

Tailoring Capacitive Switch Technology for Reliable Operation

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Abstract: *Recent improvements in characterization, modeling, and testing methods for MEMS capacitive switches are making new inroads to improving reliability. This paper provides an update on the methodologies, tools, and techniques being applied to improve the longevity of MEMS capacitive switches.*

Keywords: MEMS, capacitive switch, dielectric charging, reliability, lifetime, accelerated testing.

Introduction

Capacitive switching technology possesses many benefits over both conventional electronics switches as well as ohmic-contact MEMS switches. These benefits include a very high figure of merit, ultra-low effective on-resistance, miniscule power consumption, and ultra-high linearity [1]. The low loss and power consumption of these switches are excellent for constructing phase shifters and routing networks at X-band and above [2]. The low on-resistance and high linearity are excellent characteristics for constructing tunable filters from VHF through X-band [3].

Given these advantages for MEMS capacitive switches, there is a significant effort to understand and address their reliability. After packaging and environmental issues are addressed, the main limitation to longevity is dielectric charging within the switch insulator. Moderate actuation voltages applied across the thin insulator generate electric fields which cause charges to tunnel into the insulator and get trapped. These charges can either add or detract from the applied field, causing the switch to become stuck when voltage is removed, or not to actuate when desired. The end result is the failure of the device to operate properly.

The main obstacles to resolving these reliability problems have been two-fold:

- 1) difficulty in quantifying the amount of charging during switch operation, specifically the ability to characterize and model the ingress and egress of charges in the switch insulator, and
- 2) lack of in-situ monitoring during life testing, allowing the ability to observe the dynamic evolution of switch characteristics as the switch dielectrically charges towards failure.

Recent advances in both of these areas provide new insights into the mechanism of dielectric charging and its impact upon switch operation. An overview of these advances is highlighted in the following sections.

Dielectric Charging Characterization

Recently, transient current spectroscopy has been successfully employed to quantify charge tunneling and trapping within a MEMS switch insulator [4, 5]. The references provide in-depth details of the technique, which is summarized here.

In transient current spectroscopy, a constant DC voltage is applied to the metal-insulator-metal sandwich of a MEMS switch while high-sensitivity current measurements are made. The polarization charge across the capacitor changes very quickly, with a time constant of pS to nS. However, a much slower charging and discharging phenomena is also observable, and is attributable to the charging of the insulator. Figure 1 depicts the measured charging and discharging current of a capacitive switch structure under 30 volts bias for 250 seconds, then zero bias for 250 seconds. Very similar curves are measured for the negative polarity.

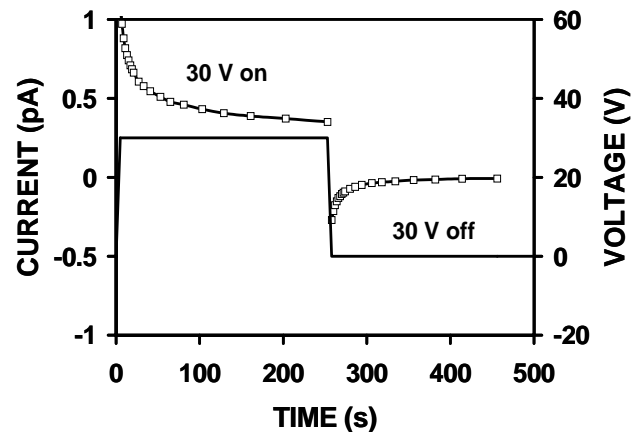


Figure 1. Measured and modeled current of 30 V charging and discharging current on a permanently down switch. Solid line indicates control voltage.

These currents, measured at varying stress (DC voltage) levels, can then be used to map out the temporal and voltage response of the charges in the switch dielectric. A composite graph of the charging and discharging data at various biases is shown in Figure 2.

