J Electroceram (2009) 22:145–149
DOI 10.1007/s10832-008-9457-7

An integrated microelectromechanical microwave switch based on piezoelectric actuation

Carsten Kügeler · Alexander Hennings · Ulrich Böttger · Rainer Waser

Received: 18 December 2006 / Accepted: 14 February 2008 / Published online: 12 March 2008

Abstract In the field of microwave applications, micro-electromechanical systems (MEMS) are attractive devices in order to force miniaturization by on chip integration. Here, we describe the design, fabrication and testing of a silicon based micromachined switch using piezo-electrically actuated elements. The microwave circuit consists of a coplanar waveguide (CPW) design with two piezoelectric activated beams integrated between the middle line and the ground planes. During operation the beams short the CPW by two overhanging bridge contacts and therefore the transmission characteristics of the microwave circuit change. The CPW is realized by 3 µm thick electroplated copper to yield good transmission characteristics, whereas the clamped—clamped beams benefit from a 250 nm thin PZT film between 100 nm thin Pt electrodes on top of a SiO_2 layer. By the use of double side clamped beams awkward stress compensation of the piezoelectric stack is omitted. Instead the system relies on some initial mechanical stress. Measurements prove deflections of more than 13 µm for a 1400 µm long beam with operation voltages below 10 V. This is in good agreement with finite element simulations. The novel RF-MEMS is predicted to reach an isolation (in "on" state) of more than 20 dB up to 15 GHz.

Keywords RF-MEMS · Piezoelectric · Thin film · PZT · Integrated microwave switch

C. Kügeler (✉) · R. Waser
IFF, Research Laboratories Jülich,
52425 Jülich, Germany
e-mail: c.kuegeler@fz-juelich.de

A. Hennings · U. Böttger · R. Waser
IWE II, RWTH-Aachen,
Sommerfeldstr. 24,
52074 Aachen, Germany

1 Introduction

The superior piezoelectric properties of ferroelectric ceramics make them ideal materials for the use in micro-electromechanical systems (MEMS) realizing new functions [1, 2]. Especially the market potential of radio frequency (RF)-MEMS for microwave applications is tremendous and estimated to exceed US$ 1 billion within the next years [3, 4]. Microwave switches and microwave resonators are expected to gain a part of this market. Recently demonstrated piezoelectric actuated RF switches show impressive properties compared to the competitive concept of electrostatic actuation [5–9], especially, since electrostatic switches suffer from drawbacks like high operation voltages, small displacements and stiction [10–15]. The demands for RF switches are an integrated design, separation between the actuation and the signal circuit, low driving voltages, fast operation, enhanced mechanical stability and fatigue free operation.

2 Experimental procedures

The key elements of the novel microwave switch are two piezoelectric bridges. In principle those are similar to cantilevers, but clamped on both sides to the substrate. The concept is shown in Fig. 1(a). The bridge consists of a continuous bottom electrode and a stack of a PZT thin film with a Pt top electrode on the left hand and right hand side. The perpendicular stack in the middle acts as metalized contact bar to short the two overlapping copper contact strips. Several different technologies are involved in the fabrication e.g. chemical solution deposition (CSD) of the PZT films [16], sputter deposition of the Pt electrodes, dry etching in order to structure Pt, PZT and SiO_2 and isotropic underetching using a SF_6 plasma to release the structure. A detailed description of the fabrication is given in [17]. Since the piezoelectric bridges are clamped to the substrate on both ends the structure yields an enhanced mechanical stability compared to cantilevers. In addition, for the fabrication of cantilevers mechanical stress compensation is always an important and difficult issue in order to realize flat beams.

