RF Power Handling of Capacitive RF MEMS Devices

B. Pillans, J. Kleber, C. Goldsmith†, M. Eberly

RAYTHEON SYSTEMS CO. Dallas, TX 75266

Abstract — **RF MEMS switches provide a low-cost, high-performance solution to many RF/microwave applications. In this paper, progress in characterizing capacitive MEMS devices under high RF power is presented. The switches tested demonstrated power handling capabilities of 510mW for continuous RF power and 4W for pulsed RF power. In addition, the reliability of these switches was tested at various power levels indicating that under continuous RF power, the lifetime is not affected until the 510mW power level is reached. Once a power failure is observed, it is completely recoverable by lowering the RF power level below the threshold point. A description of the power failures and their associated operating conditions is presented.**

I. INTRODUCTION

As early as 1979 [1], microelectromechanical switches have been used to switch low frequency electrical signals. Since then, switch designs have utilized cantilever [2], rotary [3] and membrane [4] topologies to achieve good performance at RF and microwave frequencies. Because of their low loss, low power consumption and lack of intermodulation distortion, RF MEMS switches are an attractive alternative to traditional FET or p-i-n diode switches in applications where microsecond switching speed is sufficient. Capacitive membrane switches have shown excellent performance through 40GHz [4] and significant work has been demonstrated for the reliability of these switches [5]. Lifetimes in excess of 1 billion cycles [5] can be obtained on capacitive membrane switches under low power conditions. In real world transmit applications, however, RF power may be applied to the switch at a broad range of power levels. These power levels and their effects on RF MEMS devices need to be explored in order to better define in what applications RF MEMS switches can be used effectively. This paper details the power handling and resulting reliability of capacitive MEMS switches at various RF power levels.

II. SWITCH ACTUATION AND DESIGN

The basic capacitive RF MEMS switch discussed here is a co-planar waveguide (CPW) shunt switch as shown in Fig. 1 and Fig. 2. This device is fabricated by first depositing a thin gold electrode to serve as the signal path through the switch. A silicon nitride dielectric layer is added on top of the electrode to serve as the switch capacitor when the membrane is down. Thick gold is used as support posts for the membrane. The membrane is deposited over a sacrificial layer that is removed at the end of processing by surface micromachining. With the sacrificial layer gone, the aluminum membrane is left suspended between the two gold posts. Its natural state is in the "up" or unactuated position. When a sufficient electrical potential is applied between the membrane and electrode, the membrane snaps down into the actuated state.

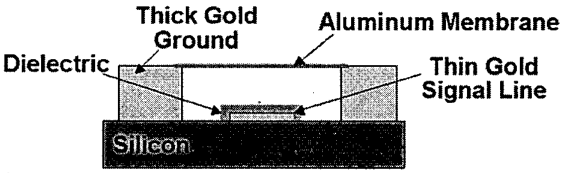

Fig. 1. Cross-section of capacitive MEMS switch

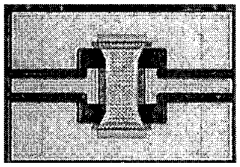

Fig. 2. Top view of capacitive MEMS switch

The switch operates as a digitally tunable capacitor with two states. When the membrane is in the up position, the signal line sees a small value of parasitic capacitance (~30fF) shunted to ground. When the membrane is actuated, the signal line now sees a high value capacitor (~3pF) shunted to the CPW ground. The performance of this switch has been shown [4] to have less than 0.25dB insertion loss in the unactuated state and better than –20dB isolation in the actuated through 40GHz.

The potential required to actuate the switch is known as the switch's pulldown voltage (V_p). This voltage is determined by (1) [6] where k is the spring constant of the membrane, g is the gap between the membrane and electrode, w is the width of the membrane and W is the width of the electrode. With W and w being constant for a given switch design, the only two factors that change the pulldown voltage are the gap g and the spring constant k.

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†Chuck Goldsmith currently works for Cogent Solutions, Inc.

