RF Characterization of Surface-Mount Packaged MEMS Switch Using Planar Configurations

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***Abstract*—This paper presents RF characterization of the in-house developed and packaged, single-pole-single-throw (SPST) RF-MEMS switch based on Silicon-on-Glass, by means of two planar configurations using coplanar waveguide and microstrip technologies. Layouts accommodating the packaged MEMS switch along with appropriate RF and DC paths are designed. This enables the direct usage of the device as a basic building block in realizing various multi-pole-multi-throw switch configurations and also in system integration. The performance of the packaged switch on these designs is compared to its die level. The measured response, exhibiting good insertion loss (return loss) of better than 1.0 dB (15 dB) and excellent isolation of better than 30 dB, from DC to 2.5 GHz, is demonstrated.**

Index Terms—MEMS, RF switch, SMX package, PCB, CPW, microstrip, microwave characterization.

I. INTRODUCTION

MEMS switches at radio frequencies (RF) are major components fabricated by MEMS technology. RF-MEMS switches are attractive in application to the next-generation communication systems for reasons of low insertion loss, high isolation, low power consumption, and good linearity in comparison with the currently used solid-state counterparts (FET or PIN diodes) [1]–[11].

Among the choices of implementations such as high-resistive silicon, silicon-on-insulator (SOI), GaAs, quartz [1]–[5] or silicon-on-glass [6]–[7], direct-on printed circuit board (PCB) [8]–[11] offers unique advantage of minimized impendence mismatch and signal loss (e.g., between RF devices and package, package and board) because it eliminates the need for wire bonds used in packaging. Though, this technology makes possible MEMS switch on any PCB substrate [10]-[11], the efficient usage of such PCB-MEMS configurations along with other normal PCB circuits is still a challenge when constructing RF systems for space applications. On the other hand, surface-mount packages, for the standard design approaches [1]-[7], simplify the board layout. The demand for hermetic packages for high frequency devices has increased as many new applications, require a more ruggedized package that can withstand the elements and protect sensitive electronic devices. Surface-mount packages in various sizes and lead counts, with coplanar leads and base,

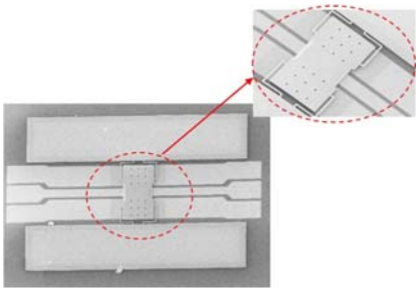

Fig. 1Top view of the present RF MEMS switch based on Silicon-on-Glass in Co-Planar Waveguide medium with the actuator structure.

are available for mounting directly on the circuit board, greatly reducing circuit board assembly costs. However, the parasitics related to packaging and wire bonds tend to degrade the device RF performance and limit the operating frequency range.

High frequency characterization of the packaged MEMS switch devices greatly necessitates appropriately designed PCB design configurations. This enables the direct usage of the PCB patterns when the device is integrated in a system or for the use of SPDT and higher switch configurations (using several SPST switches). The PCB foot print accommodating proper RF & DC paths and effective grounding is crucial for mounting and integration of the packaged devices, at the same time, any improper design may also lead to RF performance degradation in addition to the package parasitcs. In order to validate the RF characterization of the surface mount packaged (we selected packages from Stratedge SMX series 580465) MEMS switches, in this paper, two different PCB designs on high and low dielectric constant substrates are considered using planar configurations such as coplanar waveguide (CPW) and microstrip technologies, respectively. Design considerations for the PCB configurations and effective grounding are discussed. The board level RF performance, of the SMX packaged hermitically sealed MEMS switch, is demonstrated from 0.1 to 2.5 GHz.

II. DEVICE FABRICATION & PACKAGING

Fig. 1 illustrates the top view of the in-house fabricated RF MEMS switch in Silicon-on-glass [7], showing the CPW lines, actuator structure and the anchor region. The switch is basically a single-pole-single-throw (SPST) MEMS switch, intended to operate effectively from DC to X-band.

