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Toggle-Switch - A new type of RF MEMS switch for power applications

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***Abstract* — A new type of RF MEMS switch for power applications using a push-pull concept is described. The switching element consist of a cantilever which is fixed by a suspension spring to the ground of the coplanar lines. The switching voltages are 30V to close and 35V to open. The switches exhibit low loss (<0.2dB@27GHz) with good isolation (20dB@27GHz).**

I. INRODUCTION

Over the past several years, developments in Micro-Electro-Mechanical systems (MEMS) have promoted exciting advancements in the field of microwave switching. Micromechanical switches were first demonstrated in 1971 [1] as electrostatically actuated cantilever switches used to switch low-frequency electrical signals. Since then, these switches have demonstrated useful performance at microwave frequencies. Different switch topologies have been investigated and tested [2, 3, 4]. Most of them use electrostatic actuation. The advantage of using MEMS over conventional solid state switching devices such as FETs or p-i-n diodes is their low loss performance, low power consumption and lack of measurable intermodulation distortion. There are five main challenging aspects for RF MEMS switches: lowering the actuation voltage, increasing the switching speed, increasing power handling capabilities, improving lifetime and reliability. For lowering the switching speed meander spring suspension [5] and push-pull concepts have been investigated [6]. Increasing the switching speed and the power handling capabilities are still a problem. DaimlerChrysler has developed capacitive RF shunt switches with gold metallization lines and gold membranes [7]. Using these capacitive RF shunt switches 180° phase shifter has been realized [8]. DaimlerChrysler is now developing RF MEMS switches for high RF power application [9]. For this, new switching concepts are evaluated.

II. THE NEW SWITCH CONCEPT

The proposed concept is a so called "Toggle switch" (Fig. 1). The Toggle-Switch consists of a cantilever which is fixed by a suspension spring to the neighbouring coplanar ground lines. The suspension spring is build of silicone Nitride which isolates the cantilever against the ground.

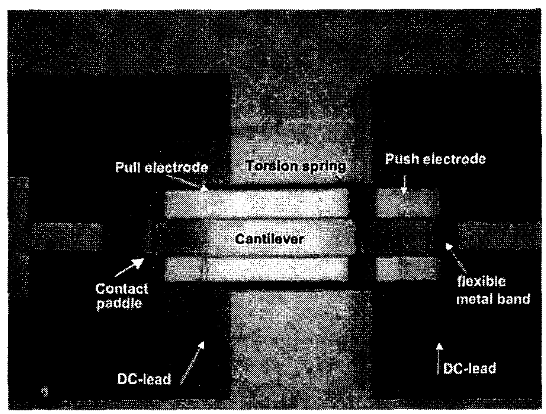

Fig. 1: Photo of the Toggle switch (closed position)

Thin electrodes on the substrate allow the switching of the cantilever using a push pull concept. As in this case no static voltages are needed on the signal line for switching, the cantilever can contact directly, without a dielectric between (ohmic contact), the inner conductor of the coplanar line. A flexible metal band builds the contact on the other side of the cantilever. This allows, in closed position of the switch, a transmission starting at DC and builds on the other hand an ideal open for DC in the open position of the switch. Due to this a large bandwidth of operation can be achieved. This is a great advantage compared to the well known Shunt-Air-Bridge switches [7] where only a capacitive shunt connection can be achieved. This capacitance limits the lowest frequency range of usage if a certain isolation must be obtained.

III. MECHANICAL SIMULATION

Mechanical simulations for this switch structure are performed. The mechanical design was optimized for a low actuation voltage and a good isolation in the off-state. From the mechanical point of view the toggle switch consists of a torsion spring which sustains the cantilever and divides it in a shorter and longer lever, a contact pad and two driving electrodes, the pull electrode to close the contact and the push electrode to lift the toggle tip out of the wafer plane (Fig. 2).