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$$V_P = \sqrt{\frac{8k}{27\varepsilon_0 Ww} g^3} \qquad (1)$$

The gap and spring constant can vary across any given wafer, so a map of pulldown voltage as a function position on a wafer is obtained for each wafer produced. An example voltage distribution plot is shown in Fig. 3. Each color represents a one volt change in pulldown voltage. Pulldown voltage averages of ~30V at room temperature and standard deviations of ~1.5V are common. This map helps characterize the fabrication process and quantifies the results of changes to lower the voltage standard deviation across the wafer.

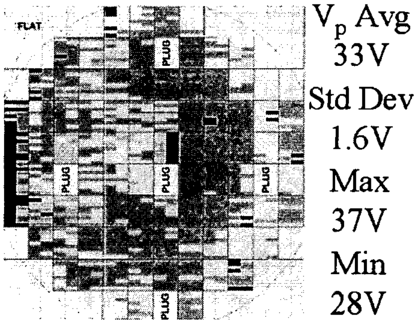

Fig. 3. Pulldown voltage (Vp) wafer map

III. RF POWER FAILURE MECHANISMS

RF power handling of capacitive RF MEMS switches is defined as the power at which the MEMS device fails to operate properly. The two types of failures are RF latching and RF self-actuation.

RF latching is a situation by which the applied RF power provides enough force on the membrane to hold the switch down when it should have released (i.e. when DC bias is removed). This situation occurs when RF power is continuously (CW) applied to the MEMS circuit. Such a failure means that once a device is actuated, it will not release until the RF power level is lowered below its threshold point. Once the power is lowered, the device is no longer in a failure mode and will continue to operate normally.

RF self-actuation is a situation in which the high RF power actually creates enough potential to pull the membrane down into the actuated position without applying a DC bias across the switch. In this case, as soon as the RF power is turned on, all RF MEMS switches in the signal path will be actuated regardless of the intended state. As with the latching failure, if the RF power level is reduced, the switch will behave normally with no ill effects caused by the self-actuation.

IV. TEST SETUP AND CONDITIONS

The following experiment was set up to obtain a more complete understanding of how RF power affects capacitive RF MEMS switches. To understand this effect, the power level required for RF latching and RF self-actuation was recorded for 10 switches. These switches were then actuated at various power levels to determine the effect of RF power on the lifetime of the switch.

Each RF MEMS device was tested in the setup shown in Fig. 4. This setup consists of the bias waveform generation circuitry, 10GHz RF power from a TWT amplifier, a temperature controlled environmental chamber filled with dry nitrogen, an RF power detector, an electronic counter and a digital oscilloscope. Each switch is tested individually in the environmental chamber. Continuous monitoring of the switch state is maintained by observing the RF signal on the detector. When the switch is unactuated, a large RF signal is observed at the detector. When the switch actuates, the shunt configuration shorts the signal line to ground and the detector registers very little signal. In this configuration, one can see a pulse on the oscilloscope relating to the detector voltage with each actuation of the switch. This pulse is counted on the electronic counter to give a total number of actuations for the switch under test. Each switch was tested at 25°C with a standard bias waveform of 40V at a repetition frequency of 2.78kHz. The waveform is as discussed in Reference [5], with a peak voltage of 40V and a holding voltage of 15 volts. The pulldown voltage lasted 50 microseconds, while the holding voltage remained for 60 microseconds.

