Floating Electrode Microelectromechanical System Capacitive Switches: A Different Actuation Mechanism

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Abstract. The paper investigates the actuation mechanism in floating electrode MEMS capacitive switches. It demonstrated that in the pull-in state the device operation turns from voltage to current controlled actuation. The current arises from Poole-Frenkel mechanism in the dielectric film and Fowler-Nordheim in the bridge-floating electrode air gap. The pull-out voltage seems to arise from the abrupt decrease of Fowler-Nordheim electric field intensity. This mechanism seems to be responsible for the very small difference with respect to the pull-in voltage.

The radio frequency (RF) microelectromechanical systems (MEMS) switches and varactors have been developed more than fifteen years ago for low loss switching/routing circuits and X-band to millimeter-wave (mm-wave) phase shifters, which have seen increasing applications in tunable filters, antennas and reconfigurable matching networks [1, 2]. Among the different designs, the capacitive switches proved to exhibit excellent RF performance and power handling [3, 4]. The performance of the capacitive switches depends on the down-state capacitance that can be limited by the finite roughness as well as the low planarity of both the dielectric layer and the beam [5, 6]. In order to diminish this effect and ensure a constant capacitance in the pull-in state, the deposition of an additional (electrically floating) metal layer on the dielectric layer was proposed [7, 8, 9]. Such devices are actuated through side actuation pads or by applying the bias directly to the transmission line. Among the two actuation methods, the former is similar to the one used in conventional capacitive switches and the pull-in condition has been analyzed in details in many papers including or not the charging effect, *e.g.* [1, 2, 10, 11. In these switches the actuation through the floating electrode has received no attention in spite of the dramatic change of bridge to floating electrode capacitance, hence the potential difference, upon the transition from pull-out to pull-in state. The aim of the present work is to analyze the actuation mechanism of the floating electrode capacitive switch, demonstrate that in the pull-in state the conventional condition $V \geq V_{pi}$ cannot further hold and the device turns from voltage to current actuation.

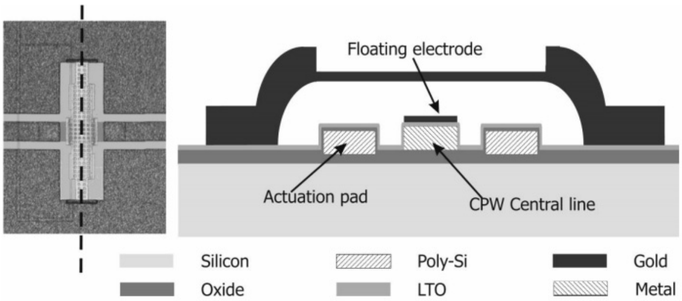
The switches used in present work were parallel single pole single through (SPST) cells. In the parallel (shunt) version of the SPST a metal membrane (movable air bridge) above the CPW substrate can electrically short the centre line to ground when electrostatically actuated, as shown in Figure 1a. Two side actuation pads were added in order to separate the DC bias from the RF signal on central line. These actuation pads were connected with polysilicon bias lines which were isolated with 300nm SiO_2 film from the ground plane and coplanar transmission line (fig. 1a). In the present work the bias was applied only to coplanar waveguide transmission line (CPW) and not to the side actuation pads. Under the bridge the central line was constituted by a metal multilayer (Ti-TiN-Al-Ti-TiN) covered by SiO_2 dielectric film (Low Temperature Oxide, LTO) with a thickness of about 100 nm. A floating metallic (Au) contact (90μm × 150μm) was deposited on the top surface of the dielectric film to ensure a constant capacitance during pull-in state where the device must behaved like MIM capacitor with a capacitance of $C_{MIM} \cong 4.66$pF.

The capacitance of the RF MEMS switches was measured at 1 MHz with a Boonton 72 B capacitance bridge that provided a resolution better than 0.5 fF. The current-voltage characteristic was measured at room temperature with a Keithley 6487 picoampere meter. All measurements were performed in vacuum and the surface humidity was removed by heating cycles at 140°C for two hours each time. Finally prior assessment the devices were stored in vacuum. Unipolar capacitance-voltage characteristic were obtained increasing the voltage from 0 to 50 V and then returning back to 0 V (fig. 1b). In all measurements the bias was applied to the transmission line with respect to the ground level. Unlike the conventional actuation without floating electrodes or by using the lateral pads, there was no apparent hysteresis. The two branches of CV curve for increasing and decreasing voltage are practically superimposed and the pull out and the pull in voltages are about the same.

