LIFETIME CHARACTERIZATION OF CAPACITIVE RF MEMS SWITCHES

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ABSTRACT — **The first experimental characterization of dielectric charging within capacitive RF MEMS switches has been demonstrated. Standard devices have been inserted into a time domain setup and their lifetimes have been characterized as a function of actuation voltage. Switch lifetimes were measured using a dual-pulse waveform with 30 to 65 V of actuation voltage. Resulting lifetimes were between 10^4 and 10^8 switch actuations, demonstrating an exponential relationship between lifetime and actuation voltage.**

I. INTRODUCTION

RF MEMS is an emerging technology capable of significantly reducing losses in passive circuits such as phase shifters or tunable filters. Several demonstrations have already occurred showing excellent performance for phase shifters at X-band [1] and Ka-band [2] frequencies. However, before this technology can be inserted into mainstream systems, adequate lifetime of the electromechanical devices must be demonstrated. Presently, neither capacitive membrane nor ohmic contact switches are limited in lifetime by mechanical considerations. In ohmic contact switches, the mechanism that limits lifetime is degradation of the ohmic contacts with repeated actuations. In capacitive membrane switches, the limiting mechanism is dielectric charging within the switch dielectric layer. Previously, individual switch lifetimes as high as 1-3 billion cycles have been demonstrated. However, these random data points did not lend any insight into the factors affecting lifetime. This paper demonstrates the first qualitative characterization of dielectric charging within capacitive membrane switches and the impact of high actuation voltage upon switch lifetime.

II. DIELECTRIC CHARGING

The exact physics of dielectric charging within RF MEMS switches is not presently understood. There are several scenarios by which charges can migrate and become trapped on the surface or within the bulk of the dielectric. A simple but unsubstantiated theory of dielectric charging involves the concept of charges tunneling into the dielectric and becoming trapped. In an effort to maximize the on-capacitance of a MEMS capacitive switch, the dielectric is typically made quite thin, usually less than 3000 Å. Since capacitive membrane switches generally require 30 to 50 V of actuation voltage, the total electric field across the dielectric in the down-state can be on the order of 1 to 3 MV/cm. Under these high field conditions, it is possible for charges to tunnel into the dielectric with a phenomenon similar to Frenkel-Poole emissions in insulating films [3]. Once charges tunnel into the device, they become trapped within the dielectric, where there is no convenient conduction path. The recombination time for these charges can be very long, on the order of seconds to days.

Even though the exact mechanisms for the transfer and trapping of charge are unknown, the effects are measurable. As charge becomes trapped within the dielectric, it tends to screen the applied electric fields that are used to control the actuation and release of the switch. The end result is that this screening voltage builds up within the dielectric and hinders operation of the switch. As the charge builds up, the screening voltage detracts from the actuation voltage until there is no longer enough force pulling on the membrane to cause it to actuate. Conversely, when the switch is unactuated and the applied electric field is removed, the electric potential of the trapped charges tends to continue attracting the membrane. Since the holding voltage for a switch is much less than its actuation voltage, the trapped charges may provide enough potential to keep the membrane down. This results in the switch being stuck down. Experience shows that stuck switches are the most common means of failure.

Given the high electric field responsible for tunneling, trapping, and the resulting failure (sticking) of the MEMS switch, we anticipate that the lifetime of the switch is related to the magnitude of applied electric field. The equation for Frenkel-Poole emissions [3] is

$$J \approx V e^{+2a\sqrt{V}/T - q\Phi_B/kT} \qquad \text{(Eq. 1)}$$

where J is the current density due to Frenkel-Poole emissions, V is the applied voltage, T is temperature in Kelvin, Φ_B is the barrier height, k is Boltzman's constant, and *a* is a constant composed of electron charge, insulator dynamic permittivity, and film thickness. This equation

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represents an exponential relationship between the emission current and the applied electric field. As such, one might expect that the lifetime of MEMS switches is exponentially related to the applied voltage. A simple experiment is to measure the switch lifetime (number of actuations until failure) as a function of applied electric field. This will lend valuable insight into the mechanisms of charging and switch failure, yielding information on how the applied actuation voltage affects switch lifetime.

