Lifetime Characteristics of Ohmic MEMS Switches

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Abstract Summary: In the future, MEMS switches will be important building blocks for designing phase shifters, smart antennas, cell phones and switched filters for military and commercial markets, to name a few. Low power consumption, large ratio of off-impedance to on-impedance and the ability to be integrated with other electronics makes MEMS switches an attractive alternative to other mechanical and solid-state switches. Radant MEMS has developed an electrostatically actuated broadband ohmic microswitch that has applications from DC through the microwave region. The microswitch is a 3-terminal device based on a cantilever beam and is fabricated using an all-metal, surface micromachining process. It operates in a hermetic environment obtained through a wafer-bonding process. We have developed PC-based test stations to cycle switches and measure lifetime under DC and RF loads. Best-case lifetimes of 10^{11} cycles have been achieved in T0-8 cans (a precursor to our wafer level cap) while greater than 10^{10} cycles have been achieved in the wafer level package. Several switches from different lots have been operated to 10^{10} cycles. Current typical lifetime exceeds 2 billion cycles and is limited by contact stiction resulting in stuck-closed failures. Stuck-closed failures can be intermittent with a large number of switches continuing to operate with occasional sticks beyond several billion cycles. To eliminate contact stiction, we need to better control the ambient gas composition in the die cavity. We expect lifetime to improve as we continue to develop and optimize the wafer capping process. We present DC and RF lifetime data under varying conditions.

1.0 Switch Fundamentals

The Radant microswitch is a 3-terminal device that employs a cantilever beam (Figure 1) and is fabricated using an all-metal, surface micromachining process on high-resistivity silicon substrate. In operation, the beam is deflected by applying a voltage between the gate and source electrodes so that the free end of the beam contacts the drain and completes an electrical path between the drain and the source. A threshold voltage of 60 V (at which the switch just turns on) and actuation voltage (including contact over-drive) of 100 V are typically employed. The contact material is a thin layer of a refractory metal deposited on the underside of the beam and on the drain, giving better stiction-free lifetime than the more common gold contacts. The device operates in a hermetic environment obtained through a wafer-level capping process (Figure 1) with a completed die dimension of 1.5 mm square and a contact area of 100 μm by 50 μm. The ability to package these switches in a wafer scale hermetic package has been a critical achievement in order to meet the simultaneous objectives of being low-cost and hermetic while minimizing impact on RF performance. This package is realized by wafer bonding a cap wafer (a silicon wafer with cavities etched into it) to the silicon switch wafer with a glass frit. Preliminary tests have shown this package to be hermetic with the stable contact resistance and long lifetimes being a testament to the hermeticity of this packaging scheme. Direct hermeticity testing of these devices has been a challenge due to the extremely small volumes (nL) encapsulated. These devices have passed both humidity and dye penetrant testing and we continue to search for a more appropriate hermeticity test.

2.0 MEMS Lifetime Testing

Radant MEMS has constructed a number of automated (PC controlled via Labview) DC and RF MEMS switch lifetime test stations for evaluating the reliability of our MEMS switches. DC lifetime measurements of uncapped (i.e., without wafer level packaging) devices in a flow-tube with carefully controlled atmosphere has exceeded 10^{11} cycles, with the current applied only during switch closure (to avoid hot "breaks" and "makes", i.e. "cold-switched"). Similar lifetimes (100 billion cycles) have also been obtained with microswitches packaged in TO-8 cans in room atmosphere. In a room atmosphere, best case DC and RF switch lifetime exceeds 10^{10} cycles for our wafer-capped switch. Typical military applications demand lifetimes that range from approximately 1 billion cycles for a switched beam antenna to 100 billion cycles for an Electronic Scanning Radar Antenna.

2.1 DC Lifetime

The lifetime of MEMS switches under DC load is measured at two stages. A wafer-probe system is used to exercise all switches on a wafer to 10^4 cycles and map functionality across the wafer. This is employed for production screening and process control development and allows us to implement 100% device testing at the wafer level. Additionally, a PC based system is used to perform life-tests over a longer number of cycles for reliability testing and characterization. Switches from each wafer are typically cycled up to 10^{10} times. During cycling, devices are cold-switched with a voltage applied across the switch during every switch closure to yield a typical switched current of 16 mA. The switch on/off-resistance are measured and recorded at intervals at least every 10^5 cycles. Lifetime tests at higher currents up to 500 mA are ongoing and do not seem to accelerate failures for our 8-contact switches as tested on a small number of devices. Typical DC lifetimes at these test currents exceed 2 billion cycles.

