Low-Cost Low Actuation Voltage Copper RF MEMS Switches

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***Abstract* — This paper presents the design, fabrication and testing of capacitive copper RF MEMS switches with various hinge geometries, fabricated on high-resistivity silicon substrate. The switches were fabricated using a simple low-cost four-mask process and 0.6-1.0μm thick membranes were made out of sputtered copper. The capacitive airgap in between the membrane and the signal line is 1.5-2.0μm. The lowest actuation voltage measured on the fabricated switches is 9V. The measured insertion loss of a fabricated switch and its associated transmission line was 0.9dB (mainly contributed by the transmission line itself) and the isolation was measured to be 25dB at 40GHz.**

I. Introduction

Low-cost MEMS switches are prime candidates to replace the conventional GaAs FET and p-i-n diode switches in RF and microwave communication systems, mainly due to their low insertion loss, good isolation, linear characteristic and low power consumption. Various designs of capacitive RF micromechanical switches made out of nickel [1], aluminum [2, 3] and gold [4] have been so far reported in literature. The need for low actuation voltage in MEMS switches (<15V) has often caused excessive design and fabrication complexity as well as increase in the size of the device [5].

This paper presents low actuation voltage surface-micromachined shunt coplanar waveguide (CPW) capacitive switches, with sputtered copper as the structural material for the switch and CPW lines, fabricated on high resistivity silicon substrate using low-temperature IC compatible processes for modular integration in a communication platform. The use of sputtered copper as the structural material has been investigated in this work with the motivation of using the copper metal layers in a CMOS process to fabricate the second generation of these relatively small size switches on CMOS wafers. Clamped-clamped (bridge-type) and clamped-free (cantilever-type) CPW switches with membrane size of 120μm×120μm and various hinge geometries (solid and meander shaped) were fabricated using a simple four-mask low-temperature process with dry release. The measured DC and microwave characteristics of a fabricated switch are reported here.

II. Mechanical Design

The actuation voltage of the micromechanical shunt switch (or the pull-in voltage of the membrane) can be calculated from the effective spring constant of the membrane support as:

$$V_{pull-in} = \sqrt{\frac{8K_z d^3}{27A\varepsilon_0}} \qquad (1)$$

where K_z is the effective spring constant of the membrane, d is the rest air-gap between the membrane and the signal line and A is the area of the membrane. When designing for low actuation voltage, choice of the membrane material and support design is critical. Increasing the area of the membrane leads to increase in the size of the device. Therefore, the stiffness of the support and the size of the air gap must be suitably chosen to reduce the actuation voltage of the switch while keeping the device size small.

For a given material, the spring constant of the membrane is reduced by using meander-shaped supports for air-bridge structures. The effective spring constant of a meander shaped structure (as shown in Fig. 1) in the z direction is given by [1]:

$$K_z = \frac{Ew\left(\frac{t}{L_c}\right)^3}{1+\frac{L_s}{L_c}\left(\left(\frac{L_s}{L_c}\right)^2 + 12\frac{1+\nu}{1+\left(\frac{w}{t}\right)^2}\right)} \qquad (2)$$

where E is the Young's modulus and ν is the Poisson's ratio. The spring constant of N such structures in series and parallel are respectively K_z/N and NK_z. The pull-in voltages calculated from the above considerations are summarized in the Table 1. The thickness of the copper membrane was assumed to be 1μm in all calculations and the Young's modulus of Cu was assumed to be 120 GPa. The size of the air-gap is 2μm and the effective area of the membrane is 120μm×120μm.

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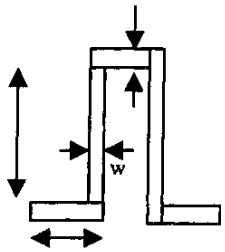

Fig. 1: Geometry of the meander-shaped support.

Table 1. Effective spring constant and actuation voltage for various hinge geometry CPW shunt switches.

