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Enhancement of RF-MEMS switch reliability through an active anti-stiction heat-based mechanism

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Abstract

MicroElectroMechanical Systems for Radio Frequency applications (i.e. RF-MEMS) show very good performance and characteristics. However, their employment within large-scale commercial applications is still limited by issues related to the reliability of such components. In this work we present the Finite Element Method (FEM) modelling and preliminary experimental results concerning an active restoring mechanism, embedded within conventional MEMS/RF-MEMS ohmic (and capacitive) relays, capable of retrieving the normal operation of the switch if stiction occurs (i.e. the missed release of an actuated switch when the controlling bias is removed). The mechanism exploits the heat generated by an electric current flowing through an high-resistivity poly-silicon serpentine (Joule effect), to induce deformations in the suspended MEMS structures. Such changes in the mechanical structure result in shear and vertical restoring forces, helping the membrane release. The FEM-based thermo-electromechanical simulations discussed in this work include the coupling between different physical domains, starting from the imposed current, to the MEMS deformation. The preliminary experimental data reported in this paper show a speed-up of the dielectric discharge time due to the generated heat, as well as a change in the S-parameters, due to the membrane expansion, compatible with an upward bending of the central contact (i.e. restoring force), useful to counteracting stiction due to micro-welding.

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1. Introduction

MEMS technology for Radio Frequency applications (RF-MEMS) has been attracting the interest of the International Scientific Community for the relevant potentialities it demonstrated. For instance, several lumped components, like variable capacitors, inductors and micro-relays (i.e. switches), with very high-performance have been already implemented and demonstrated by prominent research groups [1,2]. Besides, the availability of MEMS-based lumped components with good characteristics, like high Q-factor, low-loss, wide tuning range and so on, is pushing forward the design and fabrication of complex networks entirely implemented in such a technology. In the RF/Microwave field, a few valuable examples of the just mentioned blocks are reconfigurable phase shifters for transceiver and radar applications [3], impedance matching networks [4], and high-order switching matrices for the routing and the redistribution of RF signals, e.g. in satellites [5]. In spite of the significant boost RF-MEMS-based devices and functional blocks would give to commercial RF and transceiver platforms and applications, their penetration into the market is still limited. One of the main reasons to motivate the latter statement has to be sought in the relatively poor reliability that implementations based on RF-MEMS technology are still exhibiting. Nonetheless, reliability of MEMS is a rather complicated topic revealing a consistent number of intricacies. On one side, the sources of malfunctioning of MEMS/RF-MEMS devices are multiple, and are linked both to environmental factors, like moisture, dust particles, mechanical shocks etc., as well as to the normal operation of such devices, leading to aging, wearing, mechanical fatigue and so on [6]. On the other hand, procedures for the assessment of RF-MEMS reliability, like accelerated life tests, are not so well established as in standard solid state technologies. Given these considerations, it is clear that the efforts of the Research Community to address the reliability of MEMS have to be spent according to different points of view. In this work, we concentrate our attention on one of the most critical failure modes of MEMS, i.e. stiction, caused by normal operation of micro-relays. Stiction occurs when an electrostatically controlled MEMS switch does not come back in the rest position (OFF state) despite the controlling bias is removed, remaining indeed actuated (ON state). The main causes for this malfunctioning are the entrapment of charge within the insulating layer between the fixed and the movable membrane [7], and the micro-welding of the input/output ohmic contacts and the MEMS itself, caused by large RF signals flowing through the device [6]. We already proposed an RF-MEMS ohmic switch...
design, fabricated at Fondazione Bruno Kessler – FBK (Italy), featuring an embedded high-resistivity poly-silicon serpentine. The heat induced by a current driven into the serpentine generates, by thermal expansion of the gold MEMS structure, shear and vertical restoring forces, capable of counteracting stiction, indeed recovering the normal operation of a stuck device. Details concerning the proposed device are available in [8]. The discussed heating mechanism is suitable to reduce the discharge time of the insulating layer, indeed enhancing the reliability of RF-MEMS switches against charge entrapment [9]. We report here on the preliminary experimental testing carried out on the currently available samples, as well as on a FEM-based procedure, performed within Ansys™ through Parametric Design Language (APDL), to simulate the behaviour of the discussed RF-MEMS devices. The simulations are validated against experimental data concerning the coupled thermoelectric effect, and are then exploited to analyze the deformation of the central actuated MEMS membrane induced by the heat. Results reported in the following show that the induced heat speeds-up the dielectric discharge time. To this purpose, a switch sample was stressed with a DC bias for 6 h to accumulate charge in the insulating layer. Moreover, the S-parameters of an actuated RF-MEMS switch sample are investigated when the serpentine heater is activated. The experimental data collected so far show that the changes in S-parameters are compatible with an upward deformation of the gold membrane, proving the presence of a restoring force. Such a force might be sufficient to recover the functionality of a MEMS switch stuck because of micro-welding. Experiments in which micro-welding is purposely induced have not been performed yet and a suitable measurement setup is being assembled during the writing of this paper.