III. Devices Under Test

The switches evaluated in this characterization consisted of two of Raytheon's standard capacitive membrane switches in a shunt configuration. These devices are embedded within a 50 ohm coplanar waveguide test structure. Photographs of the standard and slightly modified devices in the unactuated state are shown in Figure 1. The processes and electrical characteristics of these devices are identical and have been described previously [4]. The only difference between the two devices is slight variations in the membrane pattern, which translates to slightly different actuation voltages. For purposes of lifetime characterization, these two devices are considered electrically equivalent.

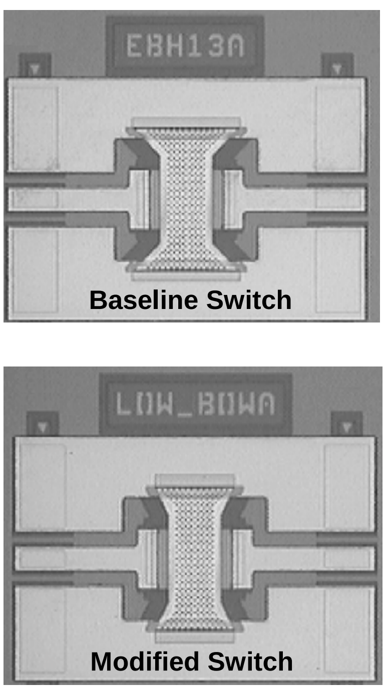

Fig. 1. Capacitive MEMS test devices.

IV. Test Setup

To test an RF MEMS switch lifetime, the switch must be repeatedly actuated until failure. The simplest method for monitoring switch actuation is to apply a continuous wave (CW) signal to the switch and measure the modulated RF envelope that results from switch actuation. This time-domain monitoring of switching allows simple but accurate analysis of switching characteristics, switching speed, and lifetime. The test setup used for accomplishing this is shown in Figure 2. An HP 8350B sweep oscillator supplies a continuous wave 10 GHz carrier with about 10 dBm of RF power. An HP 11612B bias tee multiplexes the RF carrier with the actuation waveform. The actuating signal can be produced by almost any pulse or signal generator. In this experiment, a custom waveform generator circuit was used to actuate the switches. The device was probed on a Cascade Microtech 9600 thermal probe station controlled by a Temptronic 03000 temperature controller. These provide both temperature control and a humidity-free nitrogen environment. The output RF probe was connected through a high-pass filter to an HP 8472B crystal detector. The crystal detector provided a DC voltage proportional to the modulated RF envelope and representative of the switching behavior of the device under test. The detected signal was applied to a Tektronix 2430A oscilloscope for monitoring and an HP 5245A frequency/event counter for counting switch actuations and measuring lifetime. The high-pass filter is necessary to prevent the switching transients from interfering with the crystal detector. In this case, two back-to-back X-band coaxial-waveguide adapters (HP X281B) provided ample isolation.

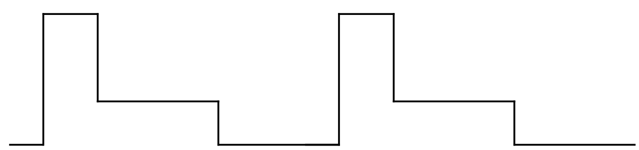

Fig. 2. Dual-pulse actuation waveform.

V. Test Conditions

To prevent stiction due to humidity, it is important that all humidity be removed from the device environment. In this case, a dehydration bake at 125°C for at least 15 minutes was used. The thermal probe station provides a humidity-free nitrogen environment within its environmental test chamber. Experiments in open air have shown that even moderate ambient humidities (>30%) can cause stiction under some circumstances. Eliminating the humidity enables better characterization of dielectric charging free from other sources of stiction.