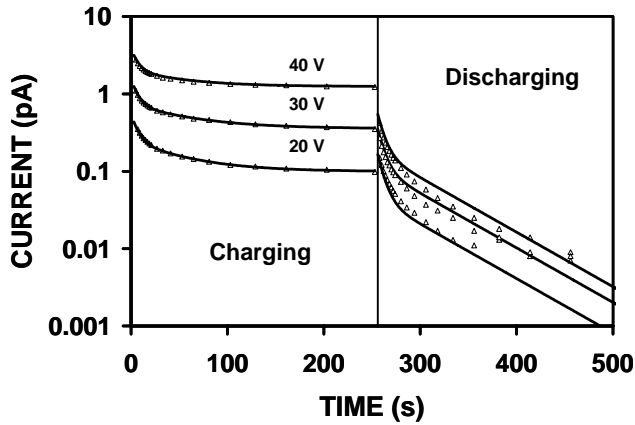


Figure 2. Modeled and measured (symbols) charging current transients under positive control voltage.

The charging and discharging characteristics of the dielectric can be extracted from these measurements, utilizing a charge model described as

$$Q = \sum_J Q^J [1 - \exp(-t_{ON} / \tau_C^J)] \exp(-t_{OFF} / \tau_D^J), \quad (1)$$

where Q^J is the steady-state charge density of the J th species of trap, τ_C and τ_D are the charging and discharging time constants, t_{ON} and t_{OFF} are the on and off times of the switch corresponding to the charging and discharging times. The result is a set of extracted model parameters which describe the charging and discharging time constants, as well as the charge density and voltage dependences of the phenomena. The above data was fitted assuming two carrier species, and resulted in the characterization shown in Table 1.

TABLE I
EXTRACTED MODEL PARAMETERS

Positive Bias				
J	τ_C (s)	τ_D (s)	Q_0 (cm ⁻²)	V_0 (V)
1	6.6	6.8	3.1×10^{10}	12.9
2	54.3	61.6	1.6×10^{11}	14.9
Negative Bias				
J	τ_C (s)	τ_D (s)	Q_0 (cm ⁻²)	V_0 (V)
1	6.5	7.0	2.4×10^{10}	11.7
2	52.5	74.7	6.0×10^{10}	10.5

In order to validate the model, the temporal shift in actuation voltage as a function of DC stress was measured on switches and calculated using the above model. The resulting response shows excellent correlation between measured and modeled voltage shift. Under the controlled set of operating conditions, the model provides an amazingly good approximation to the response of the switch to dielectric charging.

These characterization and modeling techniques have, in fact, been carried out using metal-insulator-metal (MIM) capacitors fabricated simultaneously with the actual switches. The verification, however, was executed with the actual MEMS switches themselves. While the fixed capacitors do not duplicate the response under all conditions (especially in an environment with significant humidity), it does model the switches very well under conditions which the switches are likely to be operated. This is an extremely powerful tool, in that quick evaluation of various insulating materials are possible without the necessity of fabricating full MEMS switch devices.

Lifetime and Accelerated Testing

To life test an RF MEMS switch, the switch is repeatedly actuated until failure. The most effective means of accomplishing this is to apply a continuous RF signal and monitor the modulated signal caused by the actuation of the switch [6]. This provides a real time, dynamic sensing of switch operation. The test set used to accomplish this is shown in Figure 3. An HP8350B sweep oscillator supplies a continuous 10 GHz signal at 20 mW of RF power. Meanwhile, an HP33220A arbitrary wave generator followed by a Tabor Electronics 9100 high voltage amplifier creates the drive signal to actuate the switch. These RF and DC signals are multiplexed onto the RF line by a Picosecond Pulse Labs 5585 bias tee. These signals are applied to the device under test on a Cascade Microtech 11751HT thermal probe station through Cascade Infinity probes. The temperature of the sample is controlled by a Temptronic LM00550 temperature controller, while the environment of the device is controlled by dry air flowing through the test station microchamber. The output of the probe station ultimately feeds an HP8472A crystal detector for real time monitoring of switch actuation on a digital oscilloscope. In order to mitigate the impact of control voltage switching transients on the detector, a 10 GHz bandpass filter is included between the output probe and the detector.

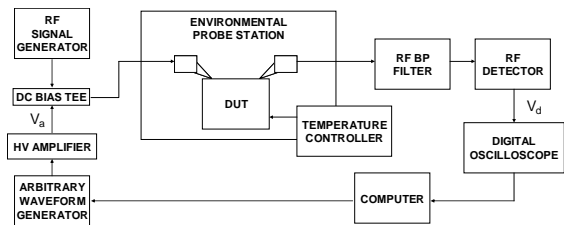


Figure 3. Accelerated and cycling life test setup.

