Reliability Study of Low-Voltage RF MEMS Switches

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Abstract

The reliability and performance of a low-voltage metal-to-metal contact shunt RF MEMS switch is investigated. The switch featured is compatible with standard MMIC processing steps. The best rf performance shows insertion loss of less that 0.1 dB and isolation of greater than 22 dB for all frequencies up to 40 GHz. Switching times are less than 25 μs. Lifetimes of 3×10^8 cycles have been achieved for tests with no input signal, and 1.3×10^6 cycles for tests with continuous input. The failure mechanism is degradation of the metal-to-metal contact, and stiction problems have been avoided through careful processing and testing conditions.

INTRODUCTION

RF MEMS switches are of interest because of the potential for low-loss, wide bandwidth operation, as they have demonstrated superior rf characteristics compared to FET and diode-based switches. Low-cost switches that can be integrated with existing technologies for high-speed electronics are an attractive proposition for a variety of applications. They are a promising element for use in reconfigurable circuits [1,2], and have been demonstrated in phase shifters [3,4]. Various groups have implemented series [5] and shunt [6] designs, with capacitive [7] or metal-to-metal [8] signal coupling.

The University of Illinois has focused on low-voltage switches that are compatible with standard MMIC processing techniques. Process and design enhancements have resulted in switches with typical actuation voltages of 15-20 V and excellent rf performance. Isolation and return loss are better than 20 dB and 0.1 dB respectively for frequencies up to 40 GHz, and switching times are less than 25 μs.

For any device to be used in a practical application it must be reliable, and while there are many reports of MEMS switches, published reports of their reliability are much more scarce. Switch lifetimes are limited by stiction of moving parts or degradation of the metal-to-metal contact. This paper will discuss efforts to characterize and improve the reliability of UIUC switches, and show that good reliability is possible with low-voltage switches.

DEVICE DESCRIPTION

The University of Illinois low-voltage RF MEMS switch [9,10,11,12] is a shunt design with metal-to-metal contact, and the switch supported at the four corners by serpentine cantilevers, as shown schematically in Fig. 1. In its up state the switch electrode forms a bridge that spans a segment of coplanar waveguide. When the switch is actuated by applying voltage to the pads beneath the bridge, an electrostatic force pulls the bridge down into contact with the signal line creating a short circuit. The shunt configuration provides very low insertion loss in the up state, and the metal-to-metal contact has the benefit of an inherently wide-band response. The serpentine supports are a key part of reducing the actuation voltage [9,13].

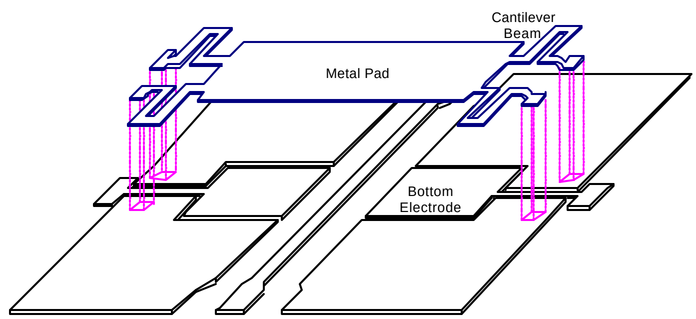

Fig. 1. Schematic diagram of an RF MEMS switch

The fabrication of this switch is based on interconnect and passivation steps found in typical MMIC processes, and switches are fabricated on gallium arsenide substrates. The five-mask-layer process consists of waveguide/actuation-pad metalization, nitride passivation, via etching, contact metal deposition, and airbridge construction. The bridge is deposited on a sacrificial layer of photosensitive polyimide, and features a dimpled center section to insure good electrical contact with the contact points beneath. Removal of the sacrificial layer includes a super-critical carbon dioxide drying procedure as the final step to prevent capillary forces from causing the bridge to permanently adhere to the substrate [14]. An SEM image of a completed switch is shown in Fig. 2.The switching pad for this particular device is 150 µm wide and 200 µm long.

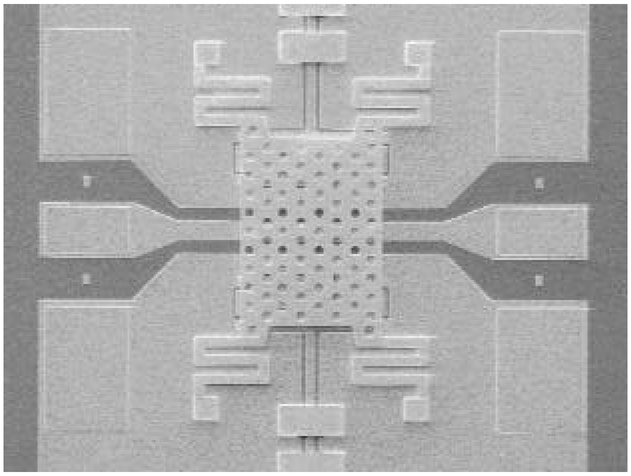

Fig. 2. Fabricated switch

TESTING AND RESULTS

Device characterization from 0.25 to 40.25 GHz is carried out on an HP 8510C Vector Network Analyzer, using on-wafer calibration standards to remove pad parasitics from the measurements. The up state data in Fig. 3 (a) shows less than 0.1 dB of insertion loss across the entire frequency range, and the down state data of Fig. 3 (b) shows better than 22 dB of isolation. This rf data indicates low shunt capacitance in the up state and a good short circuit to ground in the down state.

