A MEMS Shunt Switch on a Dielectric Membrane

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Abstract **— This paper proposes a MEMS capacitance shunt switch based on a microwave transition from a coplanar waveguide on a dielectric membrane to a coplanar waveguide on silicon. Finite element electromagnetic simulations with HFSS show a maximum insertion loss of 1.25 dB and a maximum isolation of 60 dB for the MEMS switch.**

I. INTRODUCTION

Bulk and surface micromachining methods are used with integrated circuit fabrication processes in forming microelectromechanical structures (MEMS). New materials and processes are often used in the design and fabrication of MEMS devices and components. Microelectromechanical systems are finding increasing applications in RF, microwave and millimeter-wave circuits needed for wireless and satellite communications. Microelectromechanical switches are one of important components that are useful in controlling signals or power in high frequency circuits. Microelectromechanical switches of the series type and capacitive shunt type have been reported in literature [1]. A micromechanical capacitive shunt switch is a simple single-pole single-throw switch that uses either a thin film cantilever beam or a doubly supported thin film beam to open or close the switch. A typical MEMS capacitive shunt switch consists of input and output planar transmission line sections, and a separate control electrode to which a DC potential is applied to pull down the thin film cantilever beam or the thin film fixed-fixed beam. These MEMS switches use either microstrip or coplanar waveguide (cpw) transmission line sections. New types of planar transmission lines such as dielectric membrane coplanar waveguide and microshield line that are formed by micromachining processes have been reported [1,2]. These transmission lines have superior performance compared to coplanar waveguide transmission lines formed on bulk semiconductor substrates. In this paper we propose a low loss microwave transition circuit that consists of a coplanar waveguide printed on a dielectric membrane to a coplanar waveguide formed on high resistivity silicon. We also propose a new microelectromechanical capacitive shunt switch based on the microwave transition circuit. We present results from full wave simulations based on finite element method on this microwave transition circuit and the MEMS capacitive shunt switch based on the microwave transition circuit.

II. CPW ON A DIELECTRIC MEMBRANE

A micromachined coplanar waveguide formed using a CMOS foundry process has been reported in reference 2. The signal conductor strip and the two ground conductor strips of the coplanar waveguide were formed on a thin layer of silicon dioxide on a high resistivity silicon substrate. The signal and ground planes of the coplanar waveguide were covered by a second thin film layer of silicon dioxide. The silicon substrate below the signal and ground planes of the coplanar waveguide were removed by chemical etching. The coplanar waveguide on the dielectric thin film membrane showed remarkable improvements in its loss characteristics.

We consider here coplanar waveguides that can be formed on aluminum nitride thin film membranes. Aluminum nitride thin films can be deposited on a silicon substrate by a KrF excimer ultraviolet laser inside a vacuum chamber. Aluminum nitride is a wide band gap electronic material with high thermal conductivity and a high value of 8.8 for its relative permittivity. Aluminum nitride thin films have superior physical properties and they are valuable for making microwave and RF MEMS devices that can be used at higher power levels. A coplanar waveguide formed on a suspended aluminum nitride film on a silicon substrate obtained by chemical etching can handle higher power levels of RF and microwave signals than a similar coplanar waveguide formed by standard CMOS foundry processes [2].

We present here the expressions we used to design cpw transmission line on a suspended aluminum nitride thin film from an etched silicon substrate. These expressions were deduced from conformal mapping calculations on multilayered coplanar waveguides reported in reference 3. An accurate expression for the effective dielectric constant of this cpw transmission line is not presented in reference 2. The characteristic impedance Z_0 of the cpw printed on a suspended dielectric thin film membrane was calculated using the expression given below:

$$Z_0 = (30\,\pi / \sqrt{\varepsilon_{r,eff}})\;[\;K(k_0') \;/\; K(k_0)\;] \qquad (1)$$