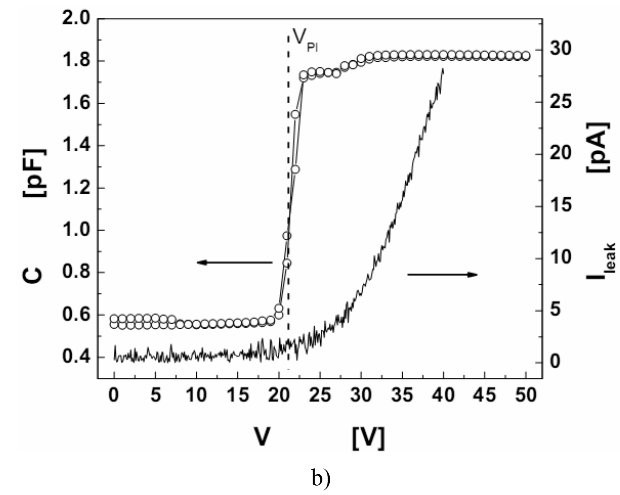
As already mentioned a metal film floating electrode was deposited on the dielectric surface in order to ensure primarily a constant capacitance during pull-in. The presence of this metallic film cap leads to uniform charge injection and screens any potential fluctuation that may arise inside the insulating film. In absence of dielectric charging, if z_0 is the air gap at equilibrium, k the spring constant, A the switch area, d the dielectric film thickness ($d \ll z_0$) and V the applied bias the pull-in voltage will be given by:

$$V_{PI} = \left(1 + \frac{3d}{2\varepsilon_r z_0}\right) \cdot \sqrt{\frac{8k z_0^3}{27 \varepsilon_0 A}} \quad (1)$$

where the first term is introduced by the capacitors voltage divider. The pull-out voltage cannot be calculated in the conventional way because of the following reasons: i) the absence of a dielectric film between the floating electrode and bridge, although the asperities and roughness will not allow the perfect contact between the electrodes and ii) the fact that as soon as the bridge lands on the floating electrode they attain the same potential and the electrostatic force vanishes. For an ideal dielectric, where no leakage occurs, the later will lead to a transitory actuation after which the bridge will return permanently to pull-out state. In Fig.1b the switch remains in the "pull-in" state, a fact that indicates the presence of electrostatic force.



a)



b)

Fig. 1. (a) Picture and cross-section of the device and (b) the unipolar capacitance-voltage and current-voltage characteristic of the MEMS switch.

The electric field between the bridge and floating electrode clearly denotes that, during contact, transferred charges are dissipated as soon as the contact is lost. The practically constant pull-in capacitance leads to the conclusion that charges are transferred from the bridge to the floating electrode and further through the insulating film to transmission line. Since the current may be injected through even one asperity, no further bridge flattening will occur when the applied bias increases. This current arises from field emission (Fowler-Nordheim, I_{FN}) in the gap and Poole-Frenkel (I_{PF}) in the dielectric film. According to this I_{FN} (V_{FN}) = I_{PF} (V_{PF}) while the applied bias will be given by $V=V_{FN} + V_{PF}$, where $V_{\rm FN}$ and $V_{\rm PF}$ are the voltages across the gap and the dielectric film controlling the Fowler-Nordheim and Pool-Frenkel effects respectively. Now, if w is the gap through which current flows, then the currents equality can be written as:

$$A\cdot C\cdot\left(\frac{V_{FN}}{w}\right)^2\cdot\exp\left(-B\frac{w}{V_{FN}}\right)=M\cdot\left(\frac{V_{PF}}{d}\right)\cdot\exp\left[-\frac{q\cdot\left(\Phi-\sqrt{\frac{q}{\pi\varepsilon}\cdot\frac{V_{PF}}{d}}\right)}{kT}\right] \qquad (2)$$