Here, the functionality of the switch relies on the initially induced mechanical stress, because it forces the bridge to bend upwards and to close the copper contacts. Therefore the switch is closed. By applying an electric field to the PZT at the left hand and right hand side, the film contracts in-plane and the bridge becomes shorter, moves downwards and opens the switch. A deflection measurement of a 1000 µm long piezoelectric bridge is shown in Fig. 1(b). The typical butterfly shaped curve is turned around indicating that with increasing electric fields the bridge moves down. Dependent on the length of the bridge the deflection is large enough to by-pass a distance of several micrometers. A 1000 µm long bridge reaches 8 µm and a 1400 µm long bridge reach a displacement of 13 µm, which is enough to achieve a sufficient insulation [18]. In [19] we proved that the piezoelectric coefficient d_{33}=70 pm/V of the PZT thin films remains stable for at least 10^9 cycles, if unipolar electric fields are applied. Therefore the PZT film is considered as fatigue free. Furthermore, the application of surface micromachining enables a high integration density and the possibility to place the micro-relay within unused areas between the microwave signal lines.

One commonly used microwave transmission line is the coplanar wave guide (CPW). It is formed from a middle conductor separated from a pair of groundplanes on top of a dielectric substrate. CPW based microwave devices offer some advantages compared to those devices based on other structures, e.g. microstrip devices. Beneficial features are the reduced sensitivity to the substrate thickness, low dispersion, the wide range of realizable characteristic impedance, and wide frequency range of use [18]. Due to the in-plane surface metallization, no vias are required to interconnect the groundplanes with other conductors. Therefore, CPW designs provide for convenient possibilities of MEMS integration with the aid of surface micromachining. However, the CPW supports two fundamental modes of wave propagation, where one mode is generally undesired, namely the so-called slotline mode or "odd mode", respectively. To make sure that this mode is not excited, CPW devices have to be designed symmetrically with respect to the longitudinal middle axis. Alternatively, the undesired slotline mode may be suppressed by balancing the electric potential of the two ground planes with additional conducting straps or bond wires, e.g. [18, 20].

The design of the developed CPW microwave switch is presented in Fig. 2(a). At a first glance, one notices the three CPW conductor strips on a Si/SiO_2 substrate, whereby the tapering at the ends of the middle line and the broadening of the two outer groundplanes matches the requirements of the probe tips used for microwave measurements. Two micro-relays are symmetrically placed in the gaps between the conductors. Compared to Fig. 1(a), the relay design is changed in the way that the contact bar of the bridge is turned by 90° to attain more compact dimensions and make them more suitable for integration. The overhanging copper contacts are directly attached to the CPW conductors and laterally displaced and overlapping the whole bridge to assure a large contact area with good contact properties.

In case of the open switch, a microwave signal can propagate from the input-port towards the output-port without being significantly attenuated. Thereby, ideally all energy is transmitted from one side to the other, if no ohmic losses occur within the structure, and if the characteristic impedance of 50 Ω is matched by proper dimensioning. If the piezoelectric bridges close the overhanging contacts, the center conductor and groundplanes are interconnected through the contact strips and the structure corresponds to a closed shunt-switch. In this state the signal propagation is blocked, and a high reflection coefficient is achievable. Such a type of shunt-switch can be employed in various microwave applications, e.g. filters, multiplexers, and phase-shifters.

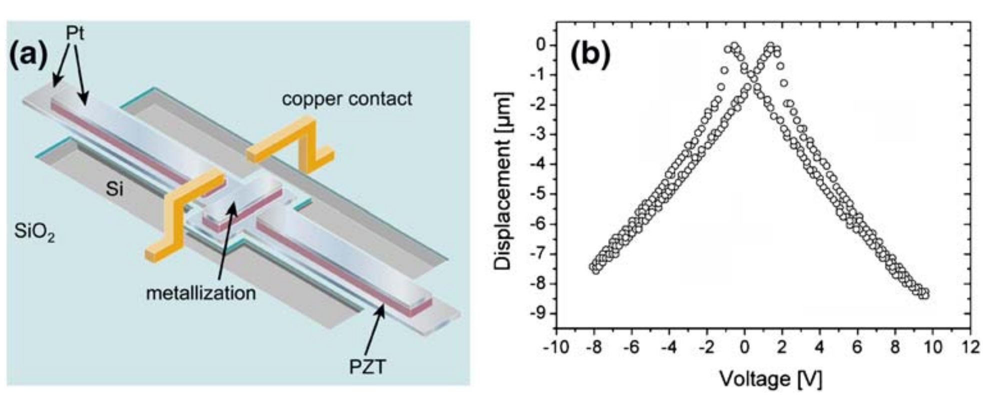


Fig. 1 (**a**) Bridge concept of a piezoelectric driven micro relay. (**b**) Displacement vs. voltage measurement of a 1000 µm long bridge (40 µm width; 250 nm thin PZT film;) measured at 10 Hz