2. FEM modelling and results validation

The schematic of the RF-MEMS switch with heating mechanism [8] is reported in Fig. 1, together with labels to identify the RF, DC biasing, and heating pads. Each poly-silicon serpentine visible in figure has a resistance of 39 kΩ (measured with a Keithley 2612 Source Meter). A piece of silicon wafer close to the wafer border (i.e. roughly a triangle with smaller edges of 2.2 cm by 2.4 cm), containing several switch samples, has been observed with a thermal camera. A current square pulse (4 mA peak value) has been driven into a single heater of one sample for 30 s, and the camera recorded the image for 1 min, in order to observe both the heating and the cooling down of the whole silicon piece. Fig. 2 reports the thermal image of the tested piece during the first 10 s of the heating phase. The micro-probes used to inject the heating current are marked in the first frame (to the left), and visible in the rightmost image, where the temperature increase of the whole piece is more evident. The gold structure of the MEMS switches looks always dark because metals exhibit a rather low emissivity [10]. The temperature behaviour of the silicon piece vs. time is reported in Fig. 3, and is compared to the curve simulated in Ansys. The traces refer to the temperature of the spot highlighted with an arrow in Fig. 2-right. The qualitative comparison of the curves is rather good, even though differences concerning the temperature are visible both during the heating and cooling down of the specimen. The temperature detected by an IR thermal camera can be subject to a constant bias due to the reflection of the radiation emitted by the camera itself. A typical approach to overcome this issue is to increase the temperature of the chuck in order to have a reference temperature higher than the one due to the camera radiation reflection. In the setup we exploited it is not possible to control the chuck temperature and it was kept at ambient condition. However, we are more interested in the temperature variation due to the heater activation, rather than in the detection of the absolute temperature of the sample. The Ansys model accounts both for radiation and convection at the boundaries of the silicon piece. In this simulation (transient) no heat sink has been set in the lower face of the substrate, i.e. where the physical specimen lays on the probe station metal chuck. On the other hand, polystyrene was placed between the chuck and the specimen, in order to limit the heat dispersion towards the metal of the probe station. However, the thermal insulation provided by this solution is not as good as the one of a continuous layer of air (Ansys simulation). Furthermore, the simulated model includes only the heated switch, while the specimen features several MEMS switch samples. Consequently, the gold heat dissipating surface is significantly underestimated in the simulation. These are the most likely reasons for which the simulation overestimates the measured temperature (see Fig. 3).

3. Effect of heating on the dielectric discharge

The influence of the induced heat on the discharge dynamic of the oxide layer is experimentally investigated on the RF-MEMS switch topology discussed thus far. First of all, the static pull-in/pull-out (PI/PO) characteristic of a switch sample is measured by applying a zero mean value triangular waveform in the range ±80 V. The positive and negative pull-in/pull-out voltages (Pl+/PO+ and Pl−/PO−, respectively) are detected by observing the S-parameters at 6 GHz (HP 8753E Vector Network Analyzer). Subsequently, the device is stressed with an 80 V DC bias for 6 h, in order to accumulate charge within the oxide layer between the fixed electrode and the actuated gold membrane. For this particular type of device, the amount of charge entrapped after 6 h is not large enough to generate a spurious bias larger than the PO+ voltage and
keep the plate actuated. However, the accumulated charge screens the applied bias, causing a significant right-hand shift of the PI/PO characteristic. By repeating the static PI/PO measurement several times after the DC bias is removed, it is possible to observe a progressive left-hand shift of the characteristic, approaching the initial one (before stress). This phenomenon is due to the entrapped charge dispersion vs. time, and gives indications on the typical discharge time of the insulating layer.

![Fig. 3. Measured vs. simulated behaviour of the specimen temperature (see Fig. 2) over time (Iheater = 4 mA, 30 s ON and 30 s OFF).](image)

![Fig. 4. Comparison of the PI/PO characteristic measured before and right after applying an 80 V DC stress for 6 h. The right-hand shift of the characteristic induced by the entrapped charge is visible.](image)

