A New Type of High Bandwidth RF MEMS Switch - Toggle Switch

Bernd Schauwecker, Karl M. Strohm, Winfried Simon, Jan Mehner, and Johann-Friedrich Luy

Abstract —**A new type of RF MEMS switch for low voltage actuation, high broadband application and high power capability is presented. Mechanical and electromagnetic simulations of this new RF MEMS switch type are shown and the fabrication process and measurement results are given. The switching element consists of a cantilever which is fixed by a suspension spring to the ground of the coplanar line. The closing voltage is 16V. The switches exhibit low insertion loss (<0.85dB@30GHz) with good isolation (>22dB@30GHz).**

I. INTRODUCTION[1]

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 arms 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 [2-17], and most of them use electrostatic actuation.

The MEMS devices offer the following advantages compared to semiconductor devices [3-6]. First, significant reduction in insertion loss, which results in higher figure of merit. Second, they consume insignificant amount of power during operation which results in higher efficiency. Third, they exhibit higher linearity and as a result lower signal distortion when compared to semiconductor devices.

However, the implementation of RF-MEMS switches does not come with impunity. The following disadvantages have to be taken into consideration: higher actuation voltages (20 - 50 volts), lower switching speed (2-20 μs), reduced lifetime, stiction and power handling [5].

Therefore, there are five main challenging aspects for RF MEMS switches: lowering the actuation voltage, increasing the switching speed, increasing power handling capabilities and improving life time and reliability. For lowering the switching speed meander spring suspension [7] and push-pull concepts have been investigated [8]. Increasing the switching speed, the power handling capabilities and improving reliability are still a problem.

In this paper a new RF MEMS switch is presented which has the characteristics of low actuation voltage, high bandwidth operation and should be capable for high power handling. In chapter 2 the new switch concept is presented, in chapter 3 the mechanical simulation of the new switch is shown, in chapter 4 the electromagnetic design and simulation is discussed, in chapter 5 the fabrication process is shown and in chapter 6 the DC and RF measurement results are given.

II. THE NEW SWITCH CONCEPT

The proposed switch consists of a part of a signal line

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in a microstrip or coplanar environment witch can be opened or closed. For this, part of the signal line consists of a movable, metallic cantilever, witch is fixed by a suspension spring and has a flexible metal connection band on one end of the signal line and opens and closes an ohmic contact on the other end of the signal line. Two electrodes are provided for opening and closure using a push-pull concept (Fig. 1). Therefore the switch is called a Toggle-Switch.

For a coplanar waveguide (CPW) environment, the cantilever is fixed by a suspension spring to the ground of the coplanar lines. The suspension spring is build of silicon nitride which isolates the cantilever against the ground.

Thin electrodes on the substrate allow the switching of the cantilever utilizing 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, 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 [2, 5] 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.

MECHANICAL SIMULATION

The Toggle switch is designed to open and close an electrical contact according to an external voltage signal. Beside of the initial position where the cantilever lies horizontally to the wafer surface its tip can either be pulled down to the contact paddle or is pushed out of the wafer plane. In the first case the pull electrode is activated to close the signal line and in the second case a voltage is applied on the push electrode to further increase the gap separation for better performance in case of high signal frequencies. Essential components of the movable microstructure are shown in Fig. 1.

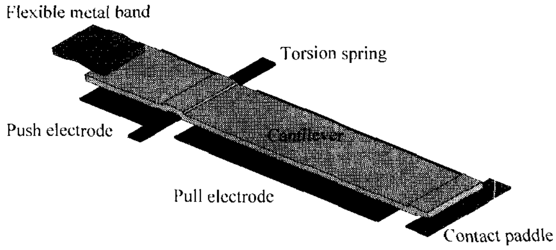

Fig. 1 Schematic view on the Toggle switch.

In a first step the Toggle switch is modeled by analytical equations for dimensional design and optimization. Results are voltage displacement functions at several points of interest. Finally the obtained results are verified by finite element simulations and additional quantities such as local stress concentrations at notches, eigenfrequencies and settling time are evaluated.