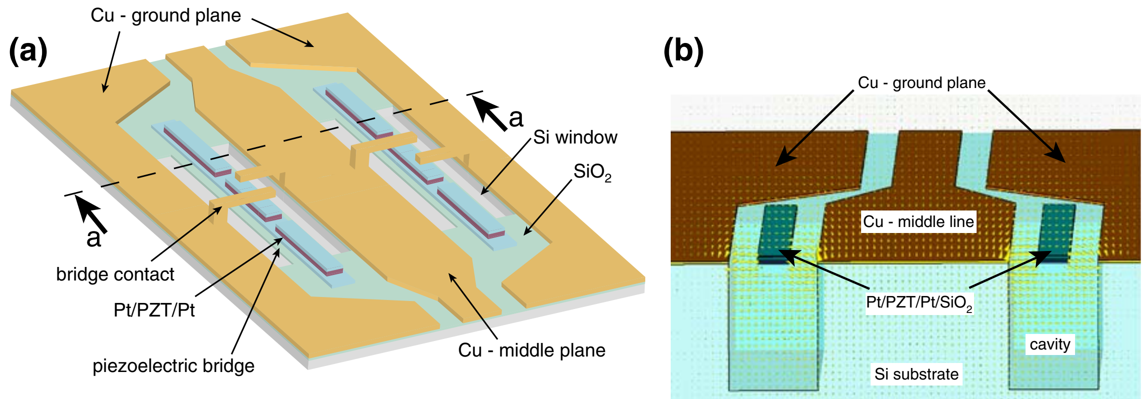


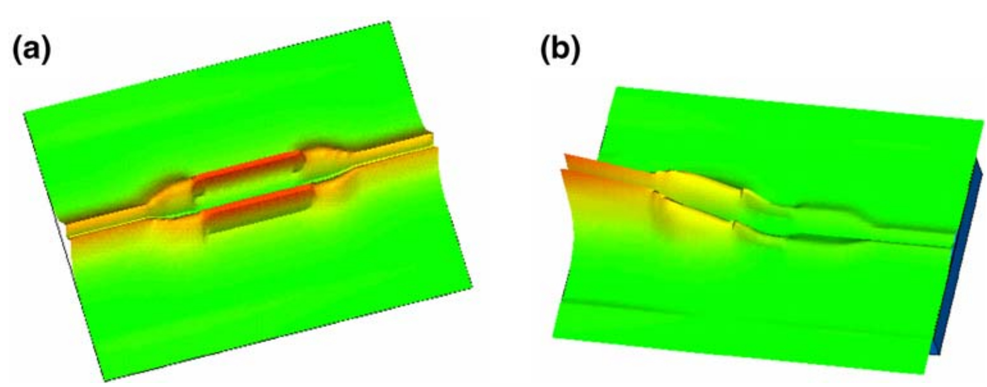
Fig. 2 (**a**) Concept of a MW-switch in coplanar waveguide configuration. (**b**) Vector representation of the electric field distribution in the cross section (*a–a*) of the CPW with integrated piezoelectric bridges and air cavities

In order to verify the working principle and to closer inspect the impact of the integrated micro-relays on the microwave response, the reflection and transmission spectra (S_{11}, S_{21}) as well as the field distributions are simulated by utilizing the Finite Difference Time Domain (FDTD) technique. Due to some simulation constraints, the PZT layer is only roughly modeled with values of thickness and permittivity close to reality. However, simulations with different values of thickness and permittivity varied over a wide range prove that the permittivity and thickness of the PZT film has only minor impact on the device performance.