Support type	K_{eff}(N/m)	$V_{pull\text{-}in}$ (V)
Solid Cantilever	16.7	17.8
4 Meander Bridge (2 on each side, 5μm wide hinge)	14.8	16.7
2 Meander Cantilever	7.4	11.5
2 Meander Bridge (with 2μm wide hinge)	1.75	5.7

III. Fabrication Process

The fabrication process flow for the CPW shunt switches is shown in Fig 2. The switches were fabricated on top of high resistivity silicon substrate (1000-5000 ohm-cm) with a 1μm thick isolation oxide layer. The CPW signal lines were fabricated by sputtering Ti/Cu/Ti (300Å/3000Å/300Å). A 2000Å thick PECVD silicon nitride was then deposited and patterned to form the dielectric layer between the membrane and the signal line. A 2.5μm thick photoresist (1827) was spin-coated and patterned to create the air-gap. The copper membrane with a thickness of 0.6-1.0μm was then sputtered and patterned. Holes that are 5μm in diameter were formed on the membrane to facilitate the release of the membrane and to reduce the damping for improved dynamic performance. In order to improve the step coverage of the photoresist during the patterning step of the membrane (to make the access holes and remove the unwanted copper), and also to improve the mechanical integrity of the membrane, copper posts can be electroplated before patterning the membrane (as shown in part c of Fig. 2). However, the step coverage can also be improved by using a thicker photoresist to pattern the membrane and therefore the use of the electroplated posts is not necessary. An alternative approach in fabricating these switches is to make the posts first and then fabricate the membrane using electron beam evaporation.

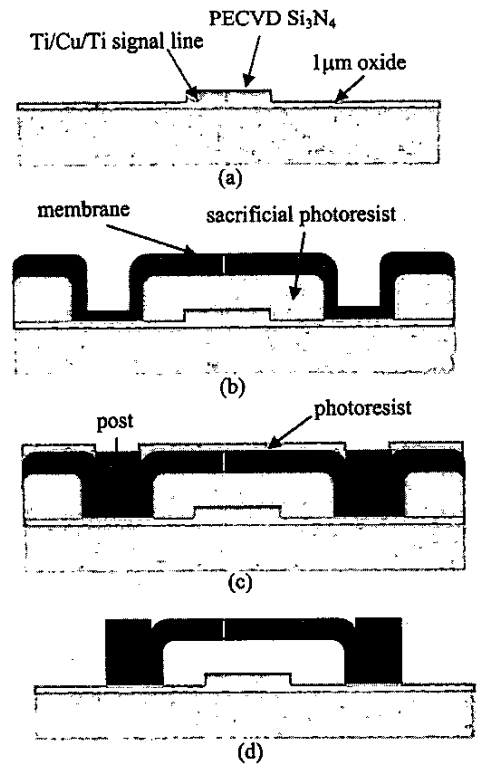

Fig. 2: Fabrication process flow for sputtered-Cu switch.

SEM pictures of the fabricated switches with various support designs and membrane thicknesses are shown in Figs. 3, 4, 5 and 6. Figure 3 shows a 1μm thick bridge type CPW switch with 4 meander-shaped supports. As it can be seen in the figure, no warping of the sputtered copper membrane was observed. The photoresist was removed using oxygen dry etch in RIE and therefore stiction of the membrane to the signal line during the release process was avoided. The power utilized in RIE during the release step was maintained at relatively low levels (100-150W) as the membrane was found to warp at higher RIE power levels. Figure 4 shows an alternative meander support (2-meander bridge) design with a lower actuation voltage. The gap between the membrane and the signal line is 2μm.

Figure 5 shows the close up of the support area for a solid cantilever switch structure with a 0.6μm thick copper membrane and 1.5-2μm air-gap. The holes in the membrane are 4-5μm in diameter. In this device, the post on the ground lines were electroplated after the Cu

membrane was sputtered. The support beams are mechanically well attached to the ground lines.

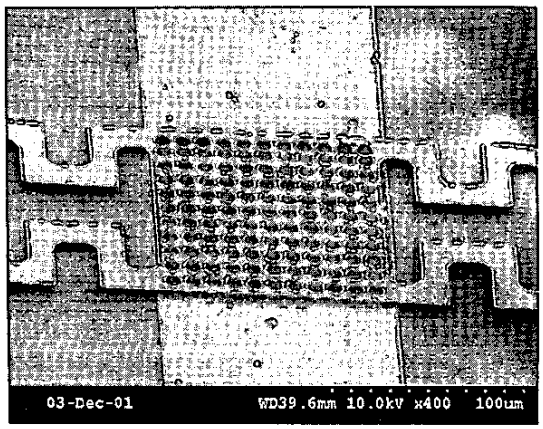

Fig. 3: SEM of a fabricated bridge-type CPW switch with 1μm thick Cu membrane and 4 meander-shaped supports. The size of the membrane is 120μm×120μm.