The analytical model of the Toggle structure is complicated by the fact that the cantilever bends significantly under electrostatic load. Fortunately the displacements vary only in one direction. Consequently, both the cantilever and the flexible metal band can be described by the beam theory. In addition to the torsion stiffness C_{rot} of the Si_xN_x suspension we consider also a transversal shift at that point by C_{trans}. Both terms are

$$C_{trans} = 2\frac{E\,h_S^{\,3}\,w_S}{l_S^{\,3}} \tag{1}$$

$$C_{rot} = 2\left(\frac{G\,h_S^{\,3}\,w_S}{3\,l_S} + \frac{E\,h_S^{\,3}\,w_S^{\,3}}{12\,l_S^{\,3}}\right) \tag{2}$$

where h_s, w_s and l_s are the geometrical dimensions of the spring and E and G are Young's and shear modulus of Si_xN_x.

Because the system is highly non-linear due to deflection dependent electrostatic forces we need an iterative solution procedure. The following approach is based on the principle of Castigliano ([18] see Appendix):

Compute the electrostatic pressure along the beam axis as a function of the local displacements.

Evaluate the lateral force and bending moment along the beam axis.

Calculate of the total strain energy.

Compute the reacting spring force and moment.

Compute the displacements along the beam axis.

Repeat step 1 to 5 until convergence occur.

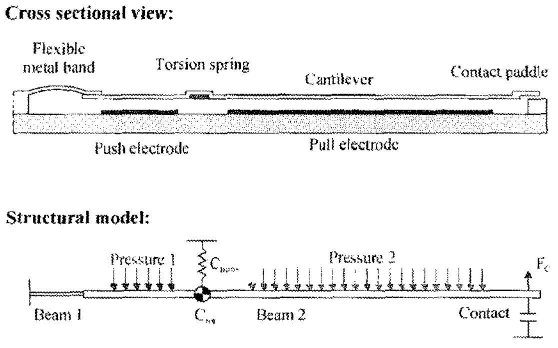

Fig. 2 Analytical model based on the beam theory.

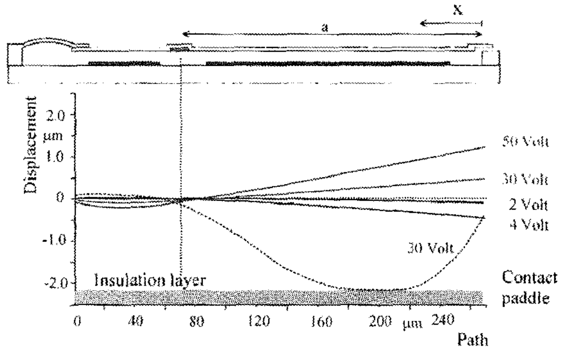

Fig. 3 Displacements at different driving voltages.

Some results of above algorithm are shown in Fig. 3. Reasonable small voltages are required to pull the lever down to the contact paddle. Any further increase of the applied voltage would lead to an instability called pull-in. Pull-in occurs if the electrostatic forces grow faster than the spring forces with respect to the displacements. As a consequence the structure snaps to the counter electrode. Usually pull-in happens if the structure is displaced to about 33% of the initial gap.

Finite element methods are state of the art to assess the equilibrium state of complex 3-dimensional systems. In our case the general purpose finite element tool ANSYS^{TM} was used to compute the static deformation state, the stress distribution and the eigenfrequencies of the cantilever.

ANSYS multiphysics capabilities allow for simultaneous modeling of different physical domains at once. The mechanical region was described by about 3000 hexahedral solid elements, the electrostatic domain by about 800 transducer elements (Fig. 4). Transducer elements are based on a quasi analytical description of the capacitance-stroke function within small gaps. Advantages are small computing time and memory consumption but fringing fields are neglected.

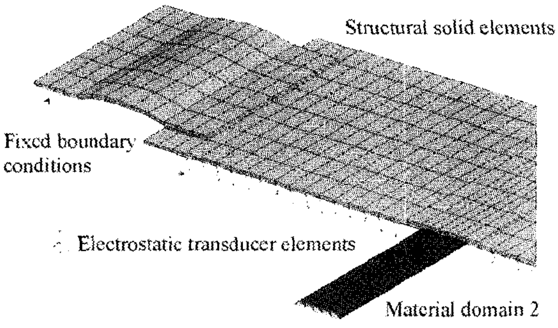

Fig. 4 Finite element model of the Toggle structure.

