Polyimide Film Based RF MEMS Capacitive Switches

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***Abstract* — A new type of RF MEMS capacitive switch using polyimide film as the structural membrane layer has been developed. Dimensions of these switches range from few hundred microns to few millimeters and are convenient for integration with the printed antennas. Fabrication and assembly of the polyimide film based switches are discussed. Electromechanical switch designs with actuation voltages as low as 73 Volts are presented. RF performance of the shunt-mounted switches on a CPW line has been demonstrated in the L-band with an insertion loss of less than 0.32 dB.**

I. INTRODUCTION

In the past decade, many RF MEMS switches have been reported [1],[2]. RF MEMS switches reported so far are based on silicon, GaAs or similar semiconductor materials fabricated by micromachining techniques. This paper describes an electrostatically actuated RF MEMS switch fabricated using flexible circuit materials and technology. Batch fabrication of such switches can be carried out using existing roll-to-roll flexible printed circuit technology, which would make the fabrication of these switches very cost effective. In addition, the use of roll-to-roll technology enables ease of integration over large areas with printed antennas and RF circuits. These switches have potential application for implementation of reconfigurable printed antenna arrays fabricated on rigid or flexible substrates. Normally, an array element with such a large number of built-in switches will be considered too costly and complicated, but the use of low-cost flexible circuit based RF MEMS switches could make this concept very feasible. The proposed RF MEMS switch has been demonstrated using the most commonly used flexible circuit material, *Kapton** E polyimide film, as the switch membrane layer.

II. FABRICATION AND ASSEMBLY

A. Switch Configuration

The schematic of an electrostatically actuated polyimide film based RF MEMS capacitive switch is shown in Fig. 1. The switch consists of three layers: substrate, polyimide film, and spacer film. CPW line patterned on the substrate serves as the bottom electrode. The switch top electrode metallization is patterned on the bottom side of the polyimide film, which serves as the switch structural layer. An adhesive bonding film is used as the spacer between the substrate and the polyimide film. The thickness of the spacer film determines the switch up-position gap height. A dielectric layer is coated and patterned on the CPW line to provide a capacitive contact in the switch down-position.

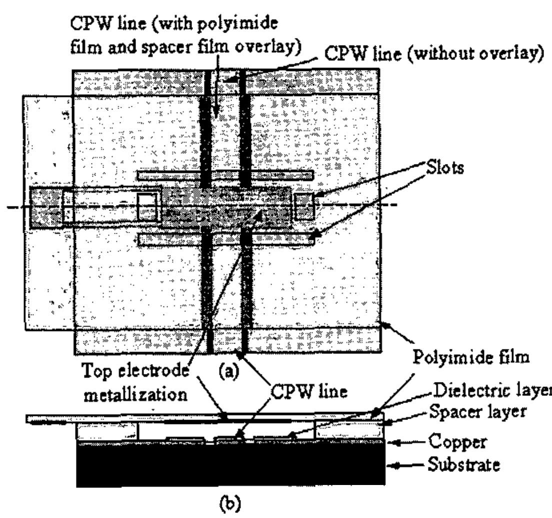


Fig. 1. Schematic of the Polyimide film based RF MEMS switch (up-position) mounted on a CPW line in shunt configuration: (a) top view and (b) cross section (not to scale)

B. Fabrication

CPW line is patterned on RT/Duroid** 6002 ($\varepsilon_r = 2.94$, $\tan\delta = 0.0012$ @ 10GHz) substrate of 30 mils thickness with ¼ oz copper cladding by photolithography and etching processes. The top electrode metallization is patterned on I-flex film (2 mil thick *Kapton* E polyimide film with 3 μm copper cladding) by photolithography and etching

*Kapton E is a registered trademark of E.I. Dupont deNemours and Co.

