CHARACTERISTICS OF MICROMACHINED SWITCHES AT MICROWAVE FREQUENCIES

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ABSTRACT

This article reviews the fundamental characteristics of micromechanical membrane switches operating at microwave frequencies. The construction and theory of operation of capacitive membrane switches is reviewed. Measurement and modeling of the electromechanical and microwave properties of these switches are presented. The inherent advantages of these switches relative to semiconductor switches is discussed.

INTRODUCTION

Developments in microelectromechanical systems (MEMS) have facilitated exciting advancements in the fields of sensors (accelerometers and pressure sensors), micromachines (microsized pumps and motors), and control components (high definition TV displays and spatial light modulators). The technologies of bulk and surface micromachining enable the fabrication of intricate three-dimensional structures with the accuracy and repeatability inherent to integrated circuit fabrication. These new structures allow the design and functionality of integrated circuits to expand into the third dimension, creating an emerging technology with applications in a broad spectrum of technical fields.

Recent developments in MEMS technology have made possible the design and fabrication of control devices suitable for switching microwave signals. Micromechanical switches were first demonstrated in 1971 [1] as electrostatically actuated cantilever switches used to switch low-frequency electrical signals. Since then, these switches have demonstrated useful performance at microwave frequencies using cantilever [2], rotary [3], and membrane [4] topologies. These switches have shown that moving metal contacts possess low parasitics at microwave frequencies (due to their small size) and are amenable to achieving low on-resistance (resistive switching) or high on-capacitance (capacitive switching). This results in switches with very low loss, electrostatic actuation (no DC current required), and a potential for ultra-linear small-signal operation.

SWITCH OPERATION

The devices described herein are micromechanical switches where the active element is a thin metallic membrane movable through the application of a DC electrostatic field. A cross-sectional view of a membrane switch element in the unactuated state is shown in Figure 1a. The upper contact of the switch consists of a 0.3-μm aluminum membrane suspended across polymer posts. Surface micromachining undercuts the post material from beneath the membrane, releasing it to actuate. The suspended membrane typically resides 4-μm above the substrate surface. On the substrate surface, a bottom contact consists of a 0.7-μm gold or aluminum first metal layer. On top of this first metal layer sits a thin dielectric layer, typically 1,000 Å of silicon nitride.

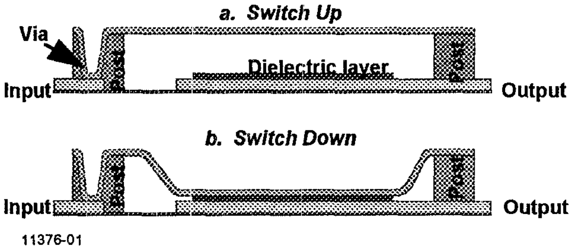

Figure 1. Cross-Sectional Views of Membrane Switch

In the unactuated state, the membrane switch exhibits a high impedance due to the air gap between the bottom and top metal plates. Application of a DC potential between the upper and lower metal plates causes the thin upper membrane to deflect downwards due to the electrostatic attraction between the plates.

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When the applied potential exceeds the pull-in voltage of the switch, the membrane deflects into the actuated position shown in Figure 1b. In this state, the top membrane rests directly on the dielectric layer and is capacitively coupled to the bottom plate. This capacitive coupling causes the switch to exhibit a low impedance between the two switch contacts. The ratio of the off- to on-impedances of the switch is determined by the on- and off-capacitances of the switch in the two switching states. Utilizing dielectric coupling prevents problems associated with stiction between the two metal layers as is commonly encountered with dry contact switching.

ELECTROMECHANICAL CHARACTERISTICS

A lumped-element one-dimensional model can be used to approximate the electromechanical motion of this switch. This simple model approximates the switch as a single rigid parallel-plate capacitor suspended above a fixed ground plate by an ideal linear spring. It has a single degree of freedom, which is the gap between the top movable plate and the bottom fixed plate. An important feature of this model is its ability to correctly predict the pull-in of the membrane as a function of applied voltage. This motion of this switch can be described by the pressure balance equation

$$P(g) = K_s(g_o - g) - \frac{\varepsilon_o V^2}{2g^2} \tag{1}$$

where P is the total pressure on the mechanical body of the switch, g is the height of the switch body above the bottom plate, g_o is the initial height of g with no applied field, V is the applied electrostatic potential. The spring constant of the switch body, K_s, is determined by the Young's modulus and Poisson ratio of the membrane metal and the residual stress within the switch body. As the electrostatic field is applied to the switch, the switch membrane starts to deflect downward, decreasing the gap g and increasing the electrostatic pressure on the membrane. At a critical gap height of 2/3 g_o this mechanical system goes unstable, causing the membrane to suddenly snap down onto the bottom plate. A graph of the gap height as a function of applied voltage is obtained by solving Equation (1). This result is shown in Figure 2.