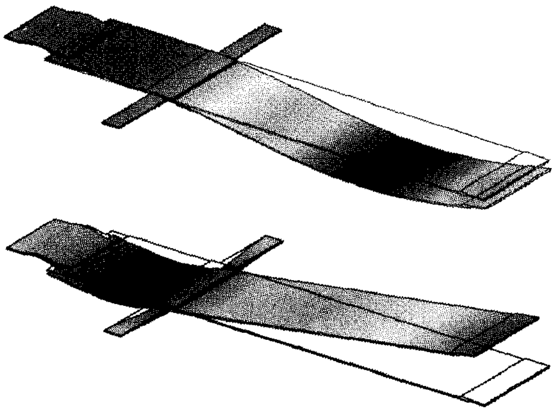

Fig. 5 Results of finite element simulations.

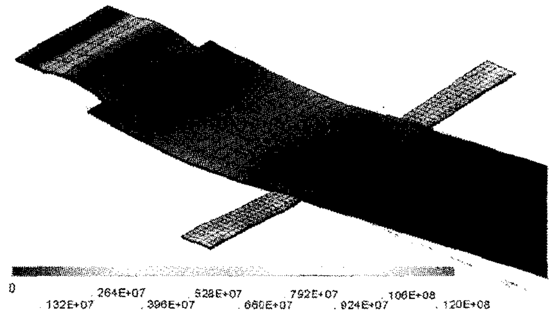

Fig. 6 Stress distribution at the displaced structure.

The computed analytical data agree very well to the finite element results. It turns out that numerical techniques are necessary to compute the release voltage after pull-in, to consider the stiffening due to pre-stress and warp owing to stress gradients. Analysis capabilities are very manifold. Some results are shown in Fig. 5 and 6.

ELECTROMAGNETIC SIMULATION AND DESIGN

The Toggle-Switch is used in a 50 Ω coplanar line environment where the Toggle is used to build an open in the center conductor (see Fig.7).

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.

A broadband compensation of the capacitance could be achieved by using the LC matching network which is shown in Figure 8.

It has been investigated which maximum capacitance could be compensated while achieving a good match up to 30 GHz. The matching at the feeding port (S_{11}), depending from the inductance L and the capacitance C that must be compensated, is shown in Figure 9. It could be seen that a capacitance of 100 fF could be compensated by a total inductance of 350 pH up to a frequency of 34.5 GHz. Frequency scaled, yields the result that a maximal capacitance of 118 fF could be compensated assuming a match of 20 dB at 30 GHz. The needed inductance is 450 pH. A higher compensating inductance will only decrease the performance in the lower frequency range.

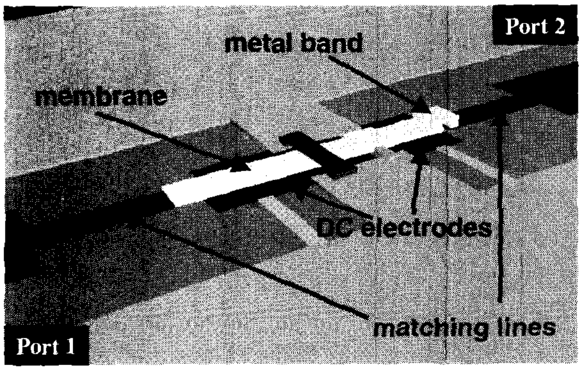

Fig. 7. Simulation model of the Toggle-Switch.

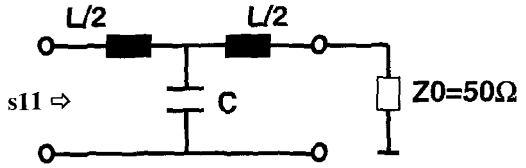

Fig. 8. L/C matching network.

