A Packaged, High-Lifetime Ohmic MEMS RF Switch

S. Majumder, J. Lampen, R. Morrison and J. Maciel

Radant MEMS, Incorporated, Stow, MA, 01775, USA

Abstract — **An electrostatically actuated broadband ohmic microswitch has been developed 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. Characteristics of the wafer-level packaged switch include DC on-resistance of less than 1 Ohm with an actuation voltage of 80 V, lifetime of greater than 10^{10} cycles with on-resistance variation of less than 0.2 Ohm and current handling capability of 1 Ampere. Key RF characteristics at 2 GHz include an insertion loss of 0.32 dB and isolation of 33 dB for our 4-contact microswitch. Preliminary measurements at higher microwave frequencies are extremely promising with full characterization and planned product improvements underway.**

I. INTRODUCTION

MEMS microswitches are receiving increasing attention, particularly in the RF community. Low power consumption, large ratio of off-impedance to on-impedance leading to low insertion loss and high isolation, excellent linearity and the ability to be integrated with other electronics; makes microswitches an attractive alternative to other mechanical and solid-state switches. MEMS switches can be used in a variety of RF applications including cell phones, phase shifters and smart antennas and also in lower-frequency applications such as Automatic Test Equipment (ATE) and industrial and medical instrumentation [1, 2].

We have developed an electrostatically actuated MEMS microswitch for both DC and RF applications. The microswitch is a 3-terminal device that employs a cantilever beam (Fig. 1) and is fabricated using an all-metal, surface micromachining process on high-resistivity silicon [3-6]. In operation, the beam is deflected by applying a voltage between the gate and source electrodes (marked G and S in Fig. 2), so that the free end of the beam contacts the drain (marked D in Fig. 2) and completes an electrical path between the drain and the source. The contact material is a thin layer of a Platinum group metal deposited on the underside of the beam and on the drain. The device operates in a hermetic environment obtained through a wafer-level capping process (Fig. 3).

Ongoing activities include manufacture of prototypes for use in a X-band Electronically Steerable Antenna (ESA) under an US Air Force contract with the Air Force Research Laboratory at Hanscom AFB, process and design modifications to optimize RF performance and contact resistance and development of a 4-terminal relay for better isolation between the actuation and signal paths.

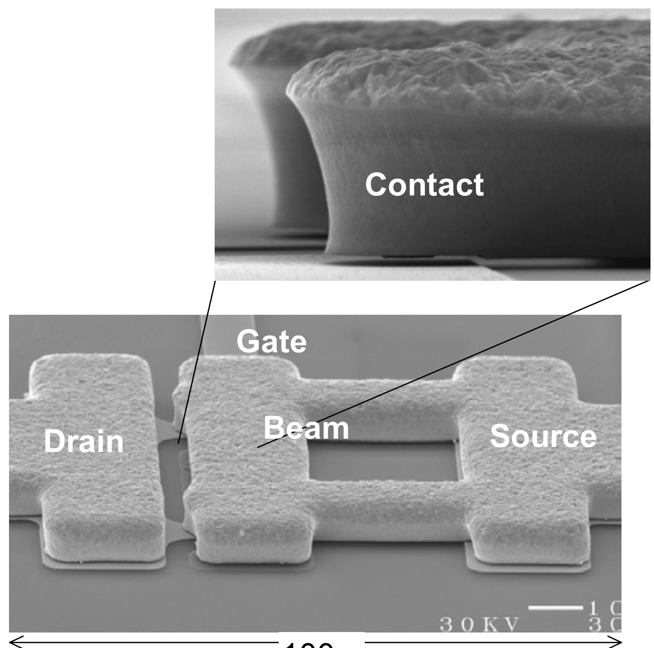

Fig. 1. SEM micrograph of the electrostatically actuated microswitch.

