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 ScienceDirect

Procedia Engineering 5 (2010) 734–737

**Procedia  
Engineering**

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Proc. Eurosensors XXIV, September 5-8, 2010, Linz, Austria

## Experimental Investigation on the Exploitation of an Active Mechanism to Restore the Operability of Malfunctioning RF-MEMS Switches

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### Abstract

RF-MEMS (MicroElectroMechanical-Systems for Radio Frequency applications) switches and components can enable the realization of high-performance and highly-reconfigurable blocks for a variety of applications in the field of telecommunications, spanning from mobile phones to scanning radar systems and satellite communications. Nevertheless, the exploitation of MEMS technology in the RF field is still limited by the relatively poor reliability of RF-MEMS devices and networks. In this work, we discuss the exploitation of an active mechanism that was recently presented by the authors, and capable of improving the robustness of RF-MEMS switches against stiction. The mechanism exploits the heat generated by an electric current driven through a high-resistivity PolySilicon serpentine, embedded within the switch structure, to recover the normal operability of the RF-MEMS relay, and is effective both against charge entrapped in the insulating layer as well as micro-welded spots due to large RF signals. The mechanism can be added with only minimal changes to a wide variety of already existing RF-MEMS switches and components topologies. In this paper we report the first experimental results showing a successful release of a stuck switch after the heater is activated. Moreover, we discuss proper activation methods of the proposed mechanism by performing FEM simulations in order to maximize the benefits of the PolySilicon heater operation without impairing the mechanical characteristic of the MEMS switch.

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*Keywords:* RE-MEMS switches; reliability; active restoring mechanism; stiction; micro-welding; entrapped charge; FEM simulations

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### 1. Introduction

MEMS (MicroElectroMechanical-Systems) technology for RF (Radio Frequency) applications has emerged in the past decade as an enabling solution to realize low-cost and high-performance lumped components, like high Q-Factor and widely reconfigurable variable capacitors and inductors [1,2], high-isolation and low-loss ohmic/capacitive switches [3]. The availability of such components speeds-up both the MEMS hybridization with

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standard semiconductor technology [4] as well as the synthesis of functional sub-blocks entirely based on microsystems, like reconfigurable phase-shifters [5], power attenuators [6] and switching matrices [7].

In spite of the significant advantages that a large-scale exploitation of RF-MEMS components and networks would bring in terms of performance and reconfigurability, their penetration into the market is still very limited, mainly because of their sensitivity to several impairing factors (both mechanical and electrical) that reduce significantly the reliability of MEMS-based implementations if compared with standard ones. Given the multi-physical behavior of MEMS (electromechanical), potential sources of malfunctioning and fatal failure are both the ones typical of standard semiconductor devices, like for instance electromigration and ESD (ElectroStatic Discharge), as well as additional causes linked to the materials and mechanical properties, e.g. plastic deformations, wearing, fatigue and fractures [8,9].

Among the most important failure modes affecting RF-MEMS devices, we focus on two that typically already start to show up in the short/medium-term operation of MEMS-based switches, namely, the charge entrapment within the insulating layer [10] and the occurrence of micro-welding [11]. To this purpose, we already presented and discussed an active solution to counteract stiction (i.e. the failed release of a MEMS switch due to one or both the above mentioned failure mechanisms), based on embedding an high-resistivity PolySilicon heater within a standard RF-MEMS ohmic switch design [12]. The heat generated by an electric current driven into the serpentine induces, on one side, deformations of the MEMS membrane and, thus, an additional contribution of shear and restoring force (useful to counteract stiction due to micro-welding). On the other hand, the heat speeds-up the dispersion of charge entrapped in the insulating layer [13].

In this paper we report the first experimental results showing the effective release of a stuck RF-MEMS switch by activating the heater, as well as an investigation, based on FEM (Finite Element Method) simulations, aimed at defining efficient operation methods of the PolySilicon serpentine, that maximize the switch restoring capabilities and minimize, at the same time, the impact of the heat on the mechanical properties of the MEMS device.

## 2. The Embedded Heating Mechanism: Experimental Measurements

The RF-MEMS series switch topology we presented in [12] is schematically reported in Fig. 1. In particular, Fig. 1-left shows the complete structure, featuring the MEMS ohmic switch, the CPW (CoPlanar Waveguide) and the DC pads for the biasing of the central plate (actuated/not-actuated positions) and for activating the PolySilicon heaters, embedded underneath the gold anchoring areas.