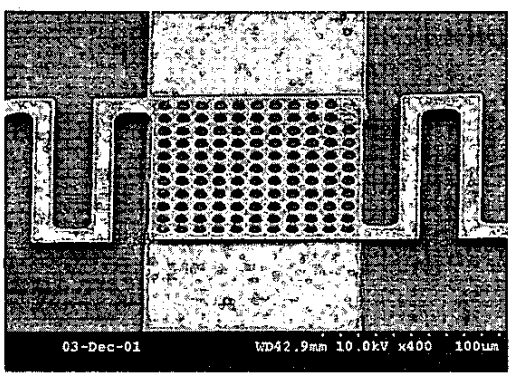

Fig. 4: SEM of a low actuation voltage meander-shaped support switch. The air-gap is 2μm.

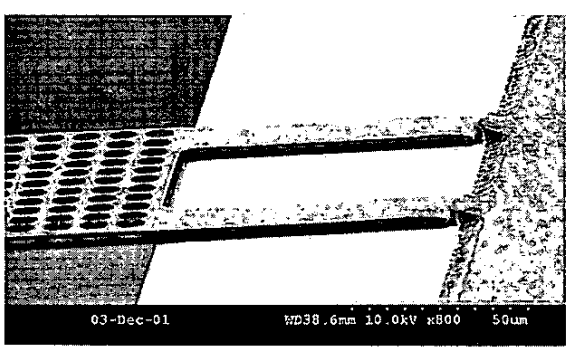

Fig. 5: The solid cantilever switch with 0.6μm membrane.

Figure 6 shows the SEM view of a cantilever type device in which the membrane was fabricated after the support posts were electroplated.

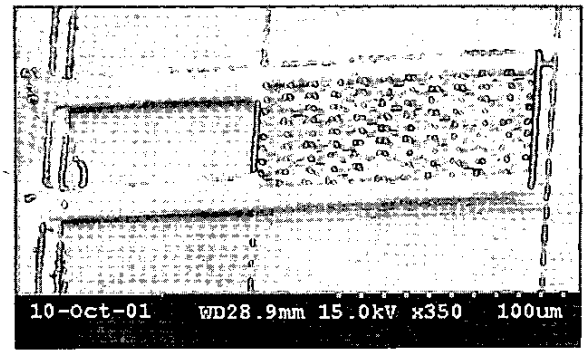

Fig. 6: SEM view of a switch with 1μm thick membrane fabricated after the ground posts were electroplated.

IV. Measurement Results

Actuation voltage of a prototype cantilever type switch with 2 meander-shaped supports was measured using an Agilent 4284A precision LCR meter. As plotted in Fig. 7, the actuation voltage was measured to be ~9V. It should be noted that the high value of the capacitance at the ON state is due to the misalignment of the membrane of this device with respect to the nitride dielectric layer, causing the edge of the membrane to come into contact with the signal line and hence creating a local short. The off capacitance of the switch is calculated and measured to be 50-70fF while the on capacitance is 4.5-5.0pF.

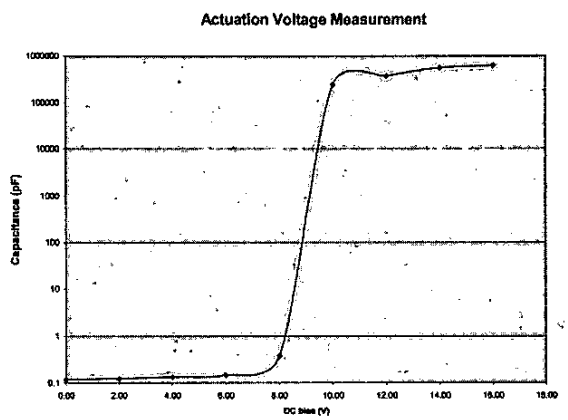

Fig. 7: DC Actuation voltage measurement results

The microwave performance of a prototype meander-shaped copper switch was measured with an Agilent 8510 vector network analyzer and a Cascade RF probe station. Cascade GSG microwave probes with a 200μm pitch were used to make the on-wafer measurements. An SOLT

