Performance of Low-Loss RF MEMS Capacitive Switches

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***Abstract*—This letter details the construction and performance of metal membrane radio frequency MEMS switches at microwave and millimeter-wave frequencies. These shunt switches possess a movable metal membrane which pulls down onto a metal/dielectric sandwich to form a capacitive switch. These switches exhibit low loss ($<$0.25 dB at 35 GHz) with good isolation (35 dB at 35 GHz). These devices possess on–off capacitance ratios in the range of 80–110 with a cutoff frequency (figure of merit) in excess of 9000 GHz, significantly better than that achievable with electronic switching devices.**

***Index Terms*— Low-loss, membrane, microelectromechanical systems, micromachining, microwave, millimeter-wave, sacrificial layer, switches.**

I. INTRODUCTION

THE use of microelectromechanical systems (MEMS) for radio frequency (RF) switching applications was first demonstrated in 1971 using bulk-micromachined cantilever switches [1]. Since then, several researchers have discussed the development of cantilever [2], [3] and rotary [4] MEMS switches for operation at RF and microwave frequencies. These switches relied an ohmic connection between microcontacts to establish the RF path. The development of RF MEMS switches using metal membranes with capacitive coupling has also been reported by the authors [5], [6]. Metal membrane switches show good insertion loss, reasonable switching voltages, fast switching speeds, and excellent linearity. This letter describes significant improvements to the design of metal membrane switches which operate with significantly reduced losses, increased operating frequencies, and improved switching speeds. These improvements were affected through improvements in switch layout, materials, and processing.

II. DEVICE STRUCTURE

The cross section of a metal membrane capacitive switch is shown in Fig. 1. The switches are built on high-resistivity silicon substrates ($>$10 kΩ·cm), with a 1-μm-thick layer of silicon dioxide used as a buffer layer. The switch circuitry is fabricated on top of the silicon dioxide using 4.0-μm-thick aluminum coplanar waveguide transmission lines. The thick aluminum metallization system is compatible with CMOS circuitry and exhibits low losses at high frequencies. The losses of these aluminum transmission lines are on the order of 0.06 dB/mm at 10 GHz. The bottom electrode of the switches is built using 0.4 μm of refractory metal. This film provides good conductivity for low loss and has a smooth surface finish. This finish is important for achieving good contact between the membrane and the lower electrode, minimizing any air gap. On top of the lower electrode is a thin film of silicon nitride. This film blocks the dc control signal from shorting out during switch activation, yet allows RF signals to capacitively couple from the upper membrane to the lower electrode. The metallic switch membrane consists of a thin aluminum less than 0.5 μm thick. This membrane has high conductivity for low RF resistance and good mechanical properties.

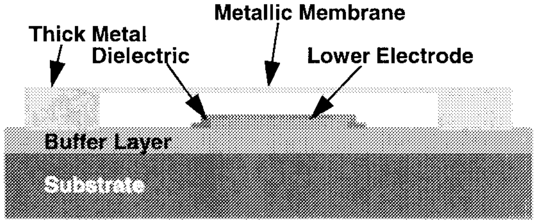

Fig. 1. Cross section of an RF MEMS capacitive switch.

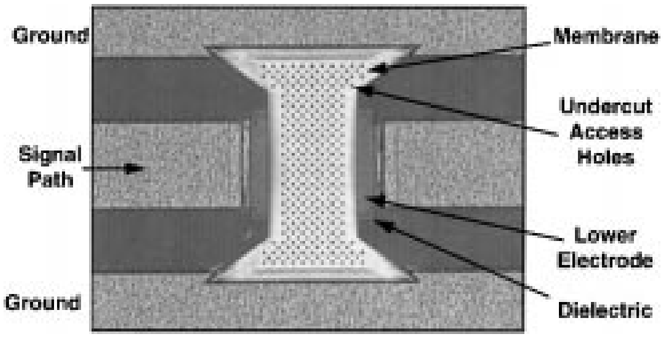

Fig. 2. Top view of a shunt MEMS capacitive switch.