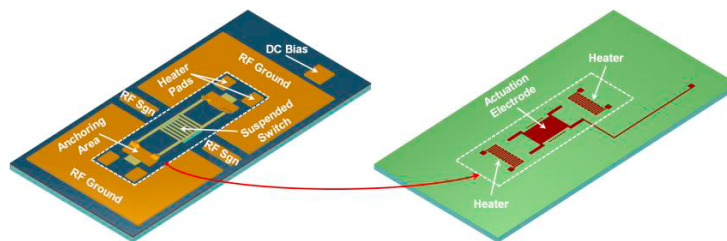


Fig. 1. (Left) 3D complete schematic of the RF-MEMS series ohmic switch featuring the heater-based active restoring mechanism. (Right) Schematic of the same switch where only the buried PolySilicon layer is visible. The central actuation electrode as well as the two serpentine heaters are visible, being the latter ones placed underneath the gold anchoring areas, where the membrane is hinged.

Fig. 1-right shows only the PolySilicon layer, highlighting the central actuation electrode for the biasing of the MEMS suspended membrane and the two serpentine heaters. Samples of the RF-MEMS switch discussed in this work are fabricated in the surface micromachining process, based on Gold, available at FBK in Italy [14].

Experimental testing is performed on a few available samples. The S11 parameter monitored at 6 GHz when the applied bias is swept between  $\pm 70$  V (triangular zero mean value signal) shows the pull-in/pull-out (PI/PO) characteristic, and is reported in Fig. 2-left. The S-parameter characteristic exhibits an unusual behavior compared to a standard series ohmic switch. This is because a low-impedance path to ground for the RF signal was included by mistake in the layout when the MEMS switch is actuated (ON state). Nonetheless, the observation of S-parameters

still holds valid to get indications on the MEMS switch state: actuated/not-actuated. The same sample is then characterized in transient condition (see Fig. 2-right). Since the device did not remain stuck with the charge entrapped in the oxide, we applied a DC hold voltage of 25.5 V after its actuation, in order to create a stiction condition. We monitored the S11 behavior when a 2 mA pulse is driven into one heater (see Fig. 1) for about 1.3 s.

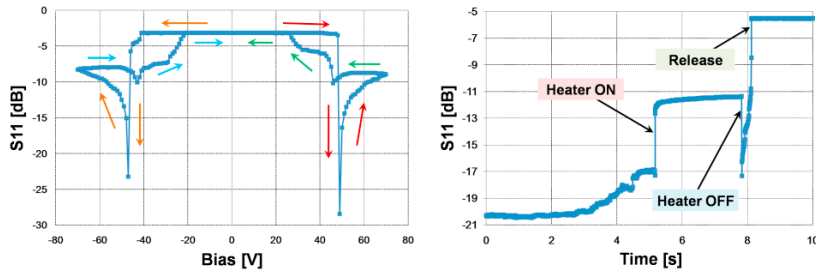


Fig. 2. (Left) Measured S11 parameter characteristic of the RF-MEMS switch of Fig. 1 in response to a zero mean value triangular bias ( $\pm 70$  V). The pull-in/pull-out (PI/PO) characteristic is visible. (Right) S11 parameter measured vs. time when the switch is kept actuated by means of a hold bias. The activation of a PolySilicon heater (see Fig. 1) with 2 mA for about 1.3 s leads to the release of the switch (rest position).

The heat induces an upward force on the central part of the MEMS membrane (i.e. the ohmic contact) as it is demonstrated by the S11 parameter shift from about 20 dB to 12 dB (i.e. towards the OFF position value). Right after the current pulse is switched off, the S11 parameter comes back for a very short time to about 17 dB, and then the MEMS membrane releases (transition to about 6 dB) despite the hold bias is still ON. The difference between the S11 values of Fig. 2-left/-right is due to a different calibration of the VNA, as the experimental data was acquired in two different measurement sessions. The same measurement was repeated several times on the same sample with different DC hold levels, as well as on a few other samples. A full release, as the one of Fig. 2-right, was observed just a couple of other times.