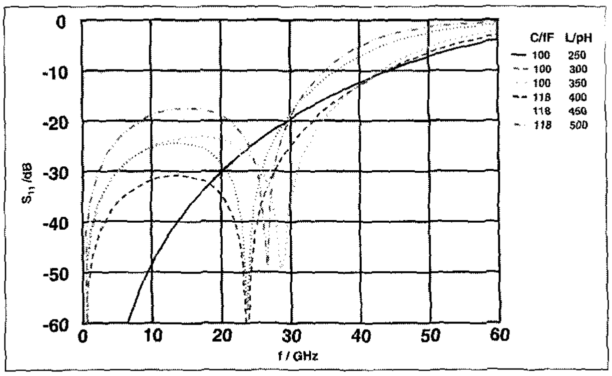

Fig. 9. Return loss at feeding port dependent from switch capacitance and inductive matching.

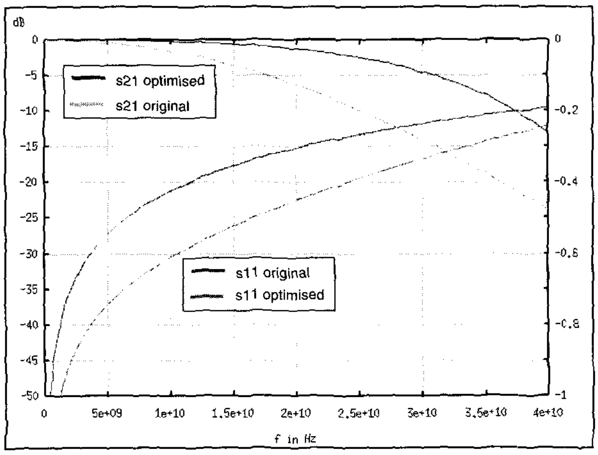

Fig. 10. Simulation results of the Toggle-Switch.

The 3D FDTD field simulator Empire™ [19] 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.

The simulation results of the optimized structure in Fig. 10 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 was increased by about 9GHz, if a match of 15dB for the return loss is assumed.