2.2 RF Lifetime

We have designed and built a PC/Labview based test station to test lifetime under RF load at frequencies from 2 to 10 GHz and powers from 1 mW to 2 W. The system first checks to ensure that the switch is operational and then a 10 KHz 100 V square wave is applied to the gate. After the MEMS switch is closed there is a 20 μs wait before a pulsed (simulating a typical operational radar waveform) RF signal is switched on and applied for 3 pulses. One RF pulse is applied when the MEMS switch is open. This waveform is referred to as our "High Cycle Rate" waveform and is employed to accelerate data collection. For example, 1 billion test cycles is accomplished in 28 hours. We also test with other waveforms with more operationally realistic switching rates from 200 Hz to 2 KHz but these waveforms considerably extend test times.

The output of the crystal detector is data logged during the on/off cycle at a rate typically every 10^4 cycles to yield data similar to that shown in Figure 2. Figure 2 shows lifetime data of a MEMS switch that is experiencing intermittent sticks (i.e., stiction that does not result in a permanent closed failure) at approximately 500 million cycles. Efforts have been put forth to reduce intermittent sticking to the point that this failure mechanism is now atypical. Recent high-power lifetime testing on a several devices has been accomplished leading to the data shown in Figure 3. This data was taken with 2 W input (10 GHz) to one of our 8-contact MEMS switches. The test was stopped at 2.5 billion cycles with the switch still functional. Both insertion loss and isolation were stable over life but the Traveling Wave Tube Amplifier (TWTA) suffered from power drift towards the end of this long duration test leading to the instability shown in both channels plotted in Figure 3, in addition to the input power channel. Typical RF lifetimes tested on numerous devices (exceeding 100) at 20 dBm exceeds 2 billion cycles. We are currently optimizing the switch design along with the wafer capping process so as to reach our goal of consistently achieving lifetimes of 100 billion cycles in a wafer level package at 1 W RF input.

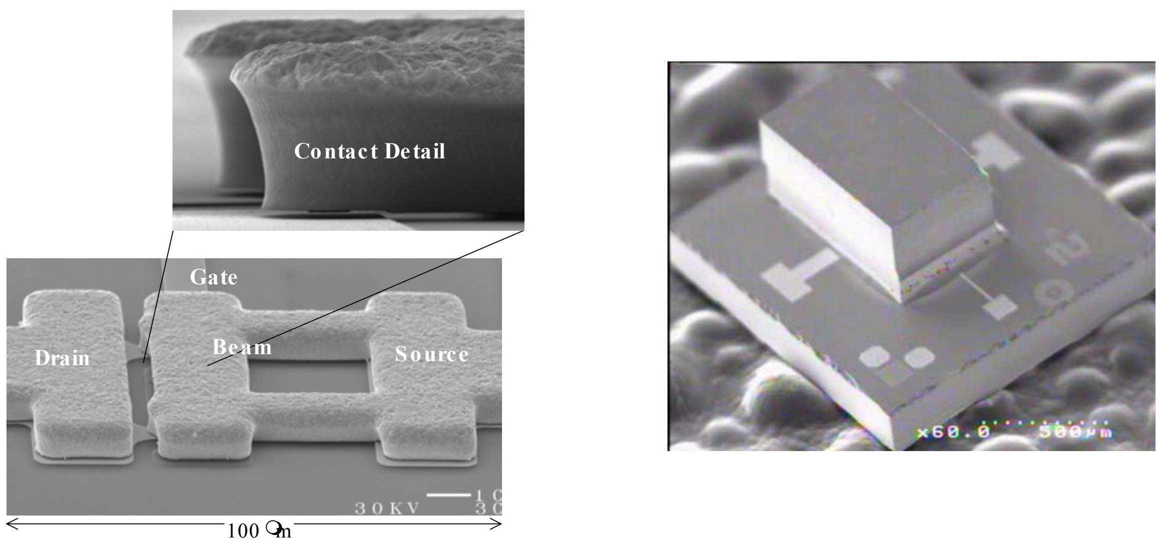

Figure 1. SEM micrograph of a capped die (right) containing an RF switch (left) as obtained through a wafer-bonding process.