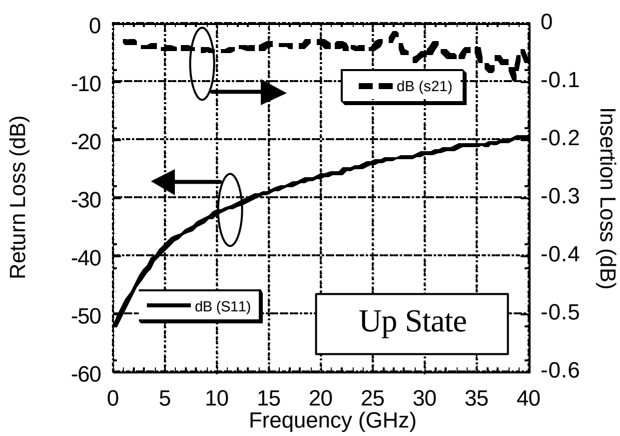

Fig. 3 (a). Measured rf performance for the up state

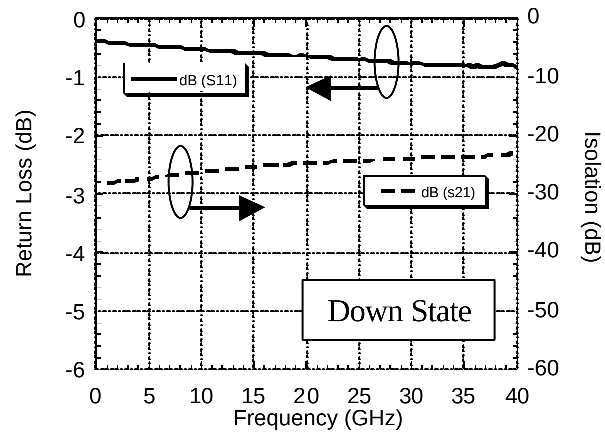

Fig. 3 (b). Measured rf performance for the down state

To examine the dynamic behavior and reliability of the switch another test is run using an amplified function generator signal for device actuation and an oscilloscope to monitor the output signal. Fig. 4 shows the scope traces for a switch tested in this manner. The input signal in this case is a 2 Volts peak-to-peak 1 MHz sine wave, and the control signal, shown in the lower trace, is a 10 Hz square wave with a peak amplitude of 9.4 Volts. When the control signal amplitude is greater than the actuation voltage of the switch, the input is shorted out and the output shows the modulated characteristic in the figure. Device isolation can be estimated by comparing the relative magnitude of the output signal for the two switch states.

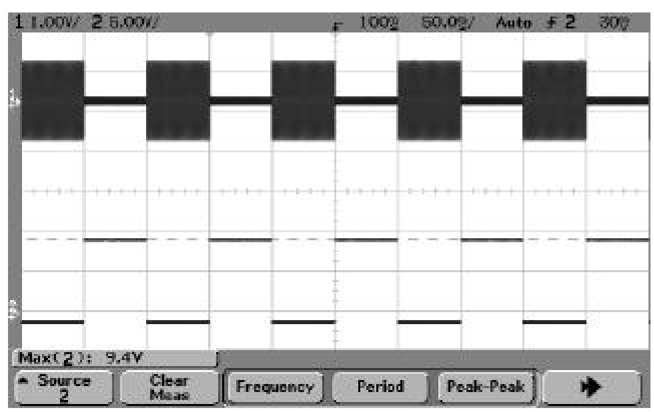

Fig. 4. Oscilloscope data for a switch operating at 9.4 Volts

These dynamic tests are done under vacuum to eliminate any environmental effects, which leads to concerns about device packaging. The problem with testing devices under ambient atmospheric conditions is humidity that can cause sticking problems, and can vary considerably throughout the year. The eventual package for this switch will have to be a sealed cavity that is filled with an inert gas such as argon or nitrogen.

Closer examination of the switch transition from up to down reveals the switching time of the device, which is the delay between the control signal turning on and the input signal being shorted out. This delay is presumably the time it takes for the switching electrode to traverse the three-µm gap and make contact to the signal line, and Fig. 5 shows a switch exhibiting a delay of 21.4 µs.