calibration was performed first using an Alumina based substrate with specified planar standards. Due to the nature of the calibration, the reference planes of the measured s-parameters were located at the end of the probe tips. The probe tip-to-CPW transitions, as well as the coplanar line lengths up to the MEMS switch were not de-embedded from the measurements. The s-parameters of a 1400μm long coplanar line, identical to the one that hosts the MEMS switch were measured first and an average insertion loss of 0.8 dB was found (see Fig. 8). The insertion loss and return loss of the switch from 1 to 40 GHz in the OFF state are shown in Fig. 9. The return loss is higher than 15 dB over the entire measurement band, while the average loss is around 0.9 dB and is very close to the loss of the thru line only. It is therefore believed that the switch contributes a minimal amount of loss that needs to be measured with a TRL calibration technique. Therefore, the dominating loss mechanism in the measured insertion loss is the copper coplanar line. The s-parameters for the switch in the ON state are shown in Fig. 10. The switch isolation was measured to be 0.8dB at 1GHz and 25 dB at 40GHz, while the return loss has an average value of 0.7 dB above 20 GHz.

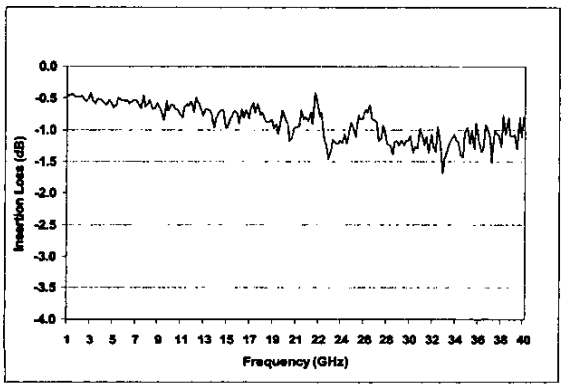

Fig. 8: Measured insertion loss of the thru line only.

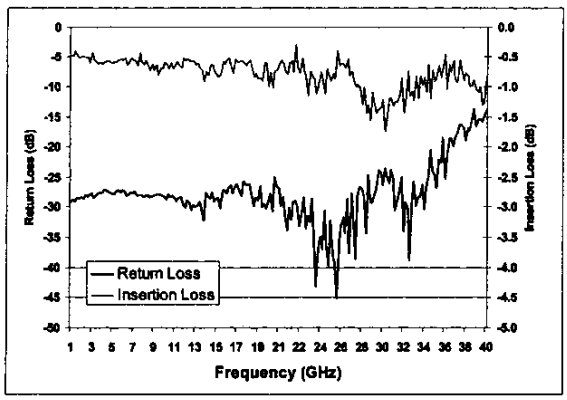

Fig. 9: Measured s-parameters for the switch in OFF state

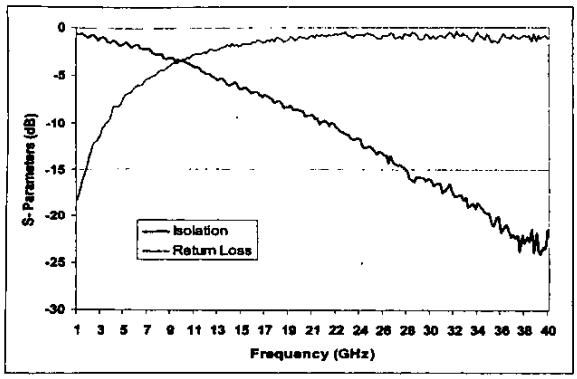

Fig. 10: Measured s-parameters for the switch in ON state

V. CONCLUSION

This paper presents the design, fabrication and testing of copper capacitive RF MEMS switches with various hinge geometries on high-resistivity silicon substrate. The switches were fabricated using a simple low cost four-mask process and 0.6-1.0μm thick membranes were made out of sputtered copper. The lowest actuation voltage measured on the fabricated switches is 9V. The measured insertion loss of a fabricated switch and its associated transmission line was 0.9dB and the isolation was measured to be 25dB at 40GHz.

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