Here $\varepsilon_{r,eff}$ is the effective relative permittivity of the dielectric thin film on which the signal and ground plane of the cpw were formed and the following equation is used to calculate its value:

$$\varepsilon_{r,eff} = 1.0 + q_1 (\varepsilon_{r1} - 1) + q_2 (\varepsilon_{r2} - 1) \quad (2)$$

Here ε_{r1} is the relative permittivity of the dielectric thin film membrane and ε_{r2} is the relative permittivity of the second dielectric thin film layer that covers the thin film signal and ground conductor planes of the cpw. The fill factors q_1 and q_2 in equation (2) were calculated using the following expressions:

$$q_1 = 2 [K(k_1) / K(k_1')] [K(k_0) / K(k_0')] \quad (3)$$

$$q_2 = 2 [K(k_2) / K(k_2')] [K(k_0) / K(k_0')] \quad (4)$$

$$k_0 = S / (S + 2 W) \quad (5)$$

$$k_1 = \sinh (\pi S / 4 h_1) / \sinh [\pi (S + 2W) / 4 h_1] \quad (6)$$

$$k_2 = \sinh (\pi S / 4 h_2) / \sinh [\pi (S + 2W) / 4 h_2] \quad (7)$$

$$k_i' = \sqrt{(1 - k_i^2)} \text{ where } i = 0, 1, 2. \quad (8)$$

Here h_1 is the thickness of first layer of dielectric thin film on which the signal and the two ground conductor planes of the cpw are formed and h_2 is the thickness of the second dielectric thin film layer that is formed on top of the signal and ground conductor planes of the cpw. Here S is the width of the signal conductor strip and W is the width of the gap or slot region between the signal and ground conductor planes of the cpw. The function $K(k_i)$ in equations (1), (3), and (4) are complete elliptic integrals of the first kind [3].

We used equations (1) to (8) to design a coplanar waveguide on an aluminum dielectric thin film membrane suspended from a high resistivity silicon (100) substrate. The characteristic impedance of this transmission line is 50 ohms. The thickness H of the silicon (100) wafer is 525 μm and the thickness h_1 of the first thin film layer of aluminum nitride is 2 μm. Our design calculations provided a value of S = 132 μm for the signal metal strip and a value of W = 12.49 μm for the width of the gap between the signal metal strip and a ground metal strip. We kept the width of each of the ground metal thin film layer at 671.5 μm in our calculations. We assumed that the signal and ground planes were formed with gold metal thin films of 1 μm thickness. The width of the first aluminum nitride thin film that is suspended from silicon substrate is 357 μm. The second aluminum nitride thin film material covers the two slot regions and the signal and ground metal planes of the cpw. The thickness of the second aluminum nitride thin film above the signal and ground metal planes is 0.05 μm. Thus the total thickness of second aluminum nitride in the two slot regions of the cpw is 1.05 μm. A 100 μm wide region of each of the ground metal planes is within the suspended region of aluminum nitride thin film and the rest of the 571.5 μm wide region of each of the ground metal planes is over the high resistivity silicon substrate.

III. A MICROWAVE TRANSITION CIRCUIT

In this section we propose a microwave circuit consisting of a transition from a coplanar waveguide printed on aluminum nitride thin film membrane to a coplanar waveguide printed on high resitivity silicon substrate. This microwave transition circuit is needed for integration of MEMS devices based on these micromachined cpw sections with other components of any microwave circuit and it is also useful for probe contacts of a wafer probe station during measurements with a vector network analyzer. The microwave transition circuit that we designed is different from the work reported in reference 2 and our design is similar to a microwave transition circuit reported by Giacomozzi and coworkers in reference 5. Our microwave transition circuit consists of a cpw section formed on suspended aluminum nitride thin film that is sandwiched between two conventional cpw sections formed on bulk high resistivity silicon wafer [5]. In our microwave transition circuit the ground planes are 671.5 μm wide and we kept the distance (S+2W) between the two ground planes of the three cpw sections constant. We kept the value of (S + 2W) as 156.98 μm. The length of the cpw section on suspended aluminum nitride thin film membrane is 1857 μm. This microwave transition circuit occupies a region of area of 1500 X 3000 μm on the high resistivity silicon (100) wafer. The suspended aluminum nitride thin film membrane is at the center of this silicon die and it covers an area of 357 X 1857 μm on the silicon die. Our design consists of removal of silicon (100) substrate over an area of 357 X 1857 μm by backside anisotropic wet chemical etching in a tetra methyl ammonium hydroxide (TMAH) solution. Anisotropic wet chemical etching will leave a slanting silicon wall over a region of width H tan (35.3°) = 371.72 μm on the silicon die [6].

