in popularity on their unique performance/size properties. Unfortunately with the size of devices going lower into micro and nano levels the complexity of the fabrication process rises and the mechanics influencing the operation of a device are harder to understand. Because of that each type of MEMS device has its own “set” of major reliability issues[5] and has to be considered separately.

This work focuses on reliability issues in MEMS RF switches. Typical failure mechanisms of switches are well documented in various sources[6][7][8] and in a quick summary they are: dielectric charging, stiction, contact degradation, creep and fatigue. Even with an extensive study in each of those areas the complex nature of micro scale interactions proves to be hard to understand and sometimes varies from a device to a device even in the same “fabrication family”. To understand the influence of different failure modes on switch reliability large scale testing is needed to gather enough comparison data and to eliminate the switch to switch variance.

This paper reports a first approach to a testing station for future statistical reliability testing of RF MEMS switches. Variation in the switch closure time over the test duration was used to introduce a model – based approach to reliability identification. The results obtained are consistent with the available literature[9] and provide an alternative method of monitoring the evolution of device parameters.

This paper is organized as follows: Section II describes both the samples and the testing station used in the experiment, Section III presents the obtained results, Section IV presents a model based analysis of the data and validation of the results while Section V draws conclusions from the work outline and proposes future developments.

II - Experiment Details

The SPST ruthenium contact MEMS switch used in this work is shown in Figure 1. It shows the top view of the SEM micrograph of the switch which has five contact points. The five tethers near the anchor are designed to reduce the switch actuation voltage. The switches were made of gold and the nominal dimensions of the switches are as follows: beam to gate gap is 0.6 μm, contact tip to contact pad height is 0.26 μm. The wide rectangular region, where the gate is positioned directly beneath has length*width of 63*38 μm. The tethers have length*width of 14*14 μm. The designed thickness of the beam is 6 μm.[10]

![Figure 1: A SEM view of discussed MEMS device](image)

The switch actuation voltage was measured before the start of the experiment to be in range of 55V to 63V depending on the switch.

The testing station consisted of a GPIB controlled waveform generator, x50 voltage amplifier, 500 mV voltage source and a GPIB controlled oscilloscope for data acquisition. The acquired data was transmitted via a GPIB connection to the PC with a Labview – based
control and data saving program. A schematic of the experiment setup can be seen on the Figure 2.

For the test presented here, the switches were actuated by a 0 to 65V square waveform at 28kHz to induce open/close actions. A 500mV DC voltage through 1000Ω resistors was applied to the switches contact pin. The data was gathered on a 4 channel oscilloscope – 3 channels for tested switches, and 1 channel to monitor the actuation voltage. Measurements were taken every 5s to limit data overflow on the data saving/control PC.

III - Results

After six days of constant actuation under a 28kHz square waveform every switch has failed in a stuck down failure mode. An example of the obtained data sets for switch dynamic response is shown in Figure 3.

The graph starts with the point of actuation voltage turned on which is visible with a previously described voltage peak. The timescale of the graph is set to 0 at that peak. As it can be seen there is a clear decrease of the closing time – \( t_c \) of the switch from 2\( \mu \)s at the first registered cycle down to 1.32\( \mu \)s in the 2.95E9 actuation cycle.

Registered oscillations after the closure event are related to the switch construction. Due to the fact that the switch has multiple contacts and does not ‘land’ on the contact pad uniformly it introduces a bending mode of motion and generates oscillations on the obtained response graphs.

The recorded data clearly presents a trend in the evolution of the closure timing of the switch. The results for monitoring of switch closure time across its lifecycle are presented in Figure 5.

This work focuses on analyzing the closure characteristics of MEMS devices thus only a certain part of the data set will be considered (time frame -0.8 to 2.5\( \mu \)s) – it has been marked with a dashed line on the presented Figure 3. Figure 4 represents a detailed view of the subject switch closure dynamic characteristic.
IV – Model Based Analysis

As reported in available literature the actuation voltage of MEMS switches have a tendency to decrease during cyclic testing. The recorded switch closure time also reduces during testing and the objective to the model based data analysis is determine if this recorded trend can be used to identify similar influencing factors as extracted from the actuation voltage trends.