Figure 2(b) displays the cross-sectional view of the electric field distribution at 25 GHz within a transversal plane which intersects the air cavities and piezoelectric bridges. The simulated field distribution is similar to the quasi-transmission electron microscopy field distribution of a conventional CPW line. However, the electric field is mainly concentrated in the cavities between the middle line and the ground plane. Here, the field magnitudes are relatively strong, and the vector orientation appears almost in parallel to the substrate surface. The magnitude of the normally oriented vector component goes down to zero in the centers of the gaps between the middle conductor and the ground planes, i.e. where the piezoelectric bridges are located. The parallel vector component (oriented in parallel to the substrate surface) does not invade the PZT layer, even if the thin PZT film is replaced by a rather bulky layer of considerable thickness. This has two reasons: First, the electric field is shorted across the Pt top and bottom electrodes. Second, the boundary conditions at the air/film boundaries do not allow the occurrence of high field amplitudes in the dielectric material due to the enormous difference of the two dielectric constants (air and PZT). As seen in the figure, the field lines are only slightly deformed in vicinity of the piezoelectric bridges but the field distribution is not essentially disturbed.

Figure 3 compares the distributions of the field magnitude for the cases of the open and closed switching states. Displayed is the magnitude of the transversal electric field component E_x at 5 GHz in the plane located 100 μm underneath the substrate surface. Whereas Fig. 3(a) illustrates the unimpeded wave propagation with increased magnitude inside the air cavities, Fig. 3(b) illustrates the wave reflection at closed switches. As seen, the microwave signal transmission is not suppressed completely by the closed shunt-switches so that the amplitude is not completely vanished at the output-port. The fabrication of such a MW-switch is similar to the fabrication of the micro-relay. First, the piezoelectric bridges are formed by the deposition of 250 nm PZT on a Pt/SiO_2/Si substrate and the forming of Pt top electrodes. After structuring the PZT, the bottom electrode and the Si window are formed by dry etching.

Fig. 3 Magnitude of the transversal electric field component E_x in the plane located 100 μm underneath the substrate surface at 5 GHz. (**a**) Case of open switch. (**b**) Case of closed switch



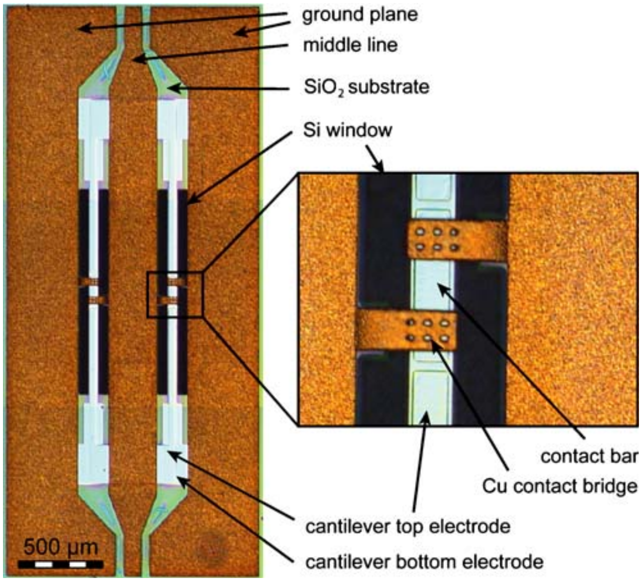


Fig. 4 Top view of a MW design with two embedded cantilever bridges and magnification of the centre part around the copper contacts

Then, the signal lines are grown by electroplating. In the first step the signal lines are defined by lithography followed by the deposition of a copper plating base by thermal evaporation. In the second step the copper bridges are defined using a second layer of photoresist and then thick copper is grown by Cu electroplating. After removal of the photoresist and the plating base the piezoelectric bridges are released by isotropic underetching.