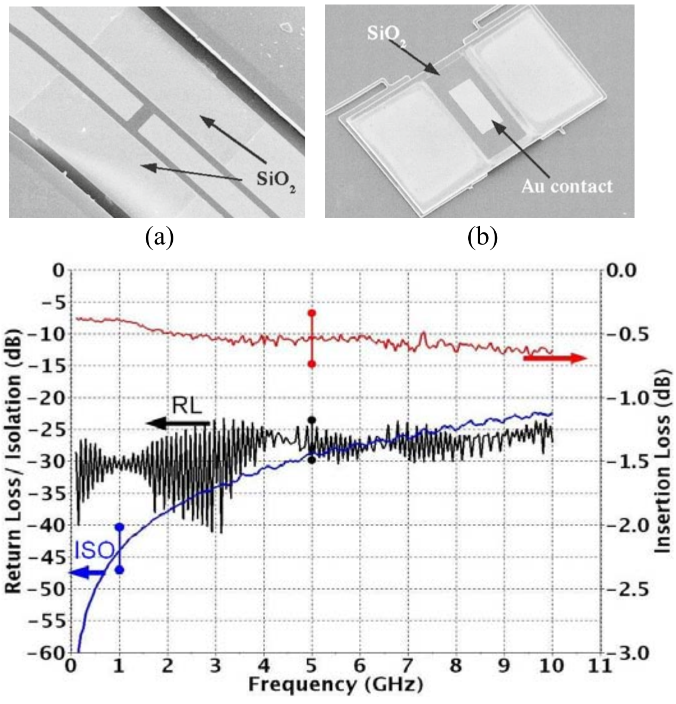

Fig. 2. SEM images of a typical fabricated device [1] (a) CPW lines with the gap in the signal lines (b) Actuator structure (flipped over) (c) Measured S-parameters at die-level.

A. *Device Working Principle and Fabrication*

The present RF-MEMS switch comprises of a monolithically etched single crystalline silicon actuator anodically bonded to a glass substrate. The glass substrate is patterned with coplanar waveguide (CPW) transmission lines. The two ends of the CPW lines are RF ports of the switch. The actuator is suspended by four beams over a gap in the signal line passing beneath it. The beams used in this device are called the *crableg* beams [7], made up of four segments (the close-up view of the actuator structure where the crableg suspension beams can be seen in Fig. 1).

Fig. 2 shows typical scanning electron microscope (SEM) images of a switch and its die level performance. In Fig. 2(a), the gap in the signal line is visible after detaching the actuator structure, where the sputtered SiO_2 isolation layers on the CPW ground lines can also be seen. A sputtered gold contact pad is patterned on the actuator directly above the gap. Fig. 2(b) shows the actuator structure, detached and flipped over, to show the Au contact region patterned over the thermally grown SiO_2 isolation layer. The contact pad is electrically isolated from the actuator by a layer SiO_2 on the silicon wafer. On either side of the central contact region, there are two drive capacitor plates. The CPW ground lines passing below the drive capacitor plates act as pull in electrodes. The insulating SiO_2 layer, deposited on the CPW ground sections overlapping with the drive capacitor plates, prevents direct electrical contact between the actuator and the pull in electrodes.

When a voltage exceeding the pull in voltage (V_p) is applied across the actuator and the pull in electrodes, the actuator snaps down on the CPW lines. In this position, the contact