II. SWITCH FUNDAMENTALS

An important achievement has been the ability to package these switches in a wafer scale hermetic package. This is accomplished by wafer bonding a cap wafer (a silicon wafer with cavities etched into it) to the silicon switch wafer. Preliminary tests have shown this package to be hermetic. Furthermore, the stable contact resistance and long lifetimes is also a testament to the hermiticity of this packaging scheme. This wafer scale package has been found to meet the simultaneous objectives of being low-cost and hermetic while minimizing impact on RF performance. All of the stated measurement results here, unless otherwise noted, have been obtained in a laboratory air environment with devices that have been packaged by this wafer bonding process.

Important operational characteristics are as follows. A gate voltage between 40 and 120 V, depending on the specific design, actuates the microswitch. Devices are usually operated at a contact force of 200 μN, and have a single contact resistance of 3 Ω. Switches typically have 4 to 8 contacts in parallel to yield a total on-resistance, including interconnects, of less than 1 Ω at DC and low frequencies.

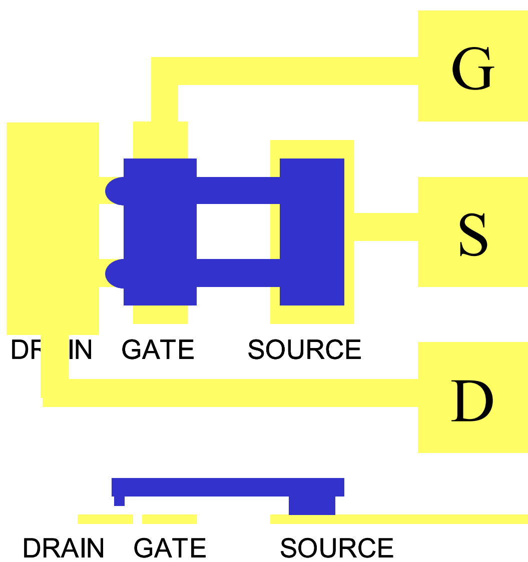

Fig. 2. Schematic representation of the microswitch shown in Fig. 1.

DC device lifetime is generally measured at a current of 10 mA or less with the current applied only during switch closure (to avoid hot “breaks” and “makes”, i.e. “cold-switched”). Under these conditions, switch lifetime exceeds 10^{10} cycles (Fig. 4) for a wafer capped switch. Measurements at higher currents, up to 500 mA per switch contact, show lifetime greater than 10^9 cycles for a capped switch. DC lifetime measurements of *uncapped* (i.e., without wafer level packaging) devices in a flow-tube have exceeded 10^{11} cycles. RF lifetime measurements at 5 GHz with 0 dBm input has exceeded 10^{10} cycles cold-switched for a capped microswitch. In all of these cases, the test was stopped while the switches were still functional. Currently, these cold-switched lifetime measurements have been limited by test time, rather than any failure mechanism. A relatively small number of hot-switching lifetime measurements with 1 V indicates a life of about 10^7 cycles with the lifetime limited by erosion of the drain metal. Similar lifetimes to those described above have also been obtained with a microswitch packaged in a TO-8 can.

The on-response time is approximately 5 μs, and is limited by squeeze-film damping of the cantilever beam. This on-response time includes contact bounce (3-4 bounces) which can be further dampened by limiting the slew rate of the actuation signal. The off-response time is much smaller, and is limited by parasitics in our measurement circuit.

Another characteristic, which is important for some applications, is the “stand-off” voltage, or the maximum voltage that can be applied across an open switch without damaging it. A voltage across the open microswitch sets up a field in the gap between the drain and the end of the beam. This can cause the switch to fail in two ways, either by causing the beam to deflect and closing the switch, or by causing an electrical breakdown of the gap. In our current designs, the failure is due to beam deflection, and occurs at about 150 V.