**RT/Duroid 6002 is a licensed trademark of Rogers Corporation, Chandler, AZ, USA.

processes. The polyimide film is machined using excimer laser to create slot openings required for formation of moveable switch membrane. A Benzocyclobutene (BCB) dielectric layer (ε_r = 2.65, tanδ = 0.002 @ 10GHz) of thickness 2.5 μm (average value) is spin-coated and patterned on the bottom electrode. A 2 mil thick Polyflon bonding film (ε_r = 2.34, tanδ = 0.002 @ 9.5 GHz) is used as the spacer layer. A slot is milled in the bonding film corresponding to the moveable switch membrane location. This allows the membrane to make contact with the BCB dielectric layer on the bottom electrode in switch down-position.

C. Assembly

The assembly process involves alignment of the switch layers followed by a thermo-compression bonding cycle. The substrate, the spacer film, and the polyimide film are aligned with the aid of a fixture containing three 1/16". (= 0.0625") pins at the periphery of the substrate. Alignment holes of diameter 0.0635" (with 1 mil clearance) are created on the substrate, the polyimide film, and the spacer film during fabrication. The thermo-compression bonding is performed in a press with a hot plate (used as bottom plate) at a pressure of 100 psi and a temperature of 130°C. Both pressure and temperature has to be maintained for 5 minutes during the bonding cycle. Before pressure is released, the assembly is cooled to room temperature.

Alternative flexible-circuit technology could be used for assembly of this kind of switches resulting in better alignment and manufacturability.

III. ELECTROMECHANICAL DESIGN AND TESTING

A. Flexure Configuration

The key step in electromechanical design is the flexure configuration that holds the switch membrane. For a chosen switch top electrode area and up-position gap height, the actuation voltage depends on the stiffness of the flexure. Soft flexures would completely collapse after pull-down, but it might not have enough mechanical restoring force to bring the membrane back to its original position. On the other hand, stiff flexures would provide high pull-down voltage and exhibit change in contact area after pull-down. An optimal flexure design would exhibit low pull-down voltage and should possess enough stiffness to restore back to its original position. Two switch designs with different flexure configurations have been investigated. Top view of these switch designs showing the polyimide film, the slots in the polyimide film layer, top electrode metallization, and the CPW line are shown in Fig. 2. The required flexure configuration is obtained by laser machining of slots on the polyimide film at the appropriate locations. The outline underneath the polyimide film layer represents the CPW line metallization that constitutes the switch bottom electrode. CPW line and the polyimide film are separated by a spacer film (as shown in Fig. 1).

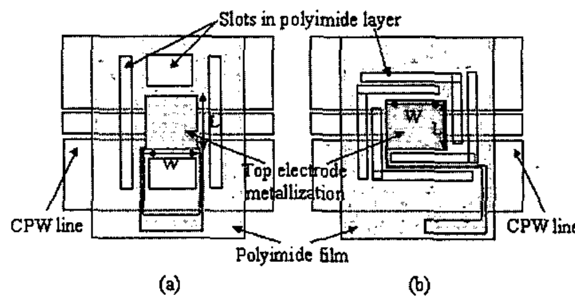


Fig. 2. Switch designs with compliant flexure design

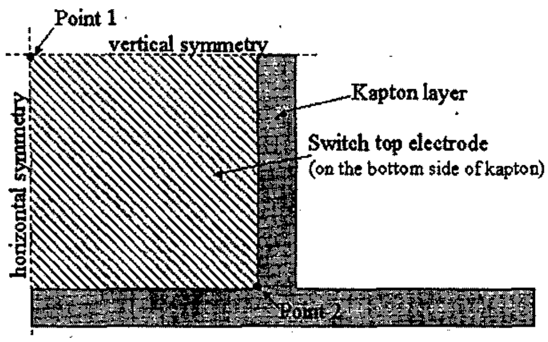
B. Electromechanical Simulation

Electromechanical simulation of these designs has been carried out using *MemMech* and *CoSolve* solvers available in *CoventorWare* [3]. Firstly, *MemMech* (a mechanical solver) is used to simulate the warpage effect caused during the switch assembly process. During the

