Low Cost RF MEMS Switches Using Photodefinable Mixed Oxide Dielectrics

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Abstract — **This paper presents the design, fabrication and testing of capacitive RF MEMS switches with a new, low processing cost dielectric layer on high-resistivity silicon substrate. The dielectric can be spun on the wafer and its parameters (dielectric constant and loss) can be controlled during fabrication to achieve the desired values. Both bridge- and cantilever-type switches were fabricated on high-ρ silicon substrate using a simple low cost four-mask process. Measured results are presented.**

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], gold [4] and copper [5] have been so far reported in literature, with a variety of applications such as phase shifters, reconfigurable filters, tuners and other planar circuits. The structure of these switches consists of a lower electrode, a very thin dielectric layer and the moveable membrane. Several studies have shown the importance of the dielectric layer in the switch performance (Cmax/Cmin ratio, isolation) and reliability [6]. In most MEMS switches reported so far, this dielectric layer is typically silicon nitride deposited with PECVD or HDICP CVD techniques [7]. A switch that uses BST as the dielectric layer has also been reported [8]. Taking into account the higher cost associated with using CVD and sputtering techniques for fabrication, there is a need for lower cost switches based on cheaper dielectric layer fabrication techniques, while maintaining flexibility in the choice of the dielectric parameters (dielectric constant and loss).

This paper presents for the first time capacitive RF MEMS switches made with a very low fabrication cost mixed oxide dielectric layer, whose parameters can be easily controlled during fabrication to achieve the desired values. In this process, a photosensitive metal-organic precursor solution is cast onto the substrate (typically by spin coating). Upon UV exposure, the organic ligands of the precursor molecule are cleaved, resulting in the formation of an amorphous metal oxide. The remaining unexposed precursor material may be subsequently washed away by rinsing with a developer solvent [9] The photosensitivity of these materials allows one to selectively deposit metal oxide structures without requiring the deposition of blanket oxides via sputtering or other means and thus without using subtractive etches that are required to pattern such blanket films. Its dielectric constant (ε_r>20) is also much higher than that of silicon nitride that is typically used in capacitive switches. Clamped-clamped (bridge-type) and clamped-free (cantilever-type) coplanar waveguide (CPW) switches with a membrane size of 100μm×200μm and various hinge geometries (solid and meander shaped) were fabricated on high-resistivity silicon substrates using a simple four mask low-temperature process. The measured DC and microwave performance the cantilever switches for a given hinge geometry has been reported at this stage. Measurements of other types of devices are currently underway and more results will be reported at the time of full paper.

II. Mechanical Design

The pull-in voltage of MEMS switch can be calculated from the effective spring constant of the membrane support as:

$$V_{pull-in} = \sqrt{\frac{8K_{eff}\,g^3}{27A\varepsilon_0}} \quad (1)$$

where K_{eff} is the effective spring constant of the membrane, g is the initial gap between the switch and the bottom electrode, and *A* is the area of the membrane, ε_0 is the permittivity of air. When designing for low actuation voltage, choice of the membrane material and support design is critical. In order to lower the pull-in voltage of the structure, three different ways can be used [1]: (1) increasing the area of membrane (2) diminishing the gap between the switch and bottom electrode, and (3) designing a structure with low spring constant. In the first case, the area can only be increased by so much before device size becomes a prevailing issue. In the second case, the return loss associated with the RF signal restricts the value of the gap. The third case is the one with the most flexibility, since the design of the springs does not considerably impact the size, weight, and/or RF performance of the circuit.

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) is given by [1]:

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

where E and ν are the Young's modulus and the Poisson's ratio, respectively. The spring constant of N such structures in series and parallel are respectively K_{eff}/N and NK_{eff}. For switches that use gold for the cantilever material the expected pull-in voltages are in the range of 10-30 V.