Microswitches are interesting candidates as replacements for low-power mechanical relays (generally reed relays), particularly in applications utilizing a large matrix of relays, often for multiplexing. Examples of such applications are pin electronics in Automated Test Equipment, transducer arrays in medical ultrasound and sensor and data acquisition applications. Microswitches can bring significant savings in size and power consumption in such applications and may also provide longer life. For example, a 8x8 array of reed relays each 2 cm x 1 cm in size would occupy 250 cm^2, the same array using microswitches would consume 1 cm^2. Certain applications may require a true 4-terminal relay, in which the signal path does not share a terminal with the actuation circuit. Prototypes of such devices have been built.

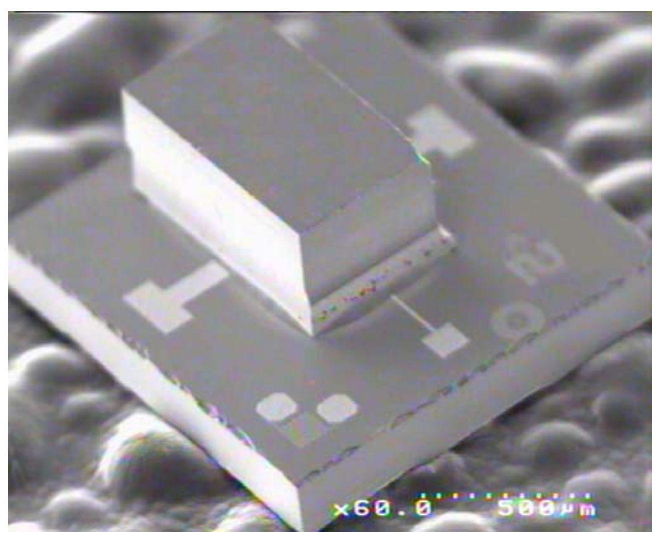

Fig. 3. SEM micrograph of a capped die containing a microswitch obtained through a wafer-bonding process.

III. RF PERFORMANCE

The benefits and applications for MEMS RF switches as fundamental building blocks, supplanting PIN diode and FET RF switches are numerous because MEMS switches combine the best features of both, having the low control power requirements of FETs, but having "on" resistances (and RF insertion losses) lower than PIN diodes. Furthermore, MEMS switches have lower off-state capacitance and, as a result, better off-state RF isolation than either FETs or PIN diodes, and, in addition, have inherently high RF linearity. Intended applications include microwave switches that replace PIN diode and FET switches, while providing lower insertion loss, higher isolation, higher linearity, higher radiation resistance, superior tolerance for high temperature environments, and lower prime power consumption. Examples of such applications include T/R switches in a variety of products such as cellular handsets and base stations, phase shifters for Electronically Steerable Antennas, tunable filters and reconfigurable antennas, to name a few.

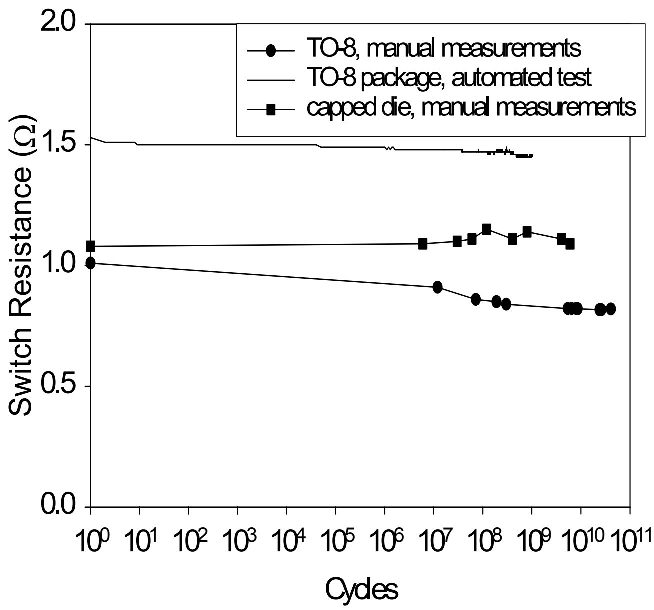

Fig. 4. Representative DC on-resistance characteristics of packaged MEMS switches. The upper trace shows results from cold switching a device in a TO-8 hermetic package with our automated test system (test stopped at 10^9 cycles). The center trace is a hot-switching manual probe measurement (10mA) for a wafer-capped switch (test stopped at $6x10^9$ cycles) and the lower trace is a similar measurement for a TO-8 packaged device (test stopped at 4×10^{10} cycles). In all cases, the devices were still functional when the test was stopped.