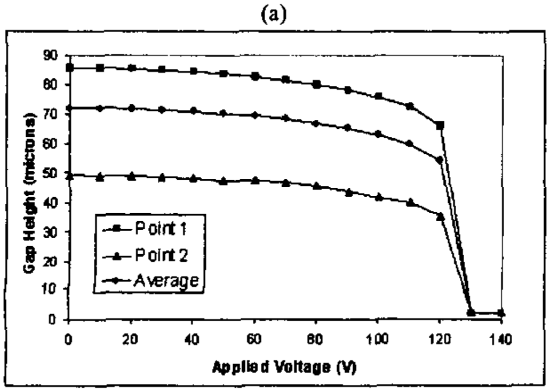
Table 1
Experimental results for the switch up-position gap height and the pull-down voltage

	Design A (shown in Fig. 2(a))	*Design B* (shown in Fig. 2(b))
Top electrode area (mm^2)	6x6	4x4
Flexure dimensions (mm^2)	3x0.5	7x0.5
Average up-position gap height (μm)	70	50
Pull-down voltage (V)	110-120	73

thermo-compression bonding cycle, the switch layers expand and contract unequally due to the mismatch in the coefficients of thermal expansion, which causes the warpage of the switch membrane. Secondly, the warped switch model is simulated in the *CoSolve* (a coupled electromechanical solver) to yield switch membrane displacement versus applied voltage characteristics. Switch pull-down voltage is obtained from this simulation.



(a)



(b)

Fig. 3. Electromechanical simulation results: (a) top view showing a quarter of the switch membrane and (b) gap-height versus applied voltage characteristics.

In Fig. 3 the top view of the switch membrane and the displacement vs. applied voltage characteristics for the switch design *A* (refer to Table 1) are shown. Fig. 3(b) shows the displacement vs. applied voltage characteristics corresponding to point 1, point 2 (shown in Fig. 3(a)), and average gap-height. For this design, the switch pull-down voltage is in the range 110-120 volts. The initial gap heights of the switch membrane at Point 1 and Point 2 are not the same because of the warpage effect. It is noted that the switch up-position gap height at the center (Point 1) is about 85 μm and at the edge (Point 2) is about 49 μm due to the warpage of the membrane. The average initial gap height of the switch membrane is about 71.5 μm. Currently, work is in progress to design switches with reduced membrane warpage.

C. *Experimental Results*

A number of switches for *Design A* were fabricated and electromechanical testing has been performed. The typical values for the gap height and the pull-down voltage are given in Table 1 (labeled as *Design A*). These results show a close agreement with the simulated results for the gap-height and the pull-down voltage. Experimental results for an improved switch design (*Design B*) with reduced actuation voltage of 73 volts are also shown in Table 1.

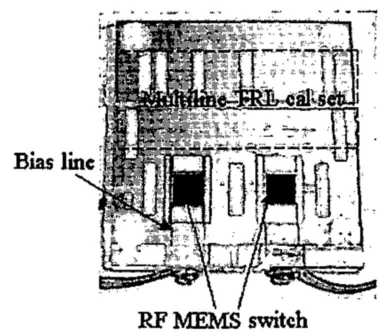


Fig. 4. A photograph of a typical switch prototype

IV. RF DESIGN AND TESTING

A. *RF Configuration*

Switches (*Design A* of Table 1) have been fabricated along with the multi-line TRL calibration set (for on-wafer calibration of network analyzer) on the same substrate. A photograph of a typical switch prototype is shown in Fig. 4. For a chosen center conductor width of 1.3 mm, the gap dimensions are 100 μm and 70 μm for a 50 Ω CPW without overlay and with overlay (polyimide film and bonding film), respectively. RF measurements have been carried out using Cascade Microtech air coplanar probes (ACP40-GSG) with 1250 μm pitch. The CPW line sections without overlay (shown in Fig. 1) are used for making probe contacts during RF measurements. The multi-line TRL calibration set consists of short (1 mm), thru (1 mm), and four delay lines (5.27 mm, 7.4 mm, 15 mm, and 40.39 mm). The loss of CPW line (with polyimide film and bonding film overlay) is obtained in the calibration process and is less than 0.01 dB/mm in the frequency range of 1-10 GHz. This confirms that *Kapton* E polyimide film and the polyflon bonding film are suitable for fabrication of polyimide film based MEMS switches.