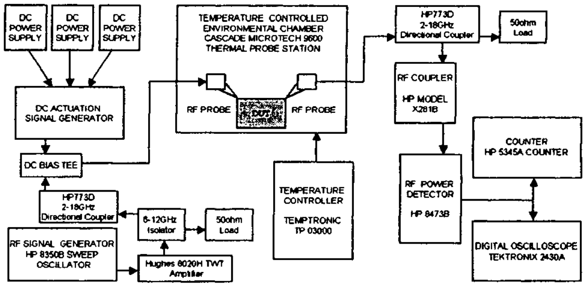

Fig. 4. Block diagram test setup

V. MEASUREMENTS AND RELIABILITY

RF power handling measurements were performed on 10 switches taken from across the single wafer portrayed in

Fig. 3. To test the RF self-actuation failure, RF power was applied to a switch and steadily increased until the switch actuated. As soon as it actuated, the RF power level was recorded. This data is shown in Table 1. Of the 10 switches tested, the average level at which self actuation occurs was 4 watts. The standard deviation was 500mW. This failure is the dominant mechanism when "cold switching" a device. Actuating the switch continuously while slowly increasing the RF power tested the latching failure. The first instance, in which the membrane did not release when the bias was turned off, the RF power level was recorded and noted as a latching failure. This data is shown in Table 1. Of the 10 switches tested, the average latching failure was observed at 510mW with a standard deviation of 50mW. This failure is the dominant mechanism when "hot switching" a device.

TABLE 1

RF POWER HANDLING LEVELS

Die	Vp	Self Actuation Power (W)	Latching Power (W)
8,2	32	4.0	0.54
13,2	31	3.6	0.49
18,6	30	3.8	0.46
18,10	30	4.1	0.54
13,8	24	3.0	0.40
8,10	31	4.9	0.51
8,6	31	4.0	0.54
8,12	30	4.3	0.51
13,12	31	4.3	0.60
18,12	28	3.9	0.51
	Average	4.0	0.51
	Standard Deviation	0.5	0.05

Another test that was performed was to see how the DC pulldown voltage of the switch changed with RF power levels. It can be seen from self-actuation that if the RF power is high enough the switch will actuate. Four switches were actuated with various power levels up to 3.2W and the minimum DC pulldown voltage required to actuate the switch was recorded for each power level. This data is shown in Fig. 5. It can be seen that a fairly liner relationship exists between the DC pulldown voltage and the RF power applied. As the RF power is increased, the DC pulldown voltage decreases until self-actuation occurs. At low power levels, this effect is minimal, but as power levels increase, the power's effect on the DC pulldown voltage must be taken into account.

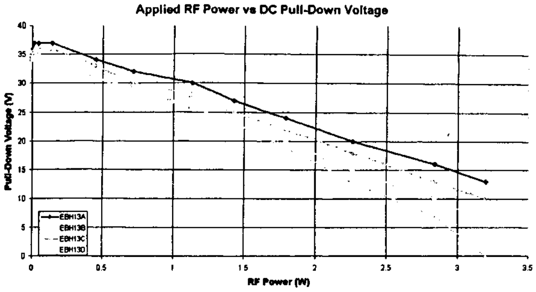

Fig. 5. DC pulldown voltage vs RF power level

The next test performed was to determine the lifetime of each switch as a function of the continuous RF power level applied. Each switch was placed under test with a particular RF power level. The standard bias waveform described above was applied and the switch was actuated until the switch failed to release. At this point, the total number of cycles actuated was recorded as the lifetime of that particular switch. In the interest of time, if a switch reached 1 billion actuations, the device was stopped and recorded as a "no failure" exceeding 1 billion actuations. The data is graphed in Fig. 6. Various RF power levels were tested between 1mW and 1W. It can be seen that all switches tested at power levels below 500mW reached 1 billion cycles and were stopped before a failure occurred. All switches tested at power levels 500mW and over failed almost immediately.