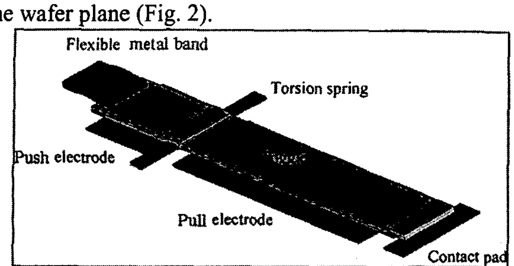

Fig. 2: Schematic view on the Toggle switch

Approximately, the toggle lever can be assumed as rigid. In static case the driving moment M_t must be in equilibrium to the reacting spring torque M_r:

$$M_t = \int_{l_l}^{l_u} \frac{\varepsilon V^2 x W}{2(g - x\varphi)^2} dx \approx \frac{\varepsilon V^2 (l_u^2 - l_l^2) W}{4 g^2} \quad (1)$$

$$M_r = \left(\frac{2}{3} \frac{G h_S^3 w_S}{l_S} + \frac{E_B h_B^3 w_B r^2}{l_B^3} \right) \varphi \quad (2)$$

where G is the shear modulus of Si_xN_y, E_B the Young's modulus of Au, ε the permitivity in air, h, w, l the spring (Index S) and metal band dimensions (Index B), W the toggle width, l_u and l_l the upper and lower electrode distance radial to the torsion axis, r the distance between metal band and torsion axis, g the initial electrode gap, V the applied voltage and φ the resulting torsion angle.

Generally, movable structures driven by electrostatic forces can only be displaced up to a characteristic limit which is called *pull-in*. If the applied voltage is increased beyond V_{PI} the toggle snaps to the fixed electrode (Fig. 3). This instability occurs if the first derivative of the applied voltage with respect to the tilt angle is equal or below zero.

Finite element simulations were performed to consider the true flexibility of all mechanical components, to regard for non-linearities caused by film stress and to consider different levels of manufacturing tolerances. The voltage deflection function of Fig. 3 for example is strongly influenced by the initial position of the cantilever which may be affected by the stress gradient.

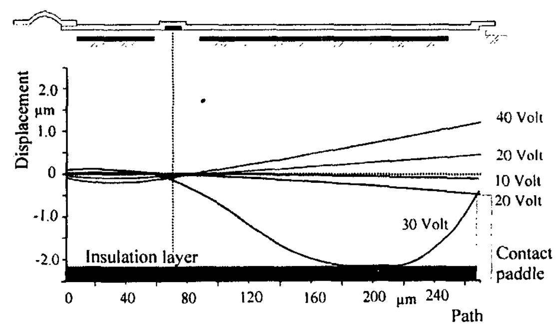

Fig 3: Displacement functions at different driving voltages

In addition to functional parameter the fracture strength and fatigue behaviour were assessed based on the results of finite element simulations [10]. Fig. 4 shows the stress distribution at the highest possible tilt angle at the rear part of the Toggle switch. Von Mises equivalent stress is about 12 MPa and consequently much lower than the yield strength of Si_xN_y (<120 MPa).

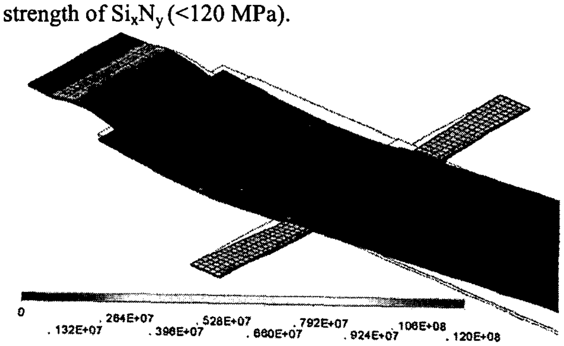

Fig. 4: Simulated stress distribution at the displaced microstructure (Units are Pa)

IV. ELECTROMAGNETIC SIMULATION AND DESIGN

The Toggle-Switch is used in a 50Ω coplanar line environment where the Toggle is used to build an open in the center conductor. In closed position the signal is routed via the direct metal contact to the cantilever and via the flexible metal band back to the center conductor of the coplanar line. The cantilever builds due to the small distance of about 3µm to the grounded DC switching electrodes a capacitance which must be compensated to achieve a good performance. The compensation is done with two inductive coplanar lines at both sides of the Toggle-Switch (see Fig. 5). The 3D FDTD field simulator Empire™ [11] has been used to simulate and optimize the Toggle-Switch. A compensation line with a width of 32µm and a length of 120µm on the left side of the switch and a line with the width of 32µm and a length of 100µm on the right side was found as optimal solution.