This rather low yield should not be interpreted as a poor effectiveness of the proposed active anti-stiction approach, but instead as the consequence of a still shallow knowledge on how the mechanism should be operated. Indeed, several degrees of freedom are available concerning, for instance, the amount of current to be driven into the serpentine as well as its waveform and period. Moreover, it should always be kept in mind that excessive heating might impair irreversibly the mechanical properties of the DUT (Device Under Test). Consequently, a deep understanding of all the just listed issues is necessary and we started to spend efforts in this direction, as reported in the following section on FEM simulations.

### 3. FEM Simulations

In this section we discuss the FEM modeling of the studied switch performed in Ansys<sup>TM</sup>. First of all, the vertical velocity of the switch is measured (laser vibrometer) by applying a CHIRP voltage (80 V peak-to-peak) up to 500 kHz to the heater, corresponding to a current of 2 mA. The thermal stimulation excites a few resonant modes, as Fig. 3-left shows, due to the heat-induced in-/out-of-plane deformations of the central suspended membrane. The MEMS switch is then studied in Ansys (modal analysis) and the first three main peaks are accurately superimposed to the measured ones (see Fig. 3-left). The Young's modulus used for the gold is 76 GPa (as reported in [15]) and we also included an in-plane 33 MPa tensile pre-stress, accounting for the stiffening due to the gold built-in residual stress. This is a best-fit value, and is in accordance with the ones proposed in [16]. Fig. 3-left also highlights several modes predicted by Ansys but not visible in the measured curve. This is very likely due to the fact that the laser vibrometer only detects the velocity of a spot in the centre of the plate. Such a spot might be very close to a node (i.e. zero displacement) of the structure for those resonant frequencies, indeed hiding them.

In order to better understand the effect of heating on the central membrane, we performed a transient simulation in Ansys applying a sinusoidal waveform (80 V peak-to-peak) to one heater with a frequency of 34.6 kHz, i.e. in correspondence with the first peak of Fig. 3-left. Fig. 3-centre shows the deformation of the central membrane after about 25  $\mu$ s of simulation (i.e. after about 1 period of the sinusoidal waveform).

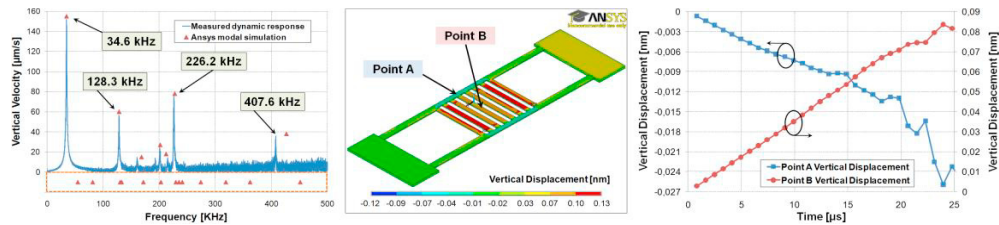


Fig. 3. (Left) Measured vertical velocity of a point on the central plate when one heater is activated with an 80 V CHIRP signal up to 500 kHz. The Ansys modal simulation predicts the first three main resonant frequencies. (Centre) The MEMS switch is simulated (transient) applying an 80 V sinusoidal waveform (34.6 kHz). (Right) Vertical displacement of the points A and B (Fig. 3-centre).

The heat-induced vertical deformation is upward in the central part of the membrane, and downward on the lateral sides. The deformation of points A and B highlighted on the plate surface in Fig. 3-centre is plotted vs. time in Fig. 3-right. The simulated deformations of the central plate are very small (less than 0.1 nm) as the temperature change induced by the applied voltage is just 0.2-0.3 Celsius [17]. However, such a type of investigation is sensible and deserves more efforts as the stimulation with a periodic signal close to the resonance promises to be a more effective approach for achieving the release from stiction than applying a constant current for a longer time (like in Fig. 2). The latter solution, indeed, causes definitely a larger impact on the MEMS mechanical properties.

#### 4. Conclusions

In this work we discussed the exploitation of an active micro-heater based mechanism to restore the operability of RF-MEMS switches that are in stiction due to either entrapped charge or micro-welding. We observed the successful release of a few MEMS switch samples when a constant current is driven into the heater.

FEM simulations showed that the dynamic activation of the heater with periodic signals close to one of the resonant frequencies of the MEMS device could improve the effectiveness of the proposed restoring approach and could, because of the smaller thermal loading, also lead to a smaller impact on the mechanical characteristics of the device. Consequently, dynamic activation concepts are in the focus of future research activities.

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