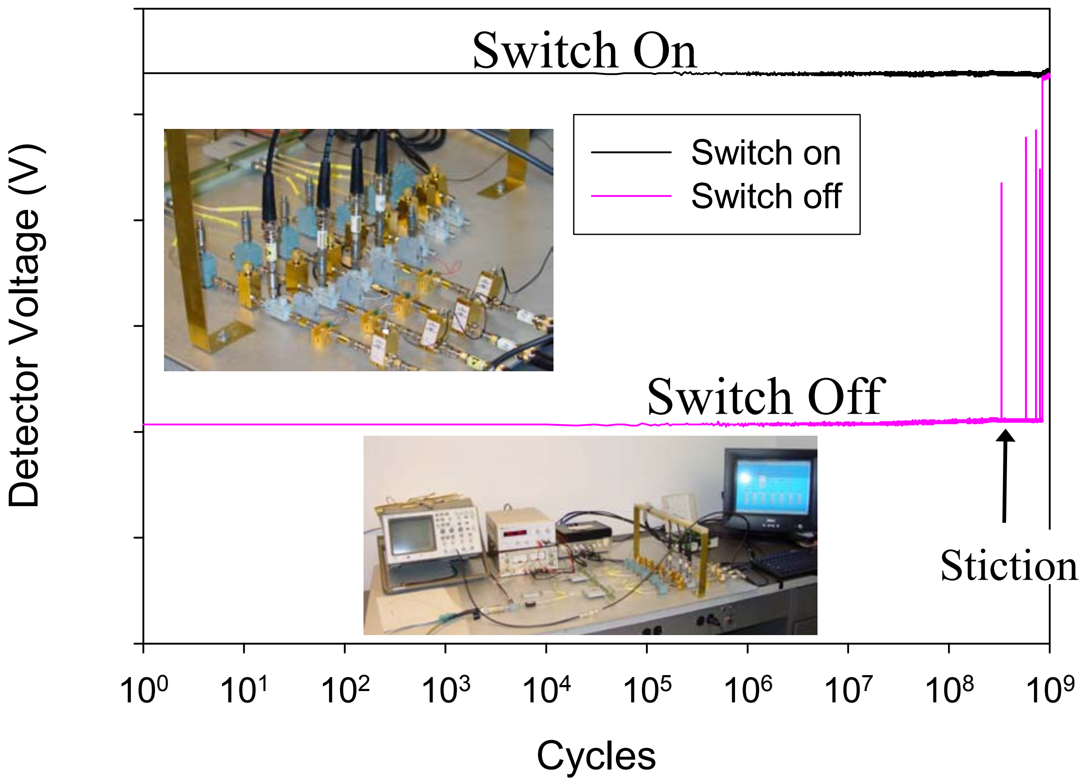

Figure 2. RF lifetime of an 8-contact MEMS switch at 10 GHz with 11 dBm of input power. Stable contact resistance is seen over the life of the switch. Intermittent sticks start to appear at approximately 500 million cycles for this switch. Efforts have been put forth to reduce this intermittent failure mechanism leading to more typical results shown in Figure 3.