The pulldown voltage for this system can be solved as

$$V_P = \sqrt{\frac{8K_s g_o^3}{27\varepsilon_o}} \tag{2}$$

When the electrostatic pressure is removed from the switch, the tension in the metal membrane pulls it back into the unactuated state. The actuation voltage for a variety of membrane sizes were measured and graphed, and is presented in Figure 3. For a stress-dominated clamped circular membrane, the pulldown voltage is inversely proportional to the membrane radius [5]. The data in Figure 3 fits quite well to this relationship. The solid line is a least-squares fit to this relationship and represents a biaxial residual stress of approximately 20 MPa.

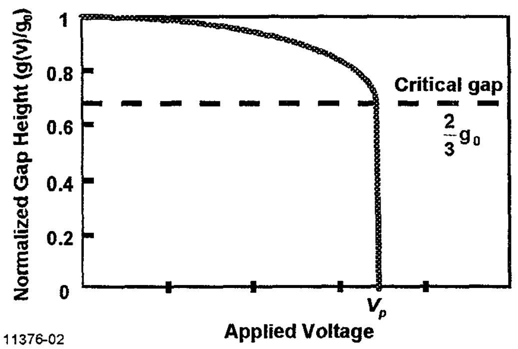

Figure 2.Gap Height Versus Applied Voltage

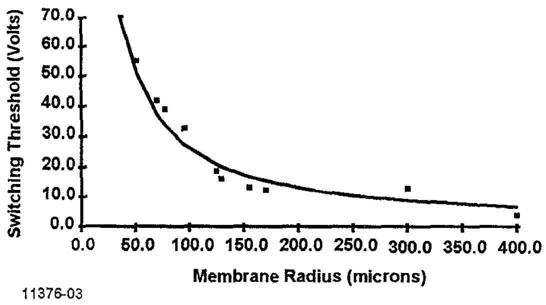

Figure 3.Measured Actuation Voltage for a Variety of Membrane Sizes

One of the critical electromechanical properties of MEMS switches is switching speed. Mechanical switches are inherently slower than electronic switches, with switching speeds in the microsecond to millisecond range, depending on the material and switch construction. The low mass of membrane switches makes for relatively fast mechanical switching compared to cantilever style switches, which have significantly higher mass. Figure 4 shows the rising and falling edges of a switched RF signal demonstrating a rise time of 6 μs and a fall time of 8 μs.

MICROWAVE CHARACTERISTICS

Test switches of the cross-section shown in Figure 1 were built into coplanar waveguide transmission lines for characterization and modeling. These switches were constructed in both series and

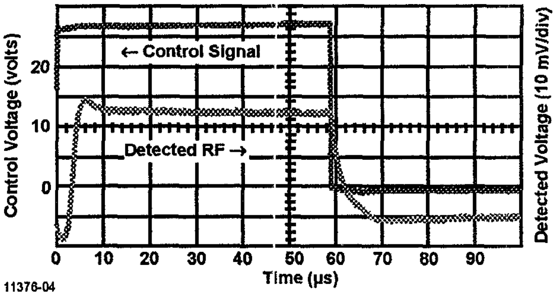

Figure 4. Switching Speed

shunt configurations. Multiport switches would consist of cascades of these series and shunt elements to achieve routing among multiple outputs. S-parameter data was taken over the 0.2- to 20-GHz frequency range using an HP 8720 vector network analyzer using an SOLT calibration. Figure 5 displays a microphotograph of a shunt switch. These switches were constructed on both high-resistivity silicon and gallium arsenide substrates. Microwave performance is relatively independent of the substrate material (which only acts as a platform for the switch) and is more dependent on the metallization and dielectric layers.

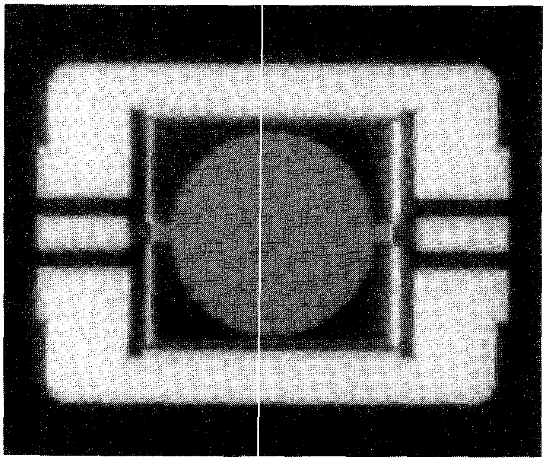

Figure 5. Shunt CPW Switch

In the transmissive state, series and shunt switch elements with a 400-µm diameter possess an insertion loss of approximately 0.3 to 0.5 dB at 10 GHz. A graph of the measured and modeled insertion loss of a shunt switch in the unactuated state is shown in Figure 6. Similarly, measured and modeled input return loss of the switch is shown in Figure 7. The modeled data is constructed using CPW and microstrip sections of transmission line, with some fitting of empirical parameters. In the actuated state, the shunt switch element possesses approximately 15 dB isolation at 10 GHz, corresponding to approximately 1.5 pf of shunt capacitance to ground. This is demonstrated in Figure 8.