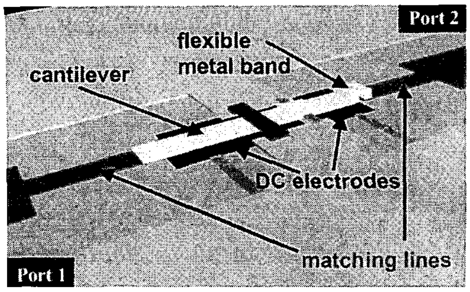

Fig. 5: Simulation model of the Toggle-Switch

The simulation results of the optimized structure in Fig. 6 show that with this matching technique the return loss is above 15dB up to 34GHz while the insertion loss is below 0.1dB. Due to the optimization the operating frequency range, if a match of 15dB for the return loss is assumed, was increased approximately 9GHz.

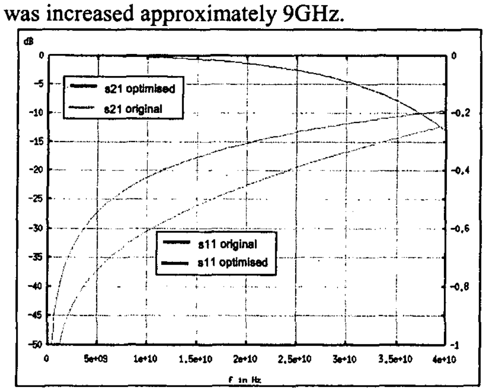

Fig. 6: Simulation results of the Toggle-Switch.

V. FABRICATION PROCESS

The Toggle-Switch is fabricated on high-resistivity silicon wafers (ρ > 4000Ωcm) with a wafer thickness of 525 μm. First, resistor layer is defined by a lift-off process. A WSi_2N_4 – layer with a high resistivity (layer resistivity = 500 Ωcm) is used. The resistivity value can be adjusted with the nitride concentration in the layer and with the deposition process parameter. After that, the lower electrode (underpass metallization) is defined by a lift-off process with 50nm Ti and 300nm Au. Then, the lower electrode is isolated by a 100nm thick PECVD silicon nitride layer under the cantilever region. Next, the CPW transmission lines are defined by a lift-off process with 50nm Ti and 2500nm Au. At this point an air-bridge resist with a height of 2.5-3μm is patterned as first sacrificial layer. After this the contact-paddle (Fig.7) is defined. Then a second isolation-layer is deposited. This layer is 500nm thick and builds the torsion spring for the Toggle switch. Afterwards, the cantilever metallization is sputtered. The cantilever material consists of 0.75μm Au. Finally, the cantilever resist is defined and the cantilever is etched.

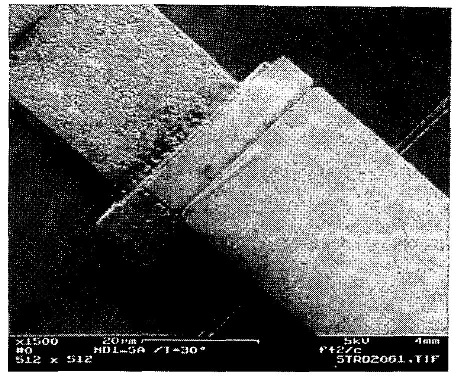

Fig. 7: SEM of ohmic contact paddle

After these steps, a flexible metal band on top must be defined (Fig. 8). For this, a second air-bridge resist with a height of 2.5-3μm is patterned as second sacrificial layer. Next, the metallization for the flexible metal band is evaporated. The material consists of 1.5μm Au and will be defined by a lift-off process. Finally, the two sacrificial air-bridge resists are removed with a solvent and a subsequent critical point drying (CPD) process.