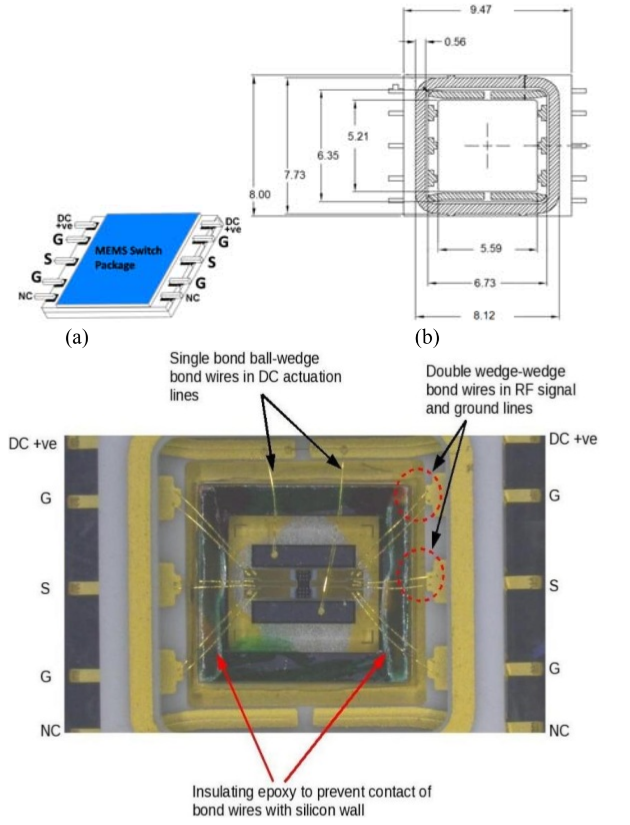

Fig. 3 Surface mount package for the RF-MEMS switch (a) 10 pin package with lid (b) typical dimensions and (c) Packaged RF-MEMS switch with bond wires [7].

region bridges the gap in the signal line, thereby connecting the two ports of the device. This represents the on state. When the applied voltage is removed, the restoring forces developed in the elastically deformed crableg beams, pull the actuator away from the substrate, and the ports are thus isolated taking the device into its off state.

The important process steps and the fabrication process flow are described in [7]. The central signal line of the CPW has width of 96 µm and the spacing between the ground and signal line is 18 µm. The gap in the signal line is 40 µm wide. The typical dimensions that determine the pull in voltage of the fabricated structure are given in [7]. The die level performance of the RF-MEMS switch from DC to 12 GHz using probe station is shown in Fig. 2(c).

B. *Assembly and Packaging*

Figs. 3(a) and (b) show the SMX package, which is basically a 10-lead design with 6 RF and 4 DC pins, incorporates a copper-composite base and Fe-Ni-Co lead frame attached to an alumina ceramic ring frame (base is about 8.0 mm × 8.0 mm). The RF MEMS switch die was bonded into the package using conductive/non-conductive epoxy. Conventional wedge bonding is recommended for optimal chip performance. Fig. 3(c) shows the photograph of the RF MEMS switch die placed into the SMX package. Single ball-wedge bond wires were used in DC actuation lines. Interconnections between package