Table 1

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>No heating</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PI(^+) (V)</td>
</tr>
<tr>
<td>Before stress</td>
<td>+29</td>
</tr>
<tr>
<td>After stress</td>
<td>+30</td>
</tr>
<tr>
<td>90</td>
<td>+32</td>
</tr>
<tr>
<td>210</td>
<td>+31</td>
</tr>
<tr>
<td>510</td>
<td>+30.5</td>
</tr>
<tr>
<td>1110</td>
<td>+30.5</td>
</tr>
<tr>
<td>2910</td>
<td>+30.5</td>
</tr>
<tr>
<td>6510</td>
<td>+30</td>
</tr>
<tr>
<td>10,110</td>
<td>+29.5</td>
</tr>
<tr>
<td>13,710</td>
<td>+29</td>
</tr>
</tbody>
</table>

consequently, the oxide layer discharge. During these measurements the serpentine heater is not activated. Table 1 reports all the PI\(^+\)/PO\(^+\) voltages detected during the discharge. The time column reports the delay of each measurement, starting from the instant when the DC bias is removed. The PI\(^+\)/PO\(^-\) voltages measured before the DC stress is applied (see Fig. 4) are also reported in Table 1. The shift of the PI\(^+\)/PO\(^-\) voltages towards the values measured before the DC stress is observable as the measurement time increases. The same measurement procedure is repeated on the sample applying a constant 2 mA current to the serpentine heater after the DC stress. The heating current influences the oxide discharge, indeed speeding-up the charge dispersion, as reported in Table 2.

In order to highlight the discharge speed-up induced by the heat, the PO\(^+\) and PI\(^-\) columns from Tables 1 and 2 are compared in Figs. 5 and 6, respectively. The discharge speed-up reported on previous tables and plots is visible despite it is not very large. Nevertheless, it should be kept in mind that the just discussed results are preliminary. Since an extensive experience in how to activate the heater has not been gathered yet, the experimental evidence of the correlation between the temperature increase and the discharge time has to be considered a promising result. Even though the analyzed switch did not get stuck with the entrapped charge, other MEMS topologies are more prone to such a failure (e.g. variable capacitors), and the discussed heater might be of critical importance for their recovery.

4. Heat-induced membrane deformation: simulations

After the validation against preliminary experimental data, Ansys is exploited to simulate the whole thermo-electromechani-
The behaviour of the membrane deformation under heating condition is also experimentally investigated. First of all, the static PI/PO characteristic showed a PI voltage of 45 V and a PO voltage of 24 V. Since an experimental setup to induce micro-welding is not available yet, we kept the MEMS plate down by applying a DC bias slightly higher than the PO voltage. Figs. 8 and 9 show the results of S-parameter measurements. A 50 V bias is applied to actuate the switch, and after 1 s it is lowered to 24.5 V and 25 V (hold voltage), as reported in Figs. 8 and 9, respectively. The serpentine heater is then activated with a current of 1, 2 and 3 mA for 3 s, and then deactivated for other 3 s before removing also the hold bias. The change in the S21 parameter due to the heat-induced deformation of the central actuated MEMS membrane is visible, as well as the dependence of the change magnitude on the amount of current driven into the heater. In the case of 24.5 V hold bias (Fig. 8) all the heating currents cause a change of the S21 towards the value measured for the not-actuated switch.
This result indicates a decrease of the contact pressure in correspondence with the in/out RF ohmic contacts, i.e. the presence of a restoring force due to the induced membrane deformation (see Fig. 7). When the applied hold bias is 25 V (Fig. 9), the 1 and 2 mA heating currents also induce a restoring force, while the 3 mA current seems to increase the contact pressure of the switch. However, the imposition of the hold bias is just a way to preliminarily determine the consequences of heating on the actuated RF-MEMS switch. In the case of a MEMS switch stuck because of actual micro-welding, the restoring force induced by the heater activation might very likely be large enough to break the micro-joints induced by large RF signals and restore, indeed, the normal operability of the micro-relay. Such an aspect urges further experimental investigation to fully validate the anti-stiction mechanism discussed in this work, and will be addressed by the Authors in the near future.

6. Conclusions

In this work we presented the preliminary experimental validation and the coupled-field FEM simulation of an RF-MEMS switch comprising an active mechanism to counteract the malfunctioning due to stiction. Such a mechanism exploits the thermal expansion of gold, due to a heating current, to generate restoring forces in the stuck (i.e. actuated) MEMS membrane. The discussed restoring mechanism is suitable to counteract stiction of micro-switches induced both from the charge entrapped in the insulating layer and from the micro-welding of ohmic contacts due to large RF signals. The preliminary experimental data discussed in this work show that the serpentine heater activation speeds-up the discharge time of the oxide layer after it is intentionally charged with a constant DC bias. Moreover, by means of S-parameters observation, it was demonstrated that the induced heat generates a vertical restoring force on the ohmic contact. This aspect is expected to be significantly useful in restoring an RF-MEMS ohmic switch stuck because of micro-welding. FEM simulations have been performed in Ansys and preliminarily validated against experimental data, in order to get a better understanding of the coupled thermo-electromechanical behaviour of the measured samples. In conclusion, the preliminary experimental activities performed on the RF-MEMS switches featuring the active restoring mechanism are very promising concerning the enhancement of RF micro-relays reliability, despite further experiments must be performed to fully prove the effectiveness of the approach discussed in this work. Eventually, the proper methodology to activate the heater without damaging the samples should also be determined.

References