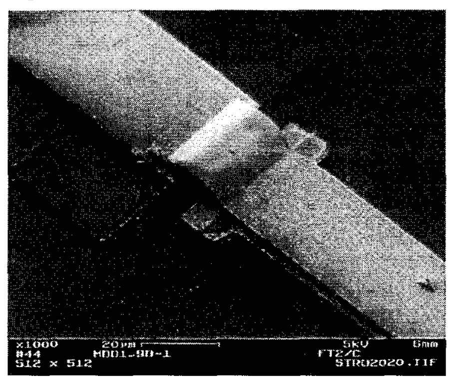

Fig. 8: SEM of the flexible metal band

VI. MEASUREMENT RESULTS

The fabricated Toggle-Switch (see Fig. 1) has been measured to characterize the DC and RF performance. The measurements were performed with a Wiltron 360B network analyzer and an OSLT calibration in the frequency range from 40 MHz up to 40GHz. Two Keithley Voltage/Current sources have been used to apply the voltages for the DC switching. A voltage of 30V is needed to close the switch totally and a voltage of 35V was needed to open the switch. In Fig. 9 one can see a comparison between the measured and the simulated results of the closed switch. The return loss of the closed switch is in the measurement up to 40GHz below −17dB while the simulation results show a value below −13dB.

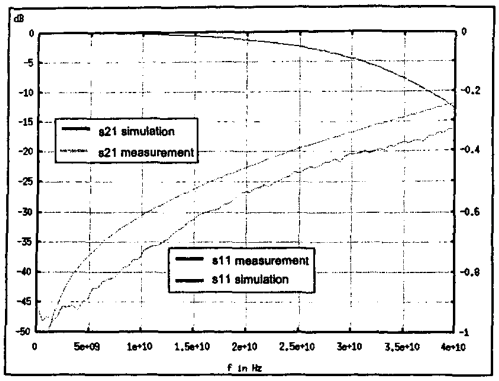

Fig. 9: Simulation and Measurement results of the Toggle-switch in closed position.

The insertion loss of the switch is in the measurements up to 30GHz below 0.3dB while the simulation shows an insertion loss of 0.1dB (metal losses have been neglected).

When the switch is in open position an isolation of at least 15dB at 30GHz was measured (Fig. 10). At 10GHz the isolation is even 24dB. The simulation predicted higher values for the isolation (about 18dB at 30GHz) which results from a lower capacitance of the simulated switch compared to the measured switch.

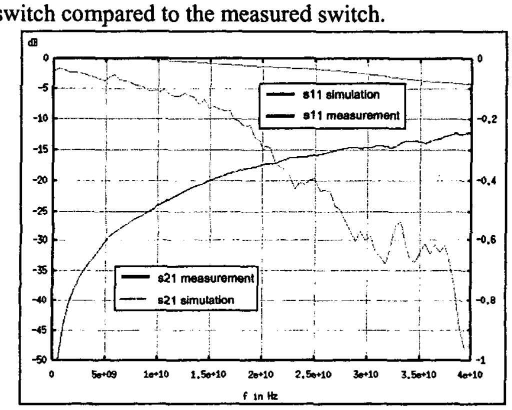

Fig. 10: Simulation & Measurement results of the Toggle-switch in open position.

The capacitance of the measured switch in open position is probably higher because the distance between the cantilever and the coplanar line is not as large as simulated (3µm). This different capacitance and the neglection of the metal losses in the simulation is responsible for the different values between measurement and simulation in the return loss (0.6dB@30GHz measured and 0.1dB@30GHz simulated). Investigations have shown, that metallic losses for the used CPW lines are about 0.1dB/mm at 30GHz.

VII. Conclusion

A new RF MEMS switch type for power application is presented. These devices offer the potential for building a new generation of low loss, high-linearity microwave circuits for a variety of phased antenna arrays for radar and communication applications. Optimization, reliability and long term stability of these switches have to be investigated in near future.

VIII. ACKNOWLEDGMENT

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