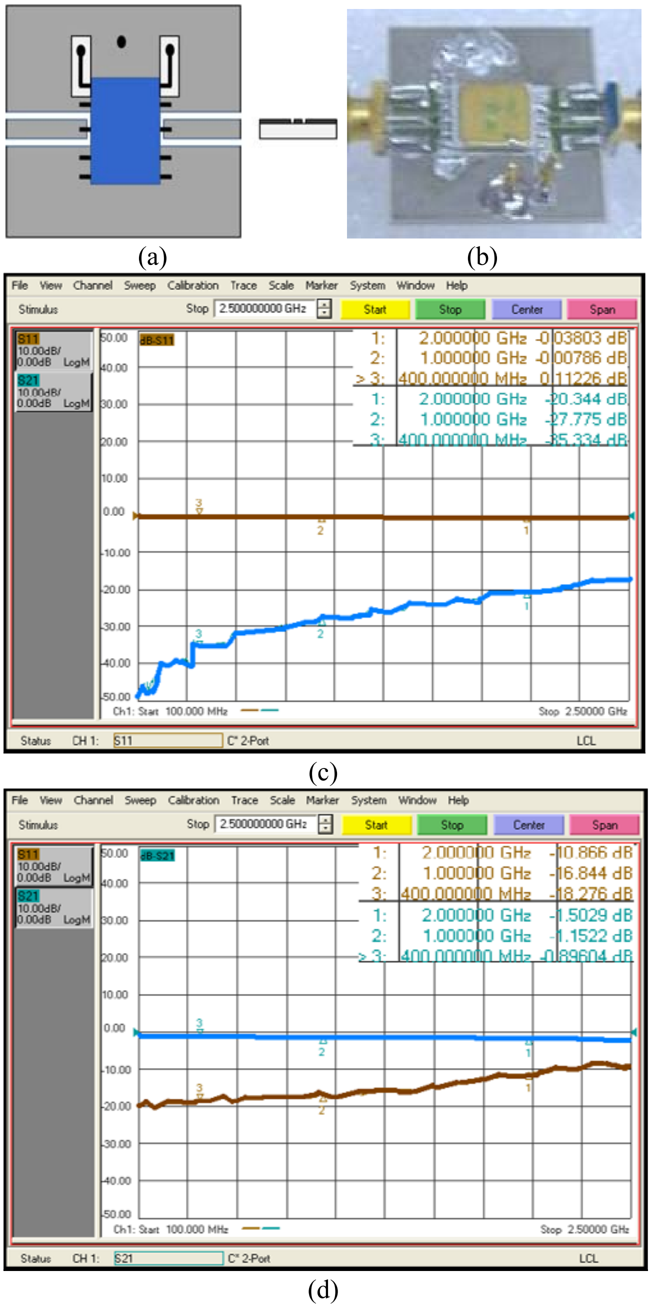

Fig. 4 CPW design (25 mil Alumina) for the packaged RF-MEMS switch (a) layout (b) photograph. Measured S-parameters: (c) *OFF* state (d) *ON* state for an actuation voltage of about 40V.

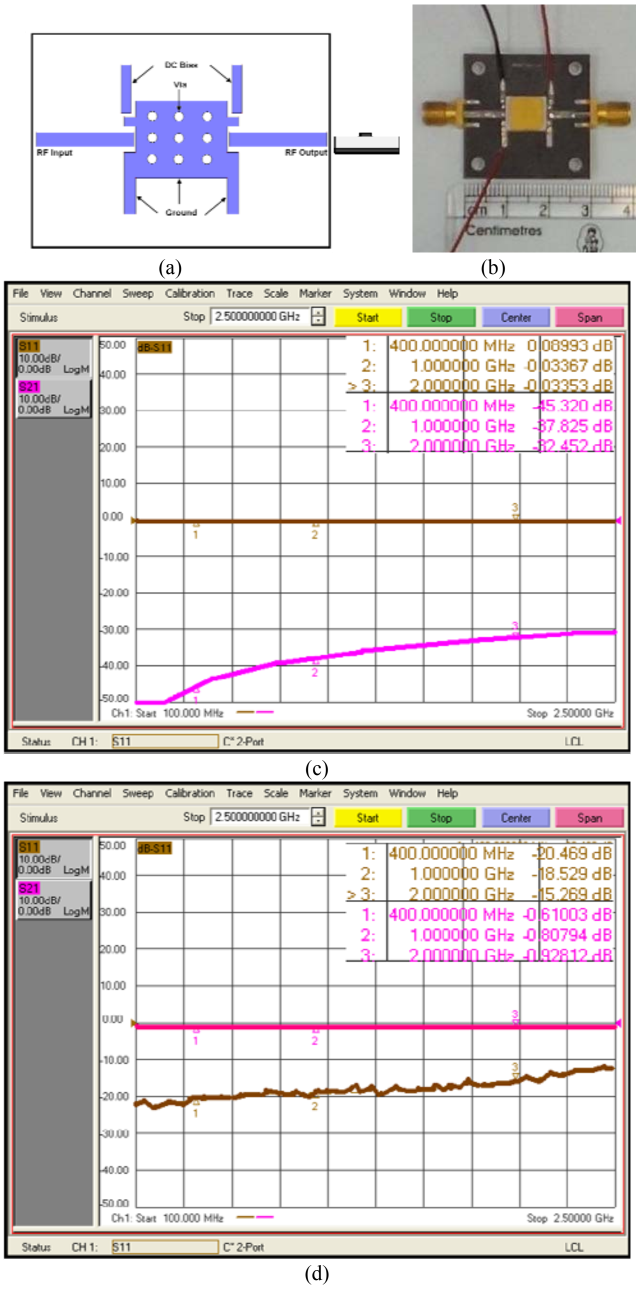

Fig. 5 Microstrip design (20 mil RT/Duroid 5880) for the packaged RF-MEMS switch (a) layout (b) photograph. Measured S-parameters: (c) *OFF* state (d) *ON* state for an actuation voltage of 40V.

pins and switch were provided through 1 mil diameter wedge-wedge wire-bonding, with two wires per connection, to minimize the inductance. The maximum optimal length of the bond wires was about 1 mm, which is a critical parameter factor affecting RF performance directly in addition to the minor package effects. The technique of hermetic sealing by flux less soldering was developed and employed for this package [7].