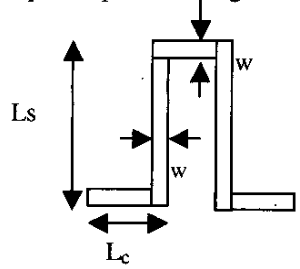

Fig. 1: Geometry of the meander-shaped support

III. Fabrication Process

The fabrication process flow for the CPW shunt switches is shown in Fig 2. The switches are fabricated on top of high resistivity silicon substrate (3000-5000 ohm-cm) with a 1μm thick isolation oxide layer. The CPW signal lines were fabricated by evaporating Ti/Au/Ti (400Å/5000Å/400 Å). A photosensitive precursor solution composed of a mixture of the metal-organic precursors for barium and titanium, was deposited by spin coating and patterned with standard DUV photolithography to form the mixed-oxide dielectric layer (ε_r~25) between the membrane and the signal line. The unexposed precursor was then washed away by rinsing with developer solvent. The dielectric was then hardbaked to a thickness of 1,400 Å. A 2 μm thick photoresist (1813) was spin coated and patterned to create the air-gap. Ti/Au/Ti (400Å/3000 Å/300 Å) seed layer was then evaporated and patterned and electroplated. Finally, after removing the sacrificial photoresist layer with a resist stripper, a critical point drying process was used to release the switches.

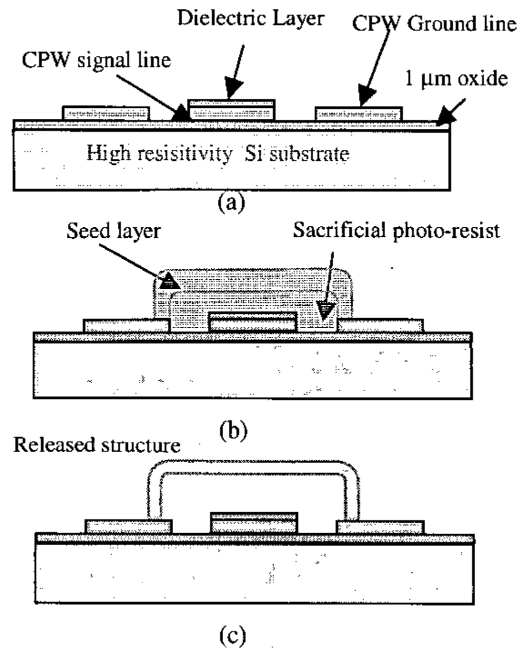

Fig. 2: The switch fabrication process flow

SEM pictures of the fabricated switches with various support design and membrane thicknesses are shown in Figs. 3 thru 5. Figure 3 and 4 shows air-bridge type CPW switch with different meander-shaped support. The photoresist was removed using photoresist stripper for overnight. Fig. 5 shows a solid cantilever switch structure with a 1.2 μm thick gold membrane, a 1.8μm air-gap and a membrane size of 90x100 μm. For comparison purposes, the same switch designs were fabricated using silicon nitride instead of the mixed oxide dielectric.

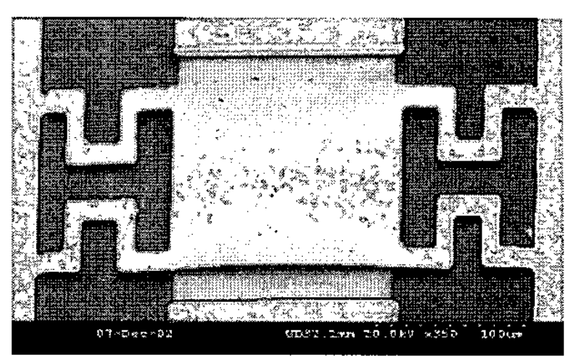

Fig. 3: SEM of a fabricated airbridge type CPW switch with 1.2μm thick Au membrane and meander-shaped support. The size of the membrane is 100μm×200μm.