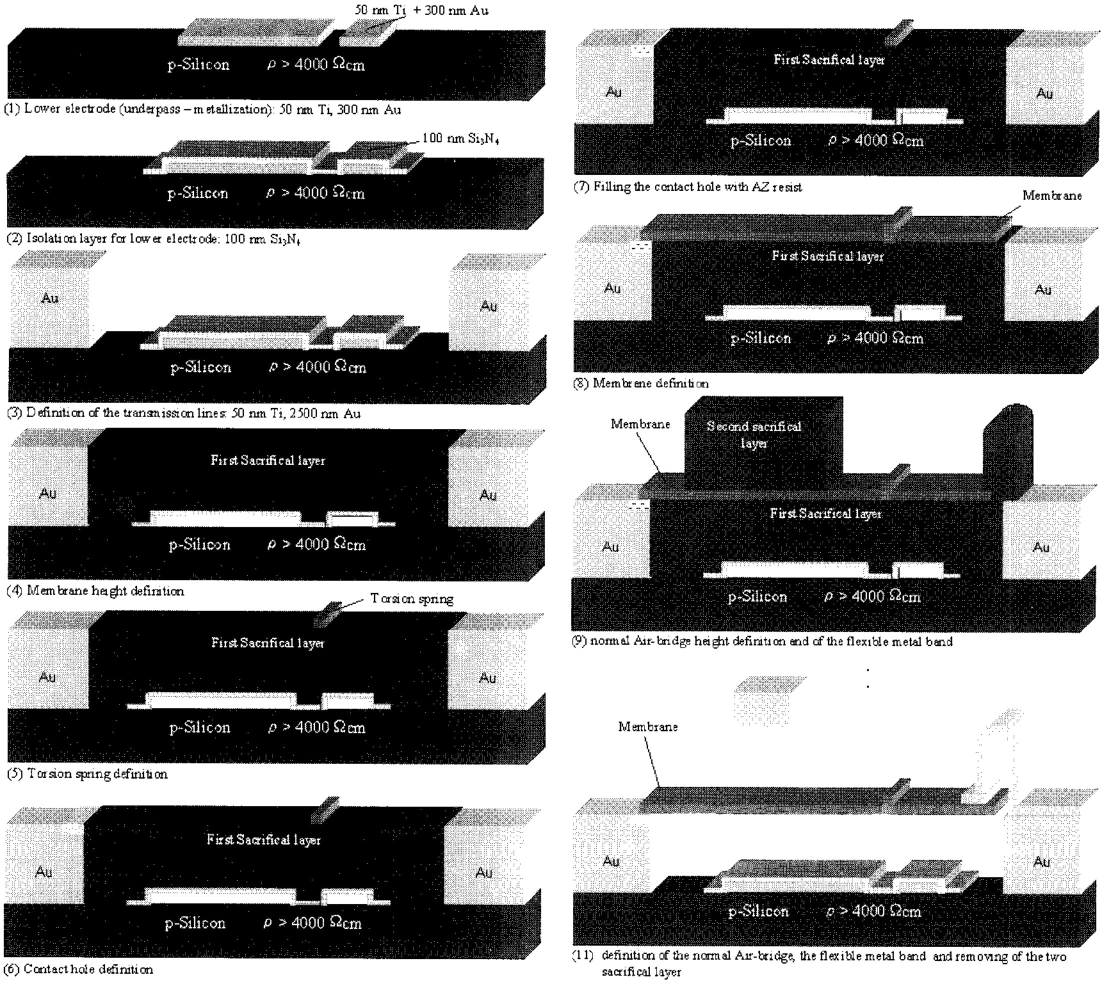

Fig. 11. Schematic process flow of the Toggle-Switch.

FABRICATION PROCESS

The Toggle-Switches are fabricated on high-resistivity silicon wafers ($\rho > 4000\Omega$cm) with a wafer thickness of 525 μm.

First, a 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 value of the resistivity can be changed with the value of the nitride content in the layer and with the process parameter. After that, the lower electrode (underpass metallization) is defined by a lift-off process with 50nm Ti and 250nm Au. Then, the lower electrode is isolated by a 100nm thick PECVD silicon nitride layer under the cantilever region. Next, the 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.12) is defined.

Then a second isolation-layer is deposited. This layer is 500nm thick and forms the torsion spring for the Toggle-Switch. Afterwards, the cantilever metallization is sputtered. The cantilever material consists of 0.8μm Au. Finally, the cantilever resist is defined and the cantilever is etched. After these steps, a flexible metal band on top must be defined (Fig. 13). 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 1.0μm Au and is defined by a lift-off process. Finally, the two air-bridge resists (sacrificial layers) are removed with a CPD process.

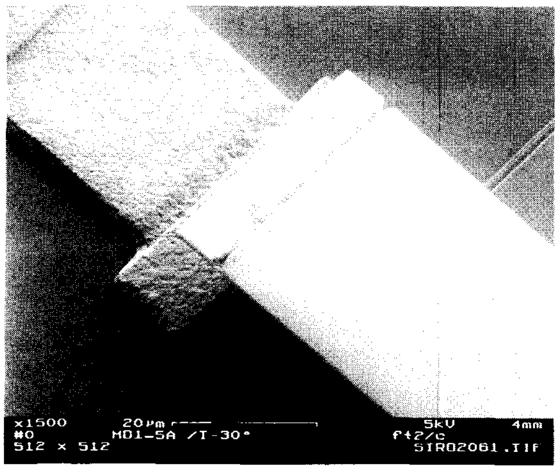

Fig. 12. SEM picture of ohmic contact paddle.

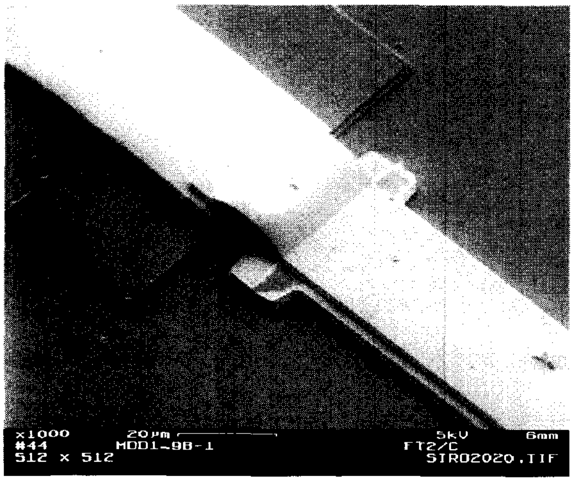

Fig. 13. SEM picture of the flexible metal band.