III. RF CHARACTERIZATION OF MEMS SWITCH

Two PCB configurations based on CPW and Microstrip technologies, are designed and fabricated (shown in Fig. 4(a) and Fig. 5(a) respectively) for mounting the RF MEMS switch package and to measure the board-level RF performance. Two high frequency low loss substrates with high and low dielectric constants (ε_r), are selected for implementation and are Alumina (ε_r = 10.2, thickness h = 25 mil and $tan\delta$ = 0.0002) and RT/Duroid 5880 (ε_r = 2.2, thickness h = 20 mil and $tan\delta$ = 0.0009), respectively. Measurements have been performed using Agilent's Vector Network Analyzer (VNA). In both cases, the responses are shown over a frequency range where the insertion (return loss) is better than 1.5 dB (10 dB) for which the MEMS switch exhibits a fair response from DC to 2.5 GHz compared to that of the die level. This can be attributed to the 1.0 mm long wire bonds used in the package for interconnections.

Using CPW Design

As the CPW transmission lines consist of a signal line and two ground planes on one side, thereby requiring no short circuit via holes for grounding purposes, the Alumina substrate is selected for this implementation. Fig. 4(a) shows the layout for mounting the package facilitating RF signal and DC paths. The fabricated PCB with mounted MEMS switch package is shown in Fig. 4(b). The package pins are soldered appropriately as per Fig. 3 and PCB mountable SMA connectors are used for connecting the board to VNA. The packaged switch exhibits good RF performance in the frequency range from 0.1 GHz to 2.5 GHz and the measured *S*-parameter responses, in *OFF* and *ON* states, are shown in Figs. 4(c) and (d), respectively. The measured isolation is better than -20 dB from 0.1 GHz to 2.25 GHz. The switch starts actuation for a DC bias voltage of 40V. The measured on-state insertion loss (including connector loss) is better than 1.0 dB (1.5 dB) in UHF band (S-band), while the return loss is better than 15 dB (10 dB) up to 1.5 GHz (2.0 GHz).

Using Microstrip Design

For performance validation, another PCB is implemented in microstrip form on low dielectric constant RT/Duroid 5880 board. Fig. 5(a) shows the layout for the package mounting facilitating RF signal and DC paths. Here, short circuit via-holes are required for grounding purposes. As the outer body of the package is served as ground, major portion of the layout is grounded as seen in Fig. 5(a), where the effective grounding is obtained by drilling a sequence of nine plate-through (vias) holes. Fig. 5(b) shows the fabricated PCB with mounted MEMS switch package and the corresponding measured S-parameters are shown in Fig. 5(c) and (d) for the switch in *OFF* and *ON* states, respectively. Here, the switch performance is improved when compared to the performance on CPW boards. The switch exhibits excellent off-state isolation that is better than 30 dB, while the on-state insertion loss is better than 1.0 dB throughout the frequency range from 0.1 GHz to 2.5 GHz. The measured return loss in on-state is better than 20 dB (15 dB) up to 0.5 GHz (2.0 GHz).

Table I compares the on-board performance of the packaged RF-MEMS switch on CPW and microstrip designs. It is observed that the switch exhibits superior performance on the microstrip configuration, when compared to the performance on CPW board throughout the frequency range.

IV. CONCLUSION

On-board RF characterization of surface mount packaged RF-MEMS switch is presented using two planar configurations. PCB configurations, using high & low dielectric constants, were fabricated in CPW and microstrip configurations accommodating RF, DC paths and effective grounding. The packaged switch exhibits superior performance on microstrip configuration from 0.1 to 2.5 GHz is demonstrated.

TABLE I : RF PERFORMANCE COMPARISON: MEMS SWITCH USING CPW AND MICROSTRIP DESIGNS

Switch State	Parameter	Frequency (GHz)	Measured (dB)	
			CPW	Microstrip
OFF	**Isolation**	0.4	35.3	45.3
		1.0	27.7	37.8
		2.0	20.3	32.5
ON	**Insertion Loss**	0.4	0.9	0.61
		1.0	1.15	0.80
		2.0	1.5	0.92
	Return Loss	0.4	18.2	20.5
		1.0	16.8	18.5
		2.0	10.8	15.3

This enables the direct usage of the microstrip PCB patterns when the device is integrated in a system or for the use of SPDT and higher switch configurations (using several SPST switches).

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