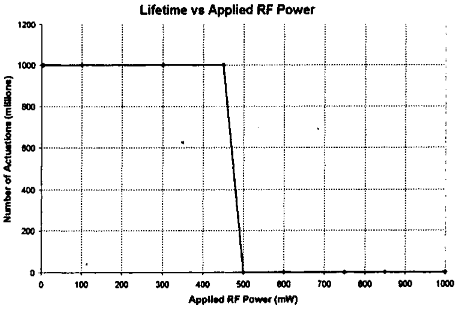

Fig. 6. MEMS switch lifetime vs RF power level

VI. Discussion And Conclusions

The RF MEMS switches tested have two levels of power handling depending on the application the switch is used in. The lowest level of power handling is when RF power is applied continuously to the switch. According to the data in Table 1, the power handling of a CW application is 510mW on average. This is when a latching failure occurs and the switch will not release when the DC bias voltage is removed because the RF power is holding the switch down. If the switch were operated in a pulsed RF power mode such as in ESA radar applications, the RF power would never be turned on when the switch is not actuated, and therefore, latching failures would not occur. In this case, the power handling of the switch is 4W on average, the RF power level for self-actuation. Each case is a failure, but depending on the application, the conditions for a latching failure may, or may not apply. When assessing the RF power handling capacity of a MEMS switch, the application and test conditions must be taken into account.

Fig. 5 shows that a fairly linear relationship exists between the minimum DC pulldown voltage and the RF power level applied. This is not intuitive because there should be a square relationship between the power and voltage. It is not readily apparent why such a linear relationship exists and we have not yet been able to model this behavior. We know that the relationship exists, but more work is needed to accurately model this effect.

An equally important issue with RF power handling is how reliable the switch is with respect to the RF power level applied. The data in Fig. 5 shows that when running in a continuous fashion, the RF power level does not affect the lifetime until the latching failure level is reached. At this power level, 500mW, the switch will no longer release and thus no longer actuates. It is true that because actual failures were not identified there could me some shape to the lifetime vs. RF power level curve, but up to 1 billion cycles, none was observed. In any case, a dramatic reduction in lifetime occurs at 500mW as expected because of the RF latching failure. If pulsed RF were used, the power failure level would be expected to be 4W because the latching failure would no longer be present. Work is currently being planned to verify this theory. It is also worthwhile to note that the RF power failure levels are not "hard" failures, meaning that if the power is reduced below the failure point, the same switch will continue to operate as before.

Understanding how capacitive RF MEMS deal with high RF power is critical in determining future transmit applications for the technology. The switches tested have not been specifically designed to operate under high power; the data presented here is simply an assessment of where the technology is today. Future wafer lots can be fabricated using different conditions to maximize the RF power handling of the switch for higher power levels. More work needs to be done to evaluate the lifetimes of switches actuated in a pulsed RF power mode. It not only enough to identify the RF levels at which failures occur, but to evaluate the reliability of the switch at those levels. RF MEMS will continue to find system applications and understanding the RF power limits will help identify new and exciting opportunities for RF MEMS switches.

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REFERENCES

[1] K. E. Petersen, "Micromechanical Membrane Switches on Silicon", IBM J. Res. Develop. 23 no.4 pp376-385, July, 1979.

[2] S. Zhou, X. Sun and W. N. Carr, "A Micro Variable Inductor Chip Using MEMS Relays", Proceedings Transducers'97, pp1137-1140, June, 1997.

[3] L. E Larson, R. H. Hakett, M. A. Melendes and R. F. Lohr, "Micromachined Microwave Actuator Technology - A new Tuning Approach for Microwave Integrated Circuits', IEEE Microwave and Millimeter-Wave Monolithic Circuit Symposium, pp.27-30, 1991.

[4] C.L. Goldsmith, Zhimin Yao, Susan Eshelman, and David Denniston, "Performance of low loss RF MEMS capacitive switches," *IEEE Microwave and Guided Wave Letters*, Vol 8, No. 8, August 1998.

[5] C. Goldsmith, J. Ehmke, A. Malczewski, B. Pillans, S. Eshelman, Z. Yao, J. Brank, and M. Eberly, "Lifetime Characterization OF Capacitive RF MEMS Switches", *2001 IEEE International Microwave Symposium*, vol. 1, May 2001.

[6] Muldavin, J.B., Rebeiz, G.M., "High-isolation CPW MEMS shunt switches. 1. Modeling," *IEEE Transactions on Microwave Theory and Techniques*, Vol 48, No 6, pp. 1045 –1052, June 2000.