MEASUREMENT RESULTS

The fabricated Toggle-Switch (see Fig. 14) has been measured to investigate the DC and RF performance. This yields information regarding pull-in voltage, switch insertion loss, return loss and isolation. S-parameter measurements were performed over the 0.5 – 40GHz frequency range using an HP network analyzer 8510C. Line-Reflect-Match (LRM) calibration was used. A Keithley Voltage/Current source has been used to apply the voltage for the DC switching.

A voltage of 16V is necessary to close the switch. Due to the high residual stress in the cantilever material the contact opens by reducing the DC voltages to 0V, and the cantilever jumps back to the original position. With an additional DC voltage at the push electrode the distance between the cantilever and the contact paddle can be increased.

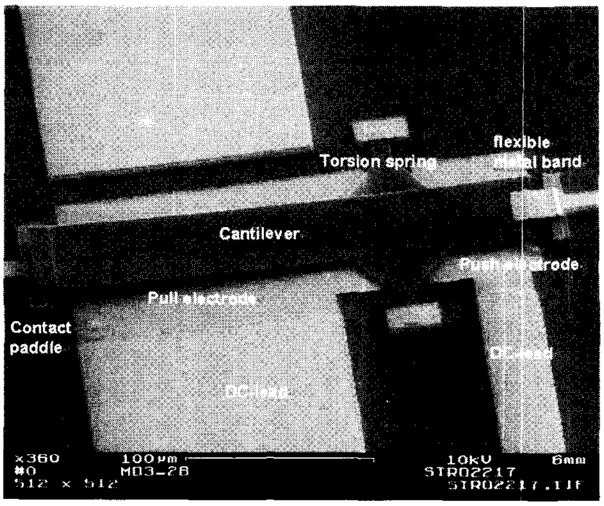

Fig. 14. SEM picture of the fabricated Toggle switch.

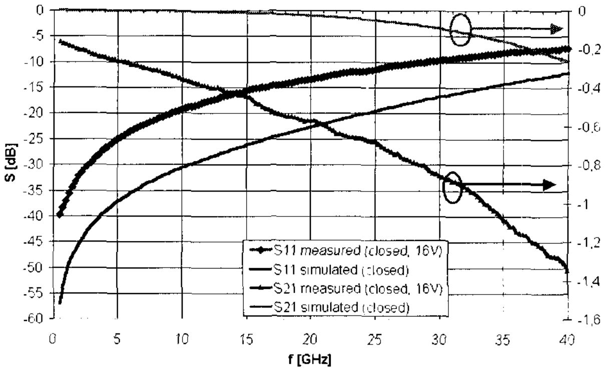

Fig. 15. Simulation and measurement results of the Toggle-Switch in closed position.

In Fig. 15 one can see a comparison between the measurement results and the simulation results of the closed switch. The return loss of the closed switch is in the measurement up to 30GHz below –10dB while the simulation results show a value below –17dB. The insertion loss of the switch is in the measurements up to 30GHz below 0.85dB while the simulation, where the metal losses have been neglected, shows an insertion loss of 0.1dB.

If the switch is in open position an isolation of at least 54dB at 1GHz, 32dB at 10GHz and 22dB at 30GHz is measured (Fig. 16). The simulation predicted lower values for the isolation (about 19dB at 30GHz) which results from a lower capacitance of the simulated switch

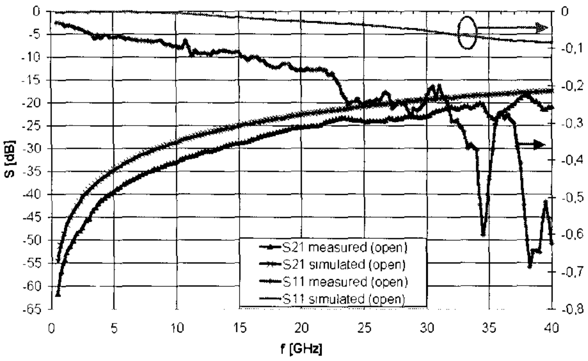

Fig. 16. Simulation & measurement results of the Toggle-Switch in open position.

compared to the measured switch.

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 causes the different values between measurement and simulation in the return loss (0.85dB@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.

The reason for the higher necessary pull-in voltage is the greater distance of the cantilever to the contact paddle. In the simulation a distance of 0.5μm is supposed. This larger gap is also the reason for the better isolation in open state in comparation to the simulation.