A top view of the RF MEMS switch element is shown in the photograph of Fig. 2. The thick transmission line metal connects to the lower electrode and dielectric materials to form the through path of a shunt switch. These coplanar waveguide lines have a width of 120 μm and a gap of 80 μm. The suspended metal membrane spans the two coplanar ground lines. There is a series of 2-μm holes patterned throughout the upper membrane. These holes allow access for sacrificial micromachining which removes the spacer polymer from beneath the membrane. Removing this material mechanically

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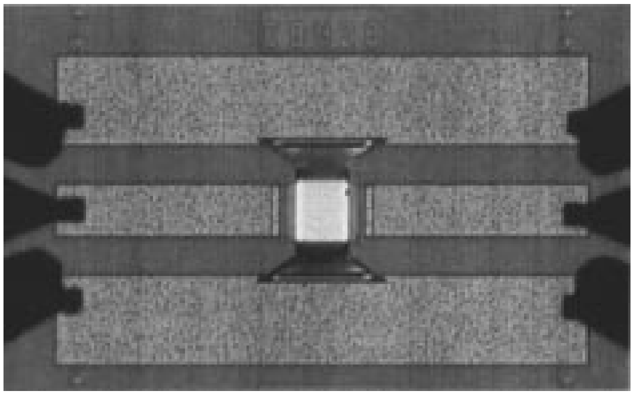

Fig. 3. Micrograph of an actuated RF MEMS switch.

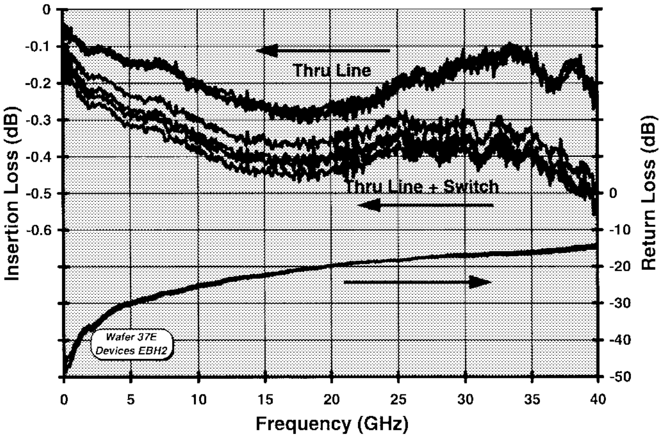

Fig. 4. Insertion loss and return loss measurements for several (four) unactuated shunt RF MEMS switch.

releases the membrane, freeing it to move up and down onto the lower electrode in response to applied electrostatic forces.

With no applied actuation potential, the residual tensile stress keeps the membrane suspended above the RF path. An RF signal traversing the coplanar transmission line will experience a capacitive reactance due to this grounded metal membrane on the order of 20–50 fF. Application of an electrostatic field between the membrane and the lower electrode causes the formation of positive and negative charges on the conductor surfaces. These charges exhibit an attractive force which, when strong enough, causes the suspended metal membrane to snap down onto the lower electrode and dielectric surface, forming a low-impedance RF path to ground. Fig. 3 demonstrates an RF MEMS capacitive switch in the actuated state. Typical capacitance in this state is 3–4 pF. By virtue of efficiently transmitting and effectively blocking the RF signal, this micromechanical variable capacitor serves as a high-performance microwave switch.

III. PROCESS SEQUENCE

Surface micomachining techniques were utilized to fabricate the switches described in this letter. The essential process steps are the following.

1) A 1-μm-thick insulating thermal oxide is grown on the substrate.
2) A 0.4-μm-thick layer of refractory metal is deposited and patterned to define the switch electrodes.
3) A layer of PECVD silicon nitride is deposited and patterned to form the switch dielectric.
4) A 4-μm-thick layer of aluminum alloy is evaporated and patterned to define the metal transmission lines and the mechanical support posts for the switch.
5) A polymer sacrificial layer is spin coated and patterned.
6) An aluminum membrane layer less than 0.5 μm thick is deposited and patterned to define the switch membrane.
7) The sacrificial layer is removed by a plasma etch to release the membrane. There are access holes patterned throughout the membrane to facilitate an accelerated release of the membrane layer.

IV. RF CHARACTERIZATION

Characterization of the RF MEMS capacitive switches consists of S-parameter measurements in the off- and on-states. This yields information regarding switch insertion loss, return loss, and isolation. S-parameter measurements were performed over the 0.13–40-GHz frequency range using a Wiltron 37 279 vector network analyzer and a Cascade Summit 10 000 RF probing system. From these measurements, equivalent resistances and capacitances are extracted to determine switch performance.