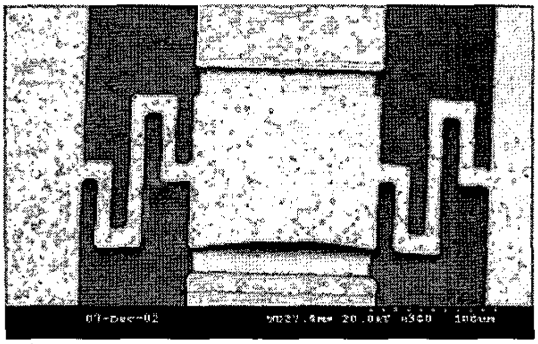

Fig. 4: SEM of a low actuation voltage meander-shaped support switch. The airgap is 1.8μm thick.

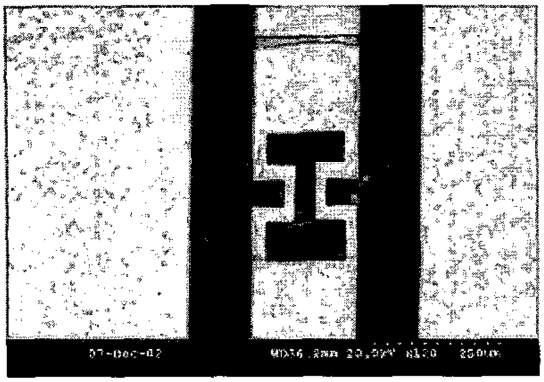

Fig. 5: *SEM* view of a cantilever switch with 1.2 μm thick membrane.

IV. Measurement Results

Measurements of the meander-shaped cantilever type switch (Fig. 5) were taken using an Agilent 8510 network analyzer. A TRL calibration was performed to de-embed the coplanar line and transition losses. The measured results were also curve-fitted with Agilent-ADS in order to extract the switch model. The model is a series combination of a capacitor, a resistor and an inductor. Measured results for the nitride switches are shown in Figs. 6-7. The pull-in voltage was measured to be 20 V. When the switch is activated, the insertion loss is around 0.4 dB at 20 GHz and C_{ON}=0.5 pF, while the return loss is around 17.3 dB at 20 GHz. When the switch is in the UP position, the isolation is around 6.5 dB at 20 GHz and C_{OFF}=45 fF. The deteriorated isolation is due to the thinner sacrificial layer (1.5 μm vs. 1.8 μm) that increases the capacitance. The measured results for the cantilever switch with the mixed oxide-dielectric can be seen in Figs. 8-9. In the up-state the isolation is 14.7 dB at 20 GHz and C_{OFF}=15 fF. The pull-in voltage was measured to be 25 V. The lower C_{OFF} is attributed to a higher sacrificial layer. For the ON-state, the loss is 0.1 dB at 20 GHz, while C_{ON} is around 4 pF. All cantilever switches

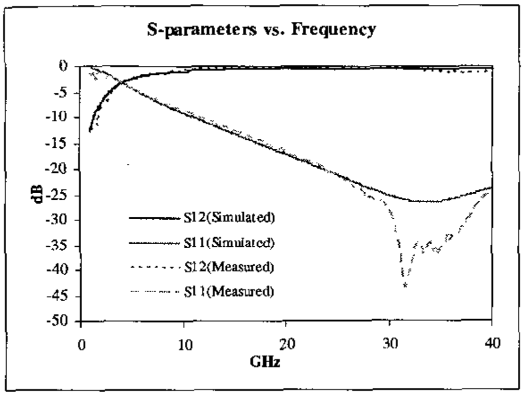

Fig. 6: Measured and Simulated s-parameters for the Cantilever switch with SiN as dielectric in ON state