Several waveforms have been used to actuate the RF MEMS switch, including raised sine wave and square wave signals. In general, these waveforms provide limited lifetimes due to dielectric charging. An alternate idea for actuating RF MEMS switches can be borrowed from PIN diode circuits. Often PIN diodes are actuated with a "dual-pulse" current pulse similar to that shown in Figure 3. A quick pulse of current injected into the depletion region turns the device on quickly. Afterward, a lesser quiescent current maintains the device in the on-state. Similarly, a dual-pulse voltage waveform can be used to actuate RF MEMS switches. The initial pulse provides enough electromotive force to deflect the switch membrane down into the on-state. The peak voltage of the waveform must exceed the switch's actuation voltage. Once actuated, the switch requires considerably less holding voltage to maintain the on-state. Accordingly, the actuation waveform switches to a lower holding voltage to maintain the switch in the down-state. This minimizes the time that high voltage is applied across the switch dielectric, and minimizes the dielectric charging. The switches described above typically require 5 to 10 V to maintain an actuated position; therefore, the waveform used in this experiment had a holding voltage of 20 to 25 V. The peak actuation voltage used in this experiment, V_A, varied between 30 and 65 V and was the controlled parameter for the experiment. In all cases, the actuation voltage was at least 7 V above the measured pulldown voltage to yield sufficient headroom for the switch to charge. The actuation voltage pulse was applied for 50 μs, sufficient time for the switch to turn on. The switching waveform was repeated at a 1 kHz switching rate with approximately 50% duty cycle.

VI. Results And Analysis

The results of evaluation of switch lifetime as a function of pull-down voltage are shown in Figures 4, 5, and 6. Each of these characterizations is from a different lot and wafer of devices. Figure 4 contains results with devices taken from a two co-located die within the wafer. Figures 5 and 6 contain data taken from die scattered throughout their respective wafers. Note that the vertical axis of each graph is the logarithm of the number of switching cycles (N). This converts the exponential relationship into a linear one for graphical purposes. Encircled data points represent test points at which the switch was stopped before failure due to time limitations.

As expected from Equation 1, in each of the graphs there is an exponential relationship between the peak actuation voltage and the switch lifetime. Observation of the data shows that there is a significant improvement in lifetime as voltage decreases, on the order of a decade of lifetime for every 5 to 7 V drop. It is also apparent that there is significant variability from one lot to the next.

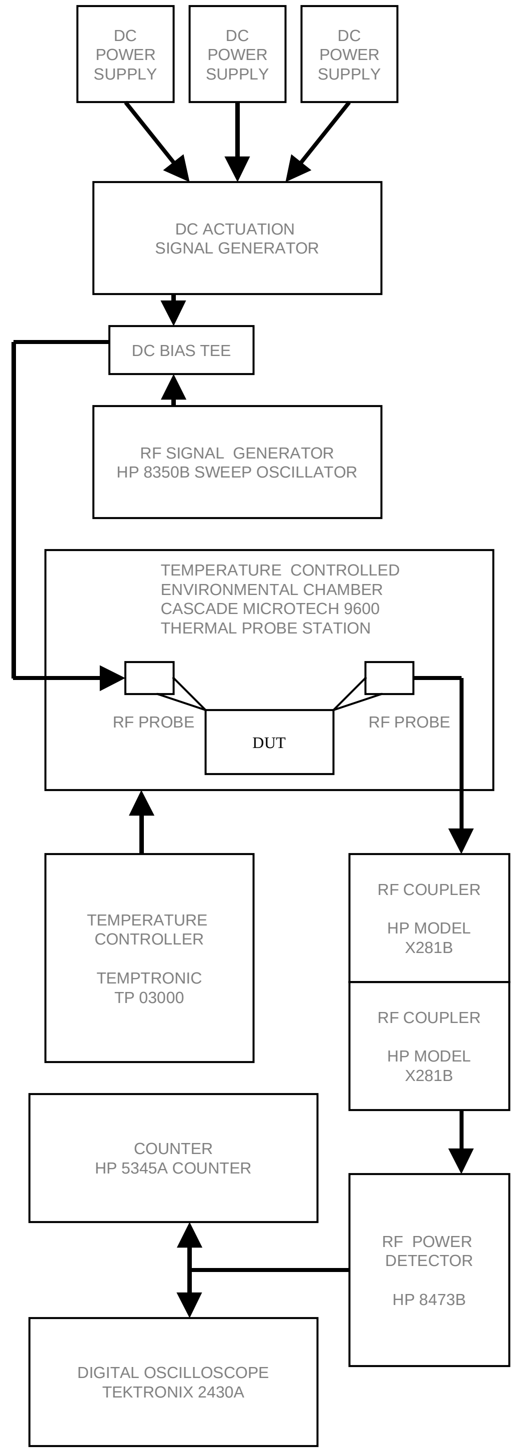

Fig. 3. Block diagram of MEMS lifetime test station.