Due to the extremely low loss of the switches in the off-state, direct measurement of insertion loss tends to be inaccurate. Therefore, comparative loss measurements were made. Fig. 4 demonstrates the loss of 1030-μm-long CPW transmission lines, and RF MEMS switches embedded within transmission lines of the same length. Accurate determination of transmission line losses were derived from measurements of lightly coupled half-wave resonators which were incorporated onto the wafers. Typical transmission losses are 0.06 dB/mm at 10 GHz to 0.12 dB/mm at 35 GHz. From these measurements, line loss for a length of transmission line equal to the size of the MEMS switch (170 μm long) was determined to be approximately 0.01 dB at 10 GHz and 0.03 dB at 35 GHz. Looking at the difference between 1-mm transmission lines with and without MEMS switches yields 0.15 dB loss at 10 GHz and 0.28 dB loss at 35 GHz. Variability of the measurements was approximately ±0.05 dB, mainly because of difficulty in making good contact between the probes and aluminum lines due to the formation of oxides.

The return loss of the RF MEMS capacitive in the off-state is also shown in Fig. 4. This reflected energy is due to the parasitic capacitance caused by the proximity of the transmission path to the grounded metal membrane suspended above. This return loss is comparable to that of a 35-fF shunt capacitance. At high frequencies, the return loss degrades to 16.8 dB at 35 GHz. This is equivalent to 0.18-dB mismatch loss. This means that the insertion loss of the RF MEMS switch at millimeter-wave frequencies can be improved by reactive matching, and as much as 0.1-dB mismatch loss might be recovered.

The isolation of this switch, when the membrane is actuated into the on-state, is shown in Fig. 5. The isolation of these switches average 15 dB at 10 GHz and improves to 35 dB at 35 GHz. At frequencies below 30 GHz, the isolation is determined

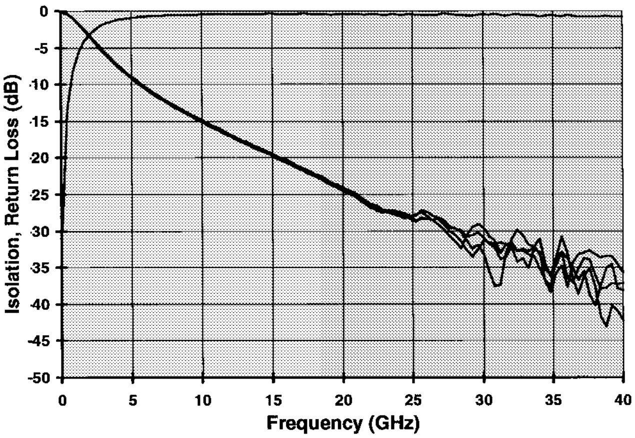

Fig. 5. Typical isolation and return loss for an actuated MEMS capacitive switch.

by the effective on-capacitance, which from this data, is determined to be 3.3 pF. Above 30 GHz, the on-capacitance becomes an RF short, and the effective series resistance of the switch dominates the isolation. Comparison of measured and modeled data shows this resistance to be approximately 0.35 Ω. The effective series inductance of this membrane is less than 0.0055 nH, owing to the very short distance between the centerline of the RF path and the grounds of the coplanar waveguide. The actuation voltage for these switches ranges from 30 to 50 V, depending on the tension in the membrane. The quiescent current for these devices is essentially zero, with current flowing only when the membrane is switching on or off (charging or discharging the capacitance of the switch). The switching speed for these devices is typically <5 μs. This is quite a bit faster than previous RF MEMS switch designs [5], mostly due to the fact that air beneath the membrane can exit more quickly through the open unsupported sides of the switch.

RF measurements demonstrate that these devices provide efficient switching of RF signals through 40 GHz. Signal losses for frequencies in the microwave and millimeter-wave frequency ranges show less than 0.2-dB loss with reactive matching at the higher frequencies. Meanwhile, isolation at high frequencies is better than 20 dB, limited most by the switch on-capacitance and ultimately the effective switch on-resistance. Higher isolation can be obtained at lower frequencies by increasing the size of the lower electrode or cascading series and shunt versions of this switch. Off-capacitance is in the range of 30–40 fF, while on-capacitance ranges from 3.2 to 3.5 pF. This yields a figure of merit for on–off capacitances in the range of 80–110. Similarly, with an effective resistance to ground of 0.35 Ω, the switch figure of merit $(1/(2\pi R_{\mathrm{on}} C_{\mathrm{off}}))$ ranges greater than 9000 GHz, more than 12× the best available electronic devices (p-i-n diodes).

V. CONCLUSION

Measurements demonstrate that these metallic membrane switches possess low insertion loss and good isolation at frequencies up into the millimeter-wave bands. The figures of merit for these switches compare well with electronic devices and other MEMS switch topologies. These devices offer the potential for building a new generation of low loss high-linearity microwave circuits for a variety of phased antenna arrays for radar and communications applications.

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