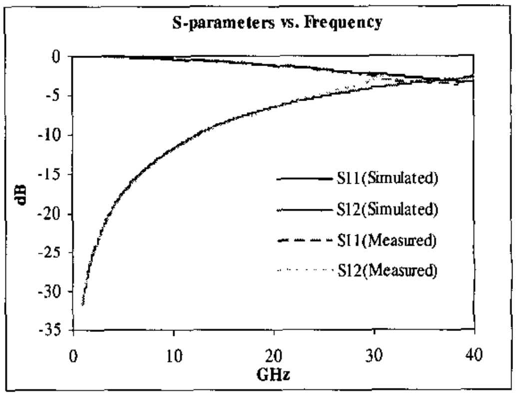

Fig. 7: Measured and simulated s-parameters for the Cantilever switch with SiN as dielectric layer in OFF state

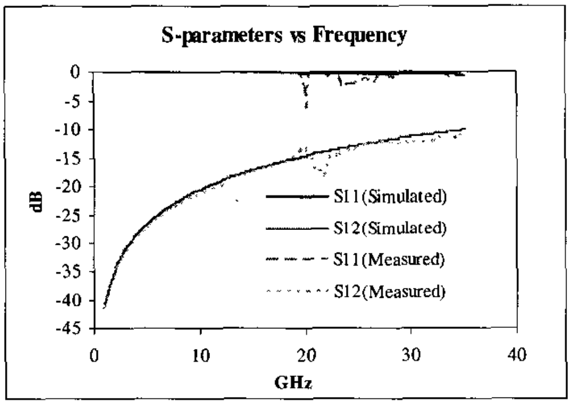

Fig. 8: Measured and simulated s-parameters for the cantilever switch with metal-oxide as dielectric layer in the OFF state

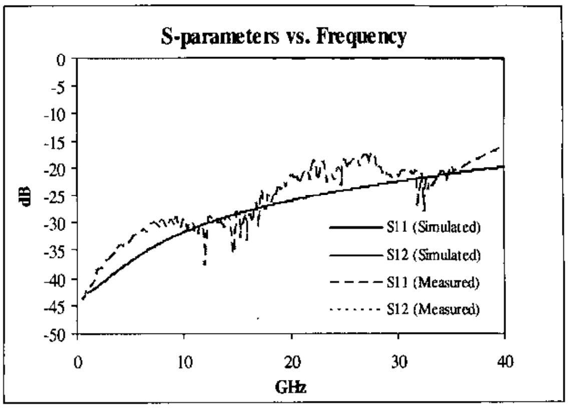

Fig. 9: Measured and simulated s-parameters for the Cantilever switch with metal-oxide as dielectric layer in the ON state.

have a series resistance of Rs=0.35 Ω. Because the material process was not optimized for the given pull-in voltage, a breakdown effect was observed with the material that resulted in a conductive dielectric for the activated switch with the metal-oxide. This breakdown effect is currently under investigation. The additional conductive path in the switch behavior is taken into account in the ADS model as a very small resistor (0.1 Ω) in parallel with the capacitor. Due to this extra conductivity, the insertion loss is extremely small at the lower frequencies and is also better than the case of the nitride. In addition, the mixed-oxide dielectric results in a C_{ON} which is approximately 8 times greater than that of the nitride. This ratio compares well with the ratio of the dielectric constants (25/3.5=7.15), showing that this technique can be a low-cost/enhanced performance alternative to the more expensive nitride deposition and etching techniques. Another fabrication run is currently under way and more results will be presented at the conference.

V. CONCLUSION

This paper presents for the first time the design, fabrication and testing of low cost capacitive RF MEMS switches that use a photodefinable amorphous metal oxide as the dielectric layer. Cantilever type switches with both nitride and the metal oxide dielectric have been developed so far for comparison purposes. Results indicate that the metal oxide dielectric indeed provides a higher capacitance in the ON state that agrees well with the dielectric constant ratio of the two materials. It is expected that this technique will lead to lower RF MEMS switch production costs, when compared to the PECVD and other plasma techniques used so far. More results will be presented at the conference.

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