Figure 4 shows the top view of a fabricated CPW with two integrated piezoelectric beams. This example possesses a distance of 200 µm between the middle and the ground lines, whereby the gap narrows at the end to 50 µm. The piezoelectric bridges are 60 µm in width and 1400 µm long. The picture on the right hand side depicts a magnification of the switch contacts. It shows the separated contact bar on the piezoelectric bridge and the copper contact strips with vias.

In order to confirm the concept, the S-parameters are simulated for both switching states (opened and closed). Thereby, all materials are assumed to be lossless, since a reasonable modeling of different loss contributions requires accounting for more experimental data. The simulated insertion loss for the open switches and isolation for the closed switches of the device are shown in Fig. 5(a). If the switches are open, the insertion loss is 0.5 dB or better within the entire frequency range of 0 to 35 GHz, indicating good transmission properties. If the switches are closed, i.e. if the middle line and groundplanes are interconnected, high isolation is obtained at frequencies below 2 GHz. Above this frequency the isolation ranges from 35 dB to 10 dB still providing considerable rejection of the passing microwave signal. Fig. 5(b) shows the S_{11} for the opened state as well as for the closed state. In opened state, an acceptable level of return loss is obtained in the low GHz range, and even at higher frequencies, return is loss always kept equal or better than 10 dB. Even though some further optimization is desirable, these results look promising.

3 Conclusion

This paper presents the concept and fabrication of a piezoelectric actuated MW-switch. Piezoelectric bridge structures, which exhibit high mechanical stability and take advantage of the initial mechanical stress are successfully integrated into a CPW design opening and closing contacts during operation. A deflection up to 13 µm at 10 V leads to a significant reduction of the driving voltage compared to electrostatic actuation. Thereby, good switching properties are verified by simulations showing a ratio of S_{21} switching levels of more than 20 dB at frequencies up to 15 GHz.

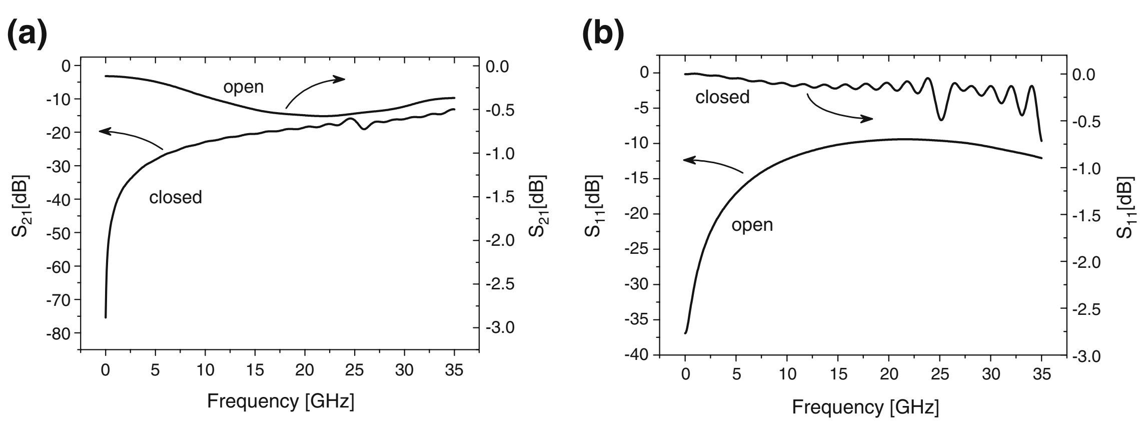


Fig. 5 Simulated S-parameters (**a**) S_{21} and (**b**) S_{11} of a MW circuit with embedded 1400 µm long micro-switches