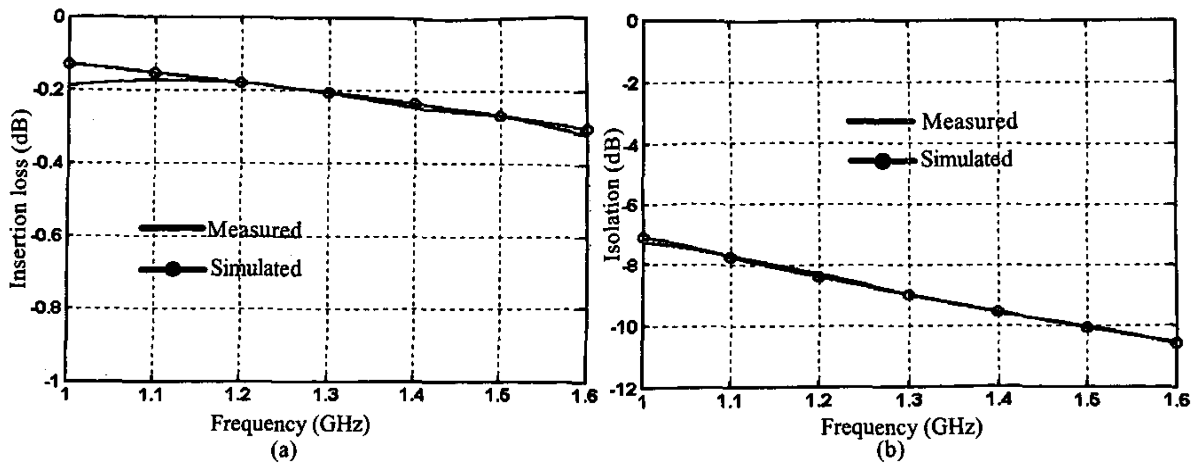


Fig. 5. RF performance of the switch prototype shown in Fig. 4 (*Design A* in Table 1).

B. Experimental Results

RF measurements of the switch have been carried out and the results are presented in Fig. 5. The insertion loss of the switch is less than 0.32 dB in the frequency range of 1 to 1.6 GHz. The insertion loss of the switch is almost same as the reflection loss when a capacitor of value 1.1 pF is connected across a 50 Ω line. Thus, due to high switch up-position capacitance value, this design is suitable only for the L-band frequency range. The switch isolation is better than 7 dB above 1 GHz and increases to 28 dB at 10 GHz. This behavior corresponds to a switch down-position capacitance value of 13 pF.

C. EM Simulation

Electromagnetic (EM) simulation of the switch in up-position and down-position has been performed in *HP-Momentum* [4] (a 2.5D EM simulator available in ADS) and these results are also shown in Fig. 5. A good agreement between the measured and the simulated results has been observed. For the switch up-position simulation, the average gap height of 71.5 μm (discussed in section III) is used. In the switch down-position, the surface roughness of the duroid substrate decreases the capacitance value. For simulation purpose, an equivalent air gap may be defined above the average value of dielectric thickness to account for the air gaps caused due to the surface roughness. The average value of BCB dielectric layer thickness is 2.5 μm. An equivalent air gap of root mean square value 1.65 μm (typical value for RT/Duroid substrate with ¼ oz. copper cladding) is used for the switch down position simulation. Currently, work is in progress to design switches operating at X- and Ku- band frequency ranges.

V. CONCLUDING REMARKS

RF operation of the polyimide film based RF MEMS switch has been successfully demonstrated. Fabrication, assembly, electromechanical testing, and RF testing have been discussed. RF performance of the shunt-mounted polyimide film based switches has been demonstrated in the L-band with an insertion loss of less than 0.32 dB.

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