We used Ansoft's Serenade microwave circuit design software to design the two cpw sections of length 200 μm on the bulk silicon portions on opposite sides of the die. The width S of the signal metal strip is 72.78 μm and the gap region width is 42.1 μm and the value of (S + 2W) = 156.98 μm for these two cpw sections on bulk silicon. The width of each of the ground metal strip is also 671.5 μm for these two cpw sections on bulk silicon.

In our design, we varied the width of the signal metal strip of the cpw over the two slanting silicon wall regions that are along the length side of the cpw transmission line. As mentioned earlier the slanting silicon walls result from anisotropic wet chemical etching in TMAH solution. The width S of the signal metal strip of cpw in this region varied from a value of 72.78 μm to a value of 122.69 μm. The width of the gap W also was varied such that the values of (S + 2W) were kept constant at a value of 156.98 μm. The ground conductor planes were 671.5 μm wide in these two regions on silicon die. We used Serenade circuit software in designing these two cpw sections on silicon substrate needed for the microwave transition circuit.

IV. FULL WAVE ANALYSIS OF TRANSITION

We implemented the geometry of the microwave transition circuit described in the previous section in Ansoft's High Frequency Structural Simulator (HFSS) [7]. We performed a full wave analysis based on the finite element method with HFSS on this microwave transition circuit over the frequency range of 0.5 to 40.5 GHz. The impedance and scattering parameters of the microwave transition circuit as a function of frequency were obtained from the HFSS simulations. The impedance values of this low loss microwave transition as a function of frequency are shown in Figure 1.

V. MEMS SWITCH ON TRANSITION CIRCUIT

We designed a microelectromechanical capacitive shunt switch that is based on the microwave transition circuit discussed above. Two thin film gold posts or anchors of 4 μm thickness and 20 X 200 μm sizes were kept in the center region of the silicon die. One of the gold anchors is on the edge of one of the ground metal strip of the middle cpw section of the microwave transition circuit. The second gold anchor is also 4 μm thickness and it is on the edge of the opposite side ground metal strip. The spacing between the two gold anchors is 157 μm. The two ends of a "fixed-fixed" gold metal beam of 197 μm length and 200 μm width (W_b) are supported by the two gold anchors. A DC potential can be applied to the signal metal strip of the microwave transition circuit to pull down the fixed-fixed gold beam and thus close the MEMS switch. The shunt capacitor of activated MEMS switch consists of the second aluminum nitride thin film layer that is sandwiched between the fixed-fixed gold beam and the center signal gold strip of the middle cpw section of the microwave transition. The capacitance of the actuated or closed MEMS shunt switch was calculated using the equation given below:

$$C_{on} = (\varepsilon_0 \varepsilon_{r1} A) / t_d \qquad (9)$$

In this equation the area of capacitor plates is $A = W_b S$ and t_d is the thickness of second layer of aluminum nitride on top of the signal metal strip and $t_d = 0.05$ μm. We obtain a value 41.1 pF for C_{on}. The capacitance value of unactuated or open MEMS switch can be calculated using the expression below:

$$C_{off} = (\varepsilon_0 \varepsilon_{r1} A) / [\varepsilon_{r1} g_0 + t_d] \qquad (10)$$

Here g_0 is the gap between the doubly supported gold beam and the top of the second aluminum nitride thin film when the MEMS switch is not activated and it has a value of 4 μm. The capacitance of the unactuated MEMS switch C_{off} was found to be 5.83 fF [8].