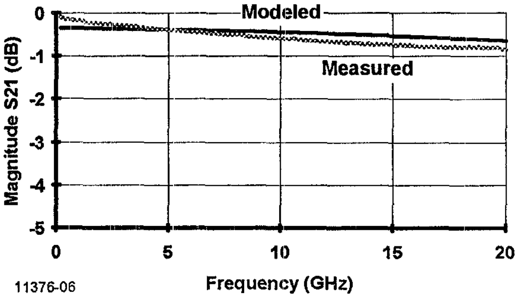

Figure 6. Shunt Switch Insertion Loss (Up Position)

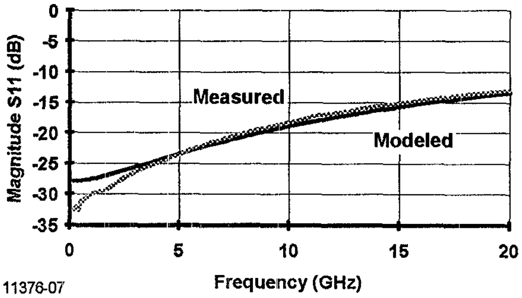

Figure 7.Shunt Switch Return Loss (Up Position)

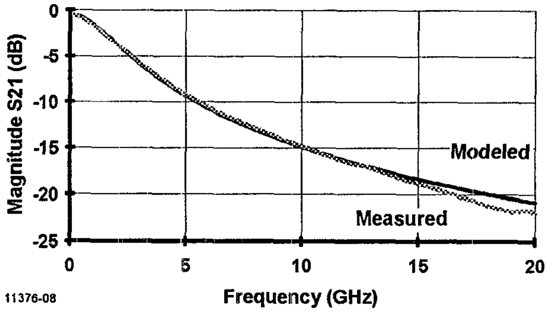

Figure 8. Shunt Switch Isolation (Down Position)

Detailed analysis of the switch losses indicate that much of the insertion loss is attributable to the narrow input/output interconnects between the 50-ohm CPW lines and the round switch contact area. A reduction in length of these lines can significantly improve the insertion loss of the switch. Micrographic analysis of the surface of the switch indicated that there were some imperfections in the deposition of the first metal layer, keeping the metal membrane from making the desired intimate contact with the bottom dielectric and metal. Process improvements are underway to improve the undercut process, which should yield more than 25 dB of isolation at 10 GHz from these elements. Currently, the microwave performance of these devices is on the order of that obtainable with p-i-n diodes. However, there are many degrees of improvement possible that will allow these switches to outperform semiconductor switch junctions. It is expected that further refinements in switch layout will improve insertion loss to less than 0.2-dB insertion loss per switch element with a corresponding 25 dB of isolation.

Theoretically, micromechanical switches do not exhibit intermodulation distortion (IMD) as there is no I-V nonlinearity. This switch possesses a moving metal contact that does not respond to microwave frequencies, only to the RMS potential between the switch contacts. Measurements were made to verify that micromechanical switches do not generate any form of intermodulation distortion. A shunt membrane test element constructed on gallium arsenide was connected to an automated IMD test station and measured from 2 to 4 GHz with power levels ranging to over 20 dBm. In all cases no intermodulation spurs were visible down to the limits of the Tektronics 2782 spectrum analyzer and IMD test system. These measurements indicate that these switches have an intercept point of at least +66 dBm.

ADVANTAGES AND APPLICATIONS

Micromechanical membrane switches have several advantages compared to FET or p-i-n diode switches. First, their loss is primarily dominated by conductor losses, and not dependent on contact and channel resistances typically seen in semiconductor switches. This can make for very low loss switching. Second, these switches are amenable to low-cost processing. The switches fabricated on silicon possess only six process layers. Additionally, silicon compatible processing on material such as silicon-on-sapphire allows fabrication on 6-inch wafers with advantageous economies of scale. Micromechanical switches require very low supply power, using DC supply current only during the switching transient. Typical switching energy is approximately 10 nanojoules. Micromechanical switches are also integratable with other technologies. Devices built on silicon-on-sapphire can be integrated with CMOS control circuitry to do level shifting and address decoding. This allows a substantial reduction in packaging complexity associated with routing control signals to each individual membrane element. These switches can also be integrated with GaAs electronics to achieve low loss, high IMD switching of low-noise amplifiers and filters for receiver front ends.

The main limitation of these switches are their switching speed. Microsecond switching precludes their use in transmit/receive switching applications. However, these speeds are more than sufficiently fast for beam-steering applications in phased antenna arrays.

The significant performance improvements possible with these devices compared to typical FET and p-i-n diode switches has important implications in system designs for both military and commercial telecommunications at microwave and milli-meter wave frequencies. Potential insertions include low loss switches, phase shifters, and antenna tuners for low noise receivers and phased array antenna apertures.

CONCLUSIONS

The basic construction and operation of micromechanical membrane switches has been introduced. A simple one-dimensional electromechanical model has been reviewed and correlates well with measured actuation voltages. Measured and modeled results for a typical capacitive switch demonstrate low loss and no measurable IMD distortion. Micromechanical switches posses the potential for very low loss, reasonable switching speeds, and operation with no quiescent current consumption.

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