Because of a higher resistivity of the resistor layer (> 800 Ωcm) the microstrip mode between the cantilever and the push electrode is not correctly stimulated. Therefore the electromagnetic field is disturbed and a higher transmission loss is measured.

CONCLUSION

A new RF MEMS switch type for high bandwidth operation 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.

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APPENDIX

Step 1:

Computation of the electrostatic pressure P_{el} along the beam axis (x) as a function of the local displacements u_y:

$$P_{el}(x,u_y) = \frac{\varepsilon_0 V^2}{2\,(d-u_y)^2} \qquad \text{(a1)}$$

V is the applied voltage and d the initial electrode gap.

Step 2:

Computation of the lateral force F_q bending moment M_b:

$$F_q(x) = \int_0^x P_{el}(s)\,ds + F_S\,\Gamma(x,a) \qquad \text{(a2)}$$
$$M_b(x) = \int_0^x F_q(s)\,ds + M_S\,\Gamma(x,a) \qquad \text{(a3)}$$

where F_s and M_s are the reacting Si_xN_x spring force and moment and $\Gamma(x,a)$ is a jump function starting with value 1 at a (Fig. 3).

Step 3:

Computation of the total strain energy W_s:

$$W_s = \frac{1}{2EI}\int M_b(x)^2\,ds + \frac{F_s^2}{2C_{trans}} + \frac{M_s^2}{2C_{rot}} \qquad \text{(a4)}$$

where E is Young's modulus and I the area moment of inertia of the cantilever cross section. The first term captures the bending energy of the cantilever and metal band, the second one the transversal string and the third one the rotational spring.

Step 4:

Computation F_s and M_s in a such an extent that the following equations are fulfilled (Castigliano's theorem):

$$\frac{\partial W_s(F_S,M_S)}{\partial F_s} = 0; \quad \frac{\partial W_s(F_S,M_S)}{\partial M_s} = 0 \qquad \text{(a5-6)}$$

Step 5:

Compute the final displacements u_y along the beam axis:

$$u_y(x) = -\frac{1}{EI}\int_0^x\int_0^x M_b(s-x)\,ds\,ds \qquad \text{(a7)}$$

Repeat step 1 to 5 until convergence occur.

Bernd Schauwecker received the Diplom and the Dr.-Ing. (PhD) in Electrical Engineering both from Technical University of Chemnitz, Germany, in 1995 and 2000, respectively for his investigations of optical waveguide components with high refractive index difference in silicon-oxynitride. He served as a Research Assistant at the University of Chemnitz until 2000. Then he joined the DaimlerChrysler Research Center in Ulm, Germany. His main interests are in RF MEMS technology, wireless communications, telematic systems and Integrated Optics.

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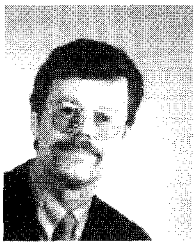

Johann-Friedrich Luy received the Dipl.Ing. degree for his investigations on heat conduction in semiconductor lasers and the Dr.-Ing. degree for his thesis on the first silicon MBE made IMPATT diodes from the Technical University of Munich, Germany in 1983 and 1988, respectively. In 1983, he joined the former AEG research center and worked on silicon IMPATT diodes. Since 1989, he has been engaged in research on Si/SiGe millimeter wave devices and circuits. The development and application of near range radar sensors and communication links employing advanced front-end configurations (software radio) is the main focus of his interest as Head of the Microwave Department, DaimlerChrysler Research Center, Ulm, Germany. He has authored and co-authored over 50 papers in referred journals and symposia proceedings. He was co-editor of *Silicon Based Mm-Wave Devices* (Berlin/New York: Springer Verlag 1994) and Distinguished Lecturer of the IEEE Electron Devices Society in 1996/1997. He is a lecturer at the Technical University of Munich. Dr. Luy is an URSI member and an IEEE Fellow of the MTT society (Jan. 2000), member of the TPC board of the International Microwave Symposium, of the editorial board of the Microwave Theory and Transactions as well as other referred journals and an appointed member of the EDS Compound Semiconductor Devices and Circuits Technical Committee.