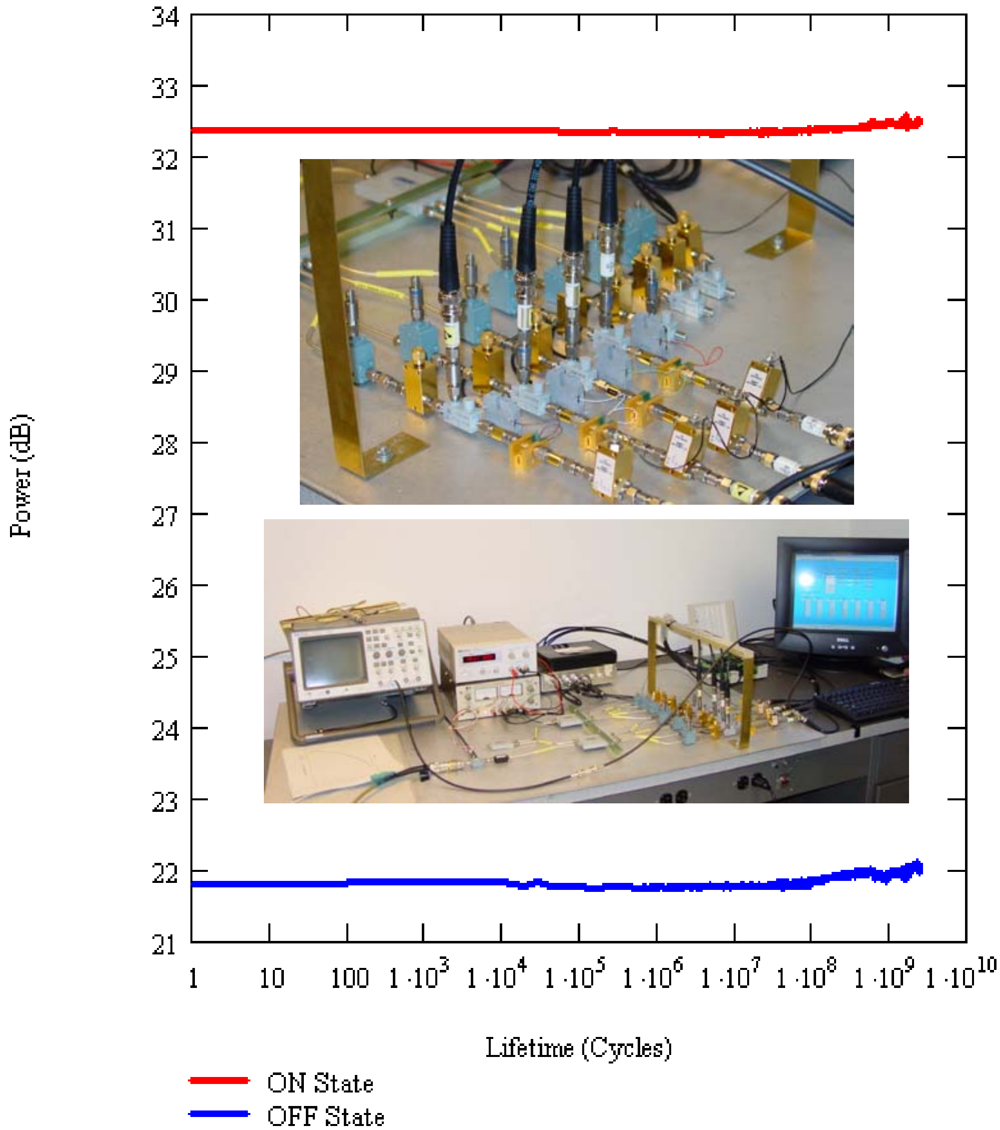

Figure 3. High-Power (2 W) RF lifetime testing at 10 GHz for our 8-Contact MEMS Switch. Switch was still functional at 2.5 billion cycles when the test was stopped. Instability in the TWT amplifier employed for this testing towards the end of this test lead to some power drift in all test channels. Both insertion loss and isolation were stable over the life of the switch.

Summary

A surface micromachined ohmic microswitch has been developed that can be used in applications from DC through the microwave region for a variety of commercial and military applications. Applications include T/R and band select switches in a variety of products such as cellular handsets and base stations, phase shifters for Electronically Steerable Antennas, tunable filters, reconfigurable antennas, and pin electronics for Automated Test Equipment. Critical to this development has been the establishment of a low-cost hermetic wafer-scale package that maintains the proper environment for the micro-contacts and yields long and stable lifetimes with minimal RF impact. This has been achieved through a wafer bonding process.

Key RF performance characteristics for a single element, series, SPST switch are; at 10 GHz, insertion loss of 0.4 dB and isolation of 20 dB for a 2 contact MEMS switch and at 2 GHz, insertion loss of 0.2 dB and isolation of 27 dB for an 8 contact switch. Further RF optimization, particularly for isolation improvement, is underway.

RF lifetimes exceeding 2 billion cycles are consistently achieved in our wafer scale package at input power levels of 20 dBm (100 mW) at X-band. Similar results are obtained for DC lifetime testing. Recent RF lifetime tests at higher power levels have achieved 2.5 billion cycles with 33 dBm (2 W) power input on a limited amount devices with additional testing underway. The uncapped microswitch has been demonstrated to 100 billion cycles and our current focus to is to achieve these lifetimes in our wafer scale package. Best case lifetimes in our wafer scale package has exceeded 30 billion cycles. Optimization of the wafer capping process and the switch design is underway.