One application of current interest is the cellular telephone market. Here, the frequency of interest is approximately 2 GHz. Measured performance of our wafer-level capped MEMS switches are very good at this frequency, with an insertion loss of 0.32 dB and isolation of 33 dB for a single element, series, SPST 4-contact switch in a 50 mil sq. capped die package similar to that of Fig. 3. This RF insertion loss is several tenths of a dB better than most current PIN diode, MESFET, and PHEMT switches with comparable isolation at this frequency. By combining series and shunt MEMS switches within the same capped package, substantially higher isolation should be attainable in the future, with little degradation in insertion loss. Future plans also include capped SP2T, SP4T, and transfer switches.

Measured insertion loss and isolation are plotted on Fig. 5 for a 4 contact switch from 0 GHz to 4 GHz. Most of the insertion loss at the higher frequencies is due to reflections (return loss) caused by inductive wire bonds and by switch inductance and is not due to switch resistance. This reflective loss will be mostly eliminated in the future by reducing switch inductance. Efforts are currently underway to increase the off-state switch isolation by modifying the switch geometry and to decrease the on-state insertion loss by identifying and minimizing the various loss mechanisms. Fig. 6 shows return loss and isolation for an 8-contact microswitch. Insertion loss is seen to be 0.27 dB at 10 GHz with an isolation and return loss (not shown) of -12 dB. Further optimizations of both designs are in process that will further improve insertion loss and isolation.

Fig. 5. Capped switch isolation and insertion loss vs. frequency for a 4-contact microswitch.

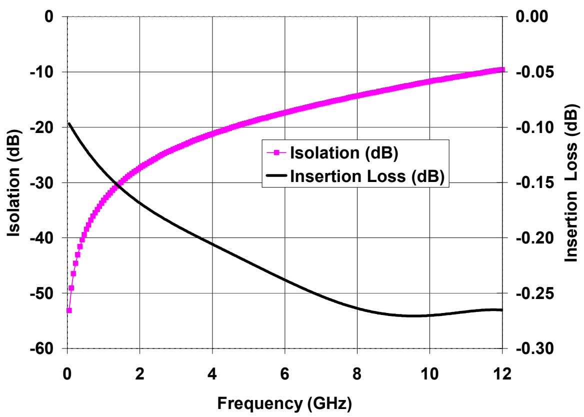

Fig. 6. Capped switch insertion loss and isolation vs. frequency for a 8-contact microswitch.

IV. SUMMARY

We have developed a surface micromachined ohmic microswitch that can be used in applications from DC through microwave. A low-cost hermetic wafer scale package has been developed that maintains the proper environment for the micro-contacts.

Key characteristics for a single element, series, SPST switch are; at 2 GHz, insertion loss of 0.32 dB and isolation of 33 dB for a 4-contact MEMS switch; at 10 GHz, insertion loss of 0.27 dB and isolation of 12 dB for an 8-contact switch. Further RF optimization is underway.

Results from DC to low frequencies include a total on-resistance, including interconnects, of less than 1 Ω, cold switch lifetimes exceeding 10^{10} cycles, and hot switch lifetimes exceeding 10^{7} cycles in the wafer level package. Additional testing is underway along with efforts to further increase the lifetime of these devices.

Applications for our microswitch include T/R switches in a variety of products such as cellular handsets and base stations, phase shifters for Electronically Steerable Antennas, tunable filters and reconfigurable antennas, pin electronics for Automated Test Equipment, transducer arrays in medical ultrasound, and sensor and data acquisition applications.

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