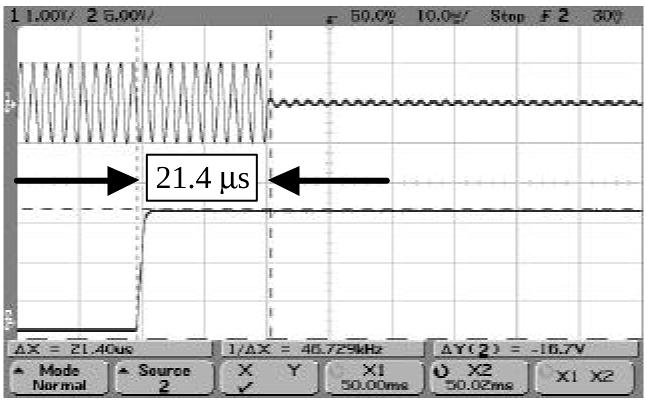

Fig. 5. Switching time data showing a delay of 21.4 µs

Switch reliability is tested by cycling the switch over a period of time and monitoring the output for degradation. Two types of test are performed: "hot-switched," in which the input signal runs continuously, and "cold-switched," in which the switch is cycled with the input only turned on occasionally to see if the device is still working. Cold switching tests are useful for examining the durability of the switch electrode to see if it can withstand the physical stresses of repeated switching. It also shows if there are any problems present with regards to charge accumulation in the passivation layer, which will cause the switch to get stuck to the actuation pads. Our tests show few sticking problems — the failures are usually a loss of ohmic contact to the signal line.

Hot-switching tests are indicative of how the switch will survive under actual operating conditions, with current flowing through the device. The failures expected with this test are a loss of isolation if the contact degrades, or a permanent short circuit if the current welds the switch to the signal line. These welding failures tend to occur if the amplitude of the input signal is too large, generally about 4 Volts, but the most common failure is a loss of isolation.

Lifetimes of 1.3×10^6 and 3×10^8 cycles have been achieved for hot-switched and cold-switched tests respectively. This data compared to other published reports is shown in Fig. 6 as a function of actuation voltage [1,5,15]. The Raytheon switch is capacitively coupled, but the rest are metal-to-metal contact devices. The figure shows that our results are comparable to those reported by other researchers but at a much lower actuation voltage.

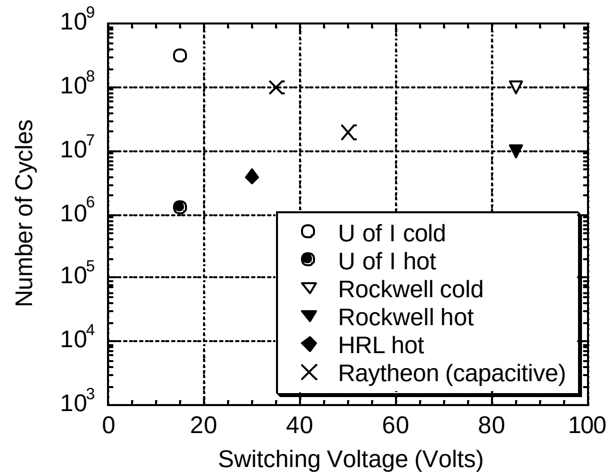

Fig. 6. Switch lifetime vs. actuation voltage for published reports

The most encouraging outcome of the reliability tests is that stiction problems seem to have been overcome through careful control of the processing and testing conditions. The metal-to-metal contact is the remaining problem that limits the lifetime of the switch. The fact that both cold-switched and hot-switched tests fail by loss of isolation indicates that the contact is negatively affected by both the physical stress of repeated pressure and the heat generated by current passing through the contacts. A solution to the contact integrity problem will extend the lifetime of these devices into a range suitable for a wide variety of applications.

CONCLUSIONS

RF MEMS switches have been fabricated in a shunt design with metal-to-metal contact that is compatible with standard MMIC processing techniques. Insertion loss and isolation of 0.1 dB and 22 dB respectively has been achieved for frequencies up to 40 GHz, and switching times less than 25 µs have been demonstrated. Reliability tests indicate that the dominant failure mechanism is a loss of isolation due to contact degradation for tests with and without a continuous input signal. Lifetimes of 1.3×10^6 and 3×10^8 cycles for hot-switched and cold-switched tests respectively are comparable to published reliability data, but at a significantly lower actuation voltage. These results show that good reliability is possible with low voltage operation.

ACKNOWLEDGEMENTS

Thanks to Dr. Shyh-Chiang Shen for early device development and Robert Lesnick for process assistance. This work is supported by Dr. Larry Corey (DARPA/SPO), Mr. Keith Stamper, and Dr. Al Tewksbury (AFRL/SNDI) under DARPA RECAP contract #F33615-99-C-1519, and Dr. James Mink under NSF ECS 99-79292.

ACRONYMS

RF: Radio Frequency
MEMS: Microelectromechanical Systems
MMIC: Monolithic Microwave Integrated Circuit
FET: Field Effect Transistor
UIUC: University of Illinois Urbana-Champaign
SEM: Scanning Electron Microscope

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