References

1. D.L. Polla, Application of PZT thin films in microelectromechanical systems. SPIE **2046**, 24–27 (1997)
2. P. Muralt, Ferroelectric thin films for micro-sensors and actuators: a review. J. Micromech. Microeng. **10**, 136–46 (2000)
3. WTC, The RF MEMS market II, 2005–2009. www.wtc-consult.de (2005)
4. J. Bouchaud, H. Wicht, RF MEMS analysis, forecast and technology review, CHIP, the Business and Technical news Unaxis Semicond. **9**, 26–29 (2003)
5. H.C. Lee, J.H. Park, J.Y. Park, H.J. Nam, J.U. Bu, Design, fabrication and RF performances of two different types of piezoelectrically actuated ohmic MEMS switches. J. Micromech. Microeng. **15**, 2098–2104 (2005)
6. J.Y. Park, H.C. Lee, Comparison of ultra-low voltage operated RF MEMS in-line switches with serial and shunt configurations. Integr. Ferroelectr. **13**, 5 (2005)
7. J.H. Park, H.C. Lee, Y.H. Park, Y.D. Kim, C.H. Ji, J.U. Bu, H.J. Nam, A fully wafer-level packaged RF MEMS switch with low actuation voltage using a piezoelectric actuator. J. Micromech. Microeng. **16**, 2281–6 (2006)
8. H.C. Lee, J.Y. Park, Bu, Piezoelectrically Actuated RF MEMS DC Contact Switches With Low Voltage Operation. IEEE Microw. Wirel. Compon. Lett. **15**, 4 (2005)
9. R.G. Polcawich, D. Judy, J.S. Pulskamp, S. Trolier-McKinstry, M. Dubey, Advances in Piezoelectrically Actuated RF MEMS Switches and Phase Shifters, Microwave Symposium, 2007(IEEE. MTT.2007), pp. 2083–2086, 3–8 June DOI 10.1109/MWSYM.2007.380297
10. B. McCarthy, G.G. Adams, N.E. McGruer, D. Potter, A dynamic model, including contact bounce, of an electrostatically actuated microswitch. J. Microelectromech. **11**(3), 276–283 (2002)
11. J.J. Yao, RF MEMS from a device perspective. J. Micromech. Microeng. **10**, R9–R38 (2000)
12. S. Melle, F. Flourens, D. Dubuc, K. Grenier, P. Pons, F. Pressecq, J. Kuchenbecker, J.L. Muraro, L. Bary, R. Plana, Reliability overview of RF MEMS devices and circuits (33rd Eur. Microw. Conf., Munich, 2003), pp. 37–40
13. J.Y. Park, G.H. Kim, K.W. Chung, J.U. Bu, Monolithically integrated micromachined RF MEMS capacitive switches. Sens. Actuat. A **89**, 88–94 (2001)
14. J. Oberhammer, G. Stemme, Design and fabrication aspects of an S-shaped film actuator based DC to RF MEMS switch. J. Microelectromech. Syst. **13**(3), 421–428 (2004)
15. H. Lee, R.A. Coutu Jr., S. Mall, P.E. Kladitis, Nanoindentation technique for characterizing cantilever beam style RF micro-electromechanical systems (MEMS) switches. J. Micromech. Microeng. **15**, 1230–1235 (2005)
16. C. Kuegeler, M. Hoffmann, U. Boettger, R. Waser, Integration, electrical and electromechanical properties of PZT and PMN-PT thin films for MEMS applications. Proc. SPIE **4699**, 114–123 (2002)
17. C. Kuegeler, S. Tappe, U. Boettger, R. Waser, Piezoelectric actuated MEMS for integrated RF switches based on PZT thin film bridges. Ferroelectrics **338**, 89–95 (2006)
18. I. Wolff, Coplanar Microwave Integrated Circuits (Wiley, Hoboken, 2006)
19. C. Kuegeler, P. Gerber, U. Boettger, R. Waser, Thickness dependence of piezoelectric properties for PZT thin films with regard to MEMS applications. Integr. Ferroelectr. **54**, 527–535 (2003)
20. N.I. Dib, M. Gupta, G.E. Ponchak, L.P.B. Kathei, Characterization of asymmetric coplanar waveguide discontinuities. IEEE Trans. MTT. **41**, 1549–1558 (1993)