This test technique has been extended to provide in-situ monitoring of switch operating parameters throughout the test. This is accomplished by switching between diagnostic and tactical waveforms during the test. The diagnostic waveform allows dynamic monitoring of electromechanical properties, such as pull-in and release voltages, as well as

RF performance, such as on-capacitance and off-capacitance. Figure 4 demonstrates a typical operating curve for a MEMS capacitive switch obtained using this technique. The diagnostic waveform consists of a series of four ramped pulses of which have periods of 1 ms. The switch operating curve is generated by graphing the detected signal against the applied voltage. Both pull-in and release events are apparent from the abrupt changes in detector voltage. The magnitude of attenuation of the detector signal during actuation yields approximate information regarding the on-capacitance of the switch.

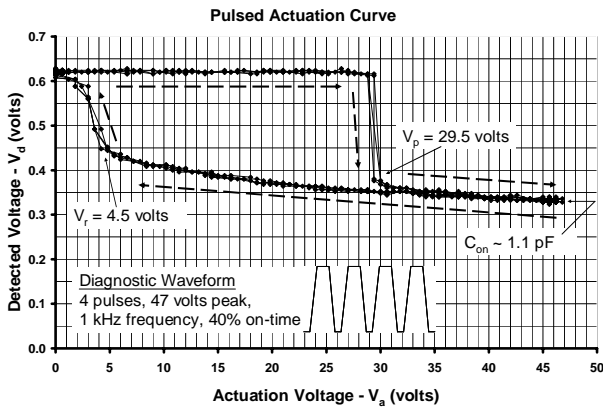


Figure 4. Pulsed actuation curve used to obtain diagnostic information on switch operation.

Accelerated dielectric charging within the switch is accomplished through the continuous application of DC voltage to the switch. A constant voltage, above the pull-in voltage, places the switch in the actuated state and provides a high electric field which continuously induces charging in the dielectric. At repeated time intervals, the waveform generator is signaled to apply the diagnostic waveform to the switch to assess its electromechanical and RF performance. Afterwards, the drive signal is switched back to the constant DC signal. The result is information which portrays the evolution of dielectric charging within the insulator. This is portrayed by the shift in pull-in and release voltages, and is depicted in Figure 5 for a capacitive switch.

This same testing regime has been utilized to test air-gap switches (proximity switches) which trade off capacitance ratio for lifetime. With significantly reduced area of the switch insulator, there is less area for dielectric charging. A switch continually actuated using the 1 kHz diagnostic waveform demonstrates considerably less shift in actuation and release voltage. This is in part due to the reduced on-time (switch is only actuated 40% of the time) and to a smaller extent the opportunity for the charges to discharge during the interval the switch is not actuated. The results are shown in Figure 6 for a proximity switch.

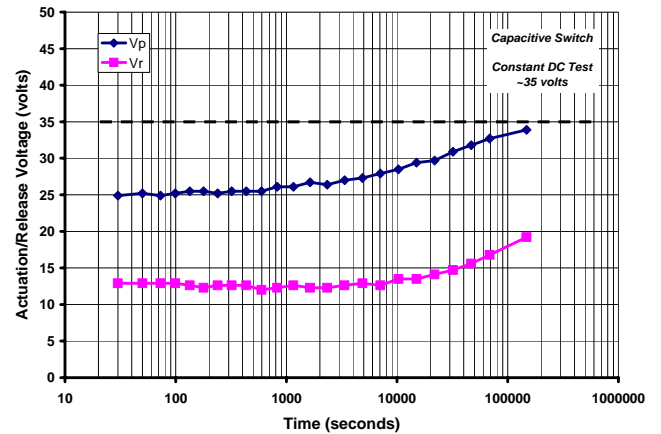


Figure 5. Evolution of capacitive switch operating characteristics (pull-in and release voltages) under accelerated life test.