Comparing Figure 4 with Figures 5 and 6, there is also significant variability even within a single wafer. However, in all three cases the trend is clear. Higher operating voltages impede device lifetime. Clearly, long lifetimes (>1 billion cycles) require devices to be run at actuation voltages less than 40 V. This provides a continuing impetus to reduce switch pull-down voltage and produce wafer lots with tight pulldown voltage distributions.

Other wafers tested (but not reported here) have demonstrated lifetime data that appears not correlated to applied voltage as in these graphs. Initial tests indicate that failure mechanisms other than dielectric charging may be responsible for the failures. These devices are part of an ongoing effort to understand lifetime limiters in capacitive membrane switches.

VII. Conclusions

The first experimental characterization of dielectric charging within capacitive RF MEMS switches has been demonstrated. Standard devices have been inserted into a time-domain setup and their lifetime characterized as a function of actuation voltage. As anticipated, there is an exponential relationship between the applied voltage and switch lifetime. Switches were measured using a unique dual-pulse waveform with 30 to 65 V of actuation voltage. Resulting lifetimes were between 10^4 and 10^8 cycles, depending on the applied voltage. According to the results, lifetime improves on the order of a decade for every 5 to 7 V decrease in applied voltage. This provides impetus to produce devices that operate with voltages less than 40 V to achieve lifetimes of more than a billion cycles.

Acknowledgments

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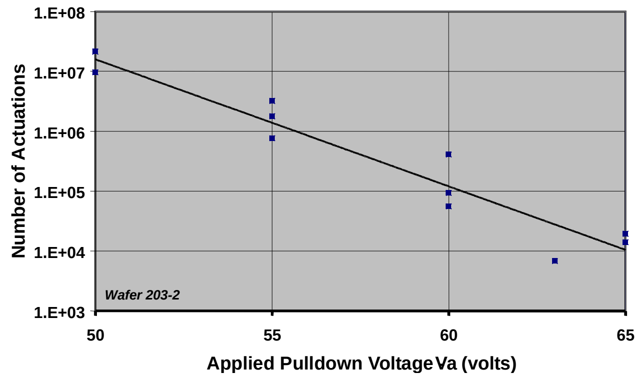

Fig. 4. MEMS lifetime characterization.

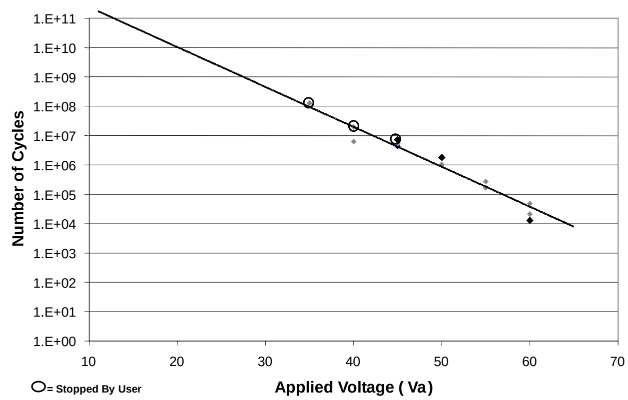

Fig. 5. MEMS lifetime characterization.

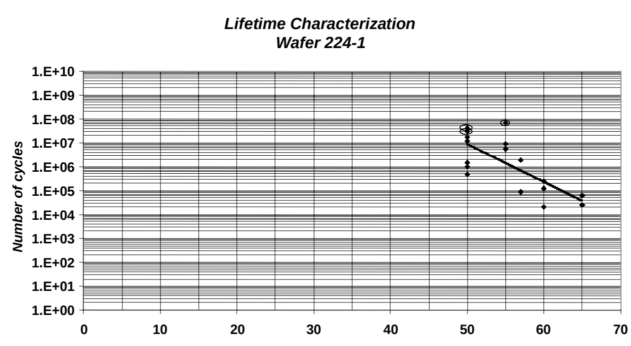

Fig. 6. MEMS lifetime characterization.