For model based analysis, the MEMS switch can be simplified to a well-known mass-spring-damper model. In any stable point of operation the forces applicable could be described as:

\[ F_s + F_d + F_e = 0 \]  \hspace{1cm} (1)

Where:
- \( F_s \) – spring restoring force
- \( F_d \) – package environment dampening force
- \( F_e \) – electrostatic actuation force

Because of the fact that the \( F_d \) does not change significantly with the switch operating cycle – switch package is an enclosed environment, it can be neglected in further discussion.

In this simplified model \( F_s \) and \( F_e \) can be described as:

\[ F_s = -k(g_0 - g) \]  \hspace{1cm} (2)
\[ F_e = \frac{\varepsilon AgV^2}{2g} \]  \hspace{1cm} (3)

Where:
- \( g_0 \) – initial beam to electrode gap
- \( g \) – current beam to electrode gap
- \( k \) – beam stiffness
- \( \varepsilon \), \( A \), \( V \) – are the permittivity of free space, electrostatic actuation area and actuation voltage, all of which are constant and do not change in the considered switch operating cycles.

The remaining parameters which can be influenced by the switch cycling operation are \( k \) and \( g_0 \). Do et al[12] confirmed that in MEMS RF switches the main variation occurs due to the change in the tip-gap which dominates over any reductions in the switch spring constant, \( k \).

Considering the above it is reasonable to state that the observable evolution of switch closure time is in direct relation to lowering of the actuation voltage for the switch which is a result of a reduction of switch gap distance between the actuation pad and the beam. Thus it could be possible to use the obtained closure time evolution to monitor switch parameters like Pull-In Voltage, Tip to contact gap distance and Beam to electrode gap distance.

To acquire stated switch parameters a precise model has to be considered. Do et al[12] recently presented an energy-based model for switch closure time calculations which was validated with experimental data. The model has been devised for a dual pulse actuation waveform as shown in Figure 6 and allows for analytic determination of the initial pulse width - \( t_a \), and the time of contact at zero velocity - \( t_c \).

\[ t_a = \frac{-\sin^{-1}\left(1 - \frac{2|A|x_a}{B}\right)}{\sqrt{A}} + \frac{\sin^{-1}(1)}{\sqrt{A}} \]  \hspace{1cm} (4)

Where:
- \( A = \frac{a - 2kg^3}{2mg^2} \)  \hspace{1cm} (5)
- \( B = \frac{a}{mg^2} \)  \hspace{1cm} (6)
- \( a = \varepsilon \varepsilon_0 A g V^2 \)  \hspace{1cm} (7)

Parameters description:
- \( m \) – mass of the switch beam
- \( t_a \) – length of the first voltage impulse
- \( x_a \) – distance travelled by the beam in time \( t_a \)

The model has been devised for dual pulse voltage actuation but it can also be used for a single pulse actuation. Substituting \( x_a \) as the distance between the tip and the contact will convert \( t_a \) into the closure time of the switch.

Results from applying the presented model with switch parameters and using a lookup table method to obtain \( x_a(t_a) \) on acquired closure times data for the estimated tip gap evolution over time are presented in Figure 7.
Calculated results for tip gap on cycle 0 indicate a value of 0.79 μm. Although it is a value which is over 2 times larger than the design gap from the process it is a valid result. This difference can be attributed to the process of beam bending up after the structure is fabricated because of existing internal stress. Obtained values will have to be confirmed experimentally in future work.

V - Conclusion

The process of MEMS switch closure time evolution has been investigated in a detailed study across the switch lifetime from unused state to a stuck–on failure. The data presents a clear trend indicating that the switch is closing faster the more open/close cycles it has been through.

Previous studies on similar devices have reported a decrease in the actuation voltage of the samples over lifetime. Through a study of influencing factors on the actuation voltage and it has been determined that the observed decrease can be mainly credited to the change in the distance between the switch beam and the actuating electrode – gap distance.

In this work, a new approach to MEMS switch reliability monitoring by using the closure time as a parameter for determining switch gap distance has been demonstrated. This method proved to be a viable alternative and does not require interruption of cycle testing to make actuation voltage or gap distance measurements. This allows for faster testing with more measured data points to accurately track switch changes over time. The use of an analytical model to predict switch closure time as a function of gap-height has been presented and shows good agreement with previous results. Future work will require improvement of the model and testing of a larger sample of devices to get statistically significant data.

References