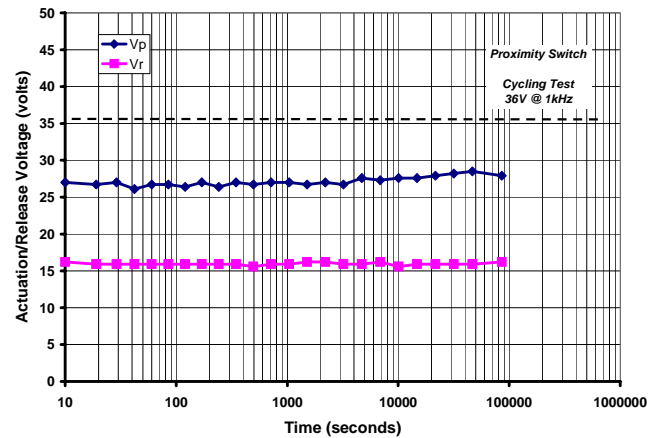


Figure 6. Evolution of proximity switch operating characteristics (pull-in and release voltages) under cycling life test.

This test methodology (switching between tactical and diagnostic waveforms) is currently being expanded to allow testing of devices at higher repetition rates. Switches from this same lot have been utilized for high repetition-rate testing (without the diagnostic waveform) at speeds ranging from 10-40 kHz, which quickly accumulate high cycle counts. These switches have operated for days to weeks, accumulating 10-20B+ cycles without failure.

Designing for Reliability

With an influx of new experimental information regarding the cause and effects of dielectric charging, the challenge is to utilize that information to improve the mechanical and electrical design of the switches for increased reliability. Several general design guidelines are apparent after reviewing the accumulated data to date. First and foremost, the actuation voltage must be kept to a reasonably low level, generally less than 40 volts. Dielectric charging increases exponentially as the applied voltage increases. Second, reducing the amount of dielectric provides a

reasonable means for improving lifetime at the expense of reduced capacitance ratio. Many phase shifter and tunable filter designs do not require 50+ on/off capacitance ratios. This allows reducing the amount of dielectric beneath the membrane to reduce the amount of charge buildup. Stiction can be viewed as a condition in which the attractive force of the trapped charge on the membrane exceeds the mechanical restoring force of that membrane. Reducing the area of the switch insulator reduces the stiction force of the charged dielectric, calculated as

$$F_{ST} = \frac{A \left(q \sum_j Q^j \right)^2}{8 \epsilon_R \epsilon_o} \quad (2)$$

where F_{ST} is the stiction force on the membrane, q is the charge of an electron, ϵ_R is the dielectric constant of the switch dielectric, ϵ_o is the dielectric constant of free space, A is the switch active area, and Q^j are the carrier densities of the trapped charges. Similarly, it is also desirable to improve the restoring force of the membrane for a given pull-in voltage. This is most easily accomplished by reducing the gap between the membrane and insulator to the point that the switch off-capacitance meets some maximum desired value.

Beyond the electromechanical design of the switch, there is also the selection of the dielectric material which composes the switch insulator. Different dielectric compositions as well as different dielectric deposition conditions can have a significant impact on the charging behavior of the switch. This is a subject of current research. The power of the dielectric charging characterization methodology highlighted above is that it can be accomplished on simple MIM test structures. This allows short-loop experiments into material characterization which are much less expensive than building full fabrication lots. While this technique is a very powerful tool, it has its limitations as issues such as ambient humidity or varying surface conditions (due to switch processing) can markedly change the results, usually degrading performance rather than enhancing it.

Finally, significant gains in reliability have previously been made by modifying the control waveform to minimize charging [6]. As our understanding of this phenomenon improves, this will continue to be a powerful tool for improving switch reliability. While more sophisticated control waveforms have the drawback of increased complexity at the system level, their benefits usually exceed those of other design tradeoffs and should receive serious consideration.

Conclusion

Recent improvements in the characterization and modeling of dielectric charging in MEMS capacitive switches is providing a much improved understanding of the effects which limit switch lifetime. New testing methods for accelerated testing and cycling testing provide insights into the evolution of dielectric charging and its impact during the lifetime of the switch. Together, these innovations provide significantly better tools for designing MEMS capacitive switches for increased longevity. Application of these tools and techniques is expected to continue improving the reliability and robustness of this critical technology for DOD applications.

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