VI. FULL WAVE ANALYSIS OF MEMS SWITCH

We implemented the geometries of the activated and unactuated MEMS capacitance shunt switch in Ansoft's HFSS. We performed finite element electromagnetic calculations on an open MEMS switch and a closed MEMS switch over the frequency range of 0.5 to 40.5 GHz. The scattering parameters of a closed switch is shown in Figure 2. The scattering parameters of an open switch are shown in Figure 3. The insertion loss of the MEMS switch in the off-state falls steadily from a value of 0.11 dB at 0.5 GHz to a value of -0.86 dB at 30 GHz. The isolation of the activated MEMS switch drastically varies from a value of 10 dB at 0.5 GHz to a value of 60 dB at 30 GHz. The isolation of closed switch shows a dip at 30 GHz and its value at 40 GHz is 50 dB.

VII. CONCULSIONS

We have presented a new microelectromechanical capacitance shunt switch that is formed on cpw supported by an aluminum nitride dielectric thin film membrane suspended from a high resistivity silicon (100) die. The value of isolation of the capacitive MEMS shunt switch presented here is better than the values of isolation reported for other capacitive shunt switches in literature [1]. The finite element electromagnetic simulations with Ansoft's HFSS software show that the overall expected performance of the proposed MEMS capacitive shunt switch will be excellent over a wide range of frequencies.

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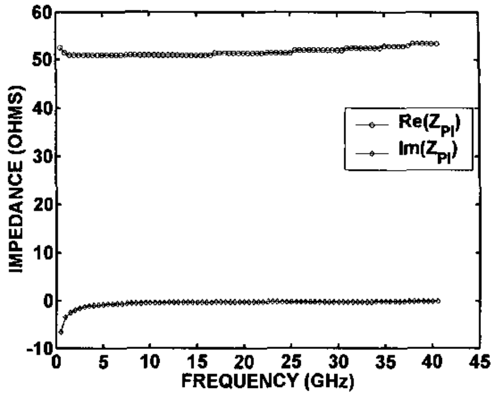

Figure1. Impedance of a Si cpw–membrane cpw– Si cpw transition.

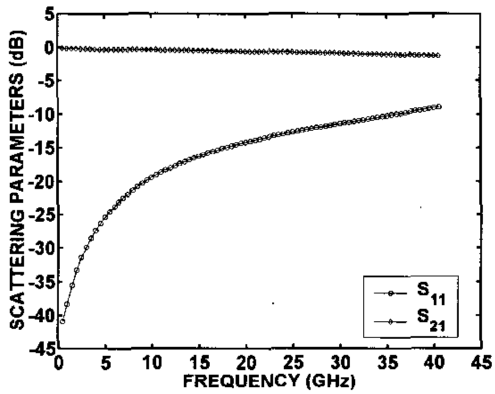

Figure 2. Insertion loss and return loss for an unactuated MEMS switch.

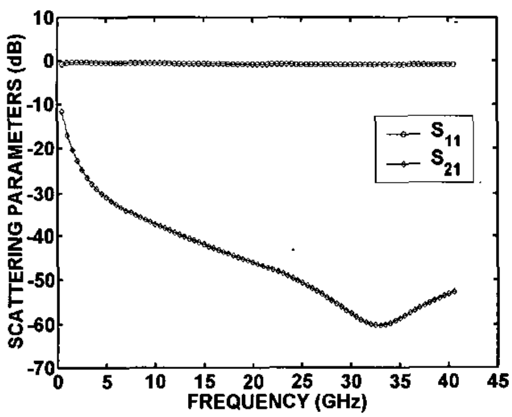

Figure 3. Insertion loss and return loss of an actuated MEMS switch.