where Φ is the trap emission barrier, $C=\frac{q^3}{8\pi h\Phi_1}=2.96\cdot10^{-7}\ \mathrm{A/V^2}$ and $B=\frac{4\sqrt{2}\cdot\Phi_1^{3/2}}{3q\hbar}\cdot\frac{m^*}{m_e}=81.0\ V/nm$, the numerical values obtained for the Au-vacuum potential barrier (Φ_1 = 5.2eV). Finally, M is a constant proportional to Poole-Frenkel conductivity. At this point we must stress that w is much smaller than the average gap measured through capacitance. The effective value of w arises from one or more asperities or surface roughness peaks that ensure the required current flow. Since (2) is valid only in the pull-in state it becomes obvious that the capacitance-voltage and current-voltage characteristics have to be monitored and plotted simultaneously. The two characteristics are presented in Fig. 1b and allow the determination of the onset of leakage current, which practically coincides with the transition to pull-in state. Here it must be pointed out that in spite of the fact that the experiment has been performed in vacuum the presence of surface leakage currents cannot be overruled. At pull-in the potential drop across the gap and w readjust in order to compensate the current through the dielectric film. Taking these into account and the fact that the Fowler-Nordheim current increases faster with the gap electric field than the Poole-Frenkel one with the electric field in the film, as deduced from (2), we are led to the conclusion that V_{FN} must not vary significantly above pull-in. This allows the fitting of Poole-Frenkel law to the measured current using V_{FN} as fitting parameter, as shown in Fig. 2.

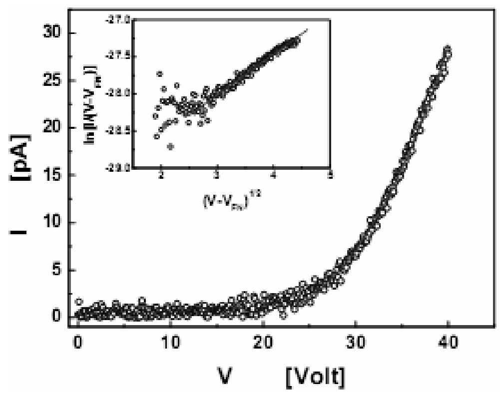


Fig. 2. Current-voltage characteristics of the MEMS switch. The inset shows the excellent agreement with Pool-Frenkel effect.

The calculated potential drop across the gap (V_{FN}) was found to be about 20.4 Volt, which is in good agreement with the pull-in voltage of V_{PI} = 21.4 Volt obtained from the capacitance-voltage characteristic (fig. 1b). The smooth transition to pull-in state, within 3 Volt, cannot be attributed to the bridge mechanical deformation, like in conventional switches, but rather to mechanism that controls the pull-in state. Nevertheless, this effect requires further investigation. The pull-out voltage (V_{PO}) when calculated in the conventional way, assuming the presence of an air gap in the pull-in state [12] and taking into account the capacitors divider, leads to:

$$\frac{V_{PO}}{V_{PI}} = \frac{3}{2} \cdot \frac{\varepsilon_r w_0 + d}{2\varepsilon_r z_0 + 3d} \cdot \sqrt{3 \cdot \frac{z_0 - w_0}{z_0}} \tag{3}$$

where w_0 is the average gap calculated from C-V characteristic in the pull-in state. For the present device, with an air gap of about 3μm, the theoretical and measured capacitances in the pull-out state are $C_{po\text{-}th} \approx 0.04$pF and $C_{po\text{-}meas} \approx 0.56$pF, the later arising from the parasitic capacitances introduced by the low frequency measurement setup. In the pull-in state on the other hand the measured pull-in capacitance is $C_{pi\text{-}meas} = 1.83$pF and being further corrected to 1.31pF by considering the parasitic capacitances, leads to an average air gap $w_0 \approx 69$nm, which is in reasonable agreement with previously reported values by S. Melle *et al.* [5]. According to these values (3) leads to a very low pull-out voltage (4% of V_{PI}) that disagrees with data in Fig.1b and clearly indicates a different pull-out mechanism. Since the phenomena occurring at pull-out could not be analytically derived we calculated theoretically I_{PF}, using the previous fitting parameters, and from this the corresponding electric field intensity for the FN effect (E_{FN}), both as a function of applied voltageHere it is important to emphasize that E_{FN} is the electric field across the shortest distance between the floating electrode and the moving armature arising from asperities where the field emission current occurs in order to fulfill (2). The results are shown in Fig. 3 and indicate an abrupt decay of E_{FN} below pull-in voltage. The abrupt decrease of E_{FN} obviously results in a decrease of current and since the continuous flow cannot be further maintained the bridge is released. Here it must be pointed out that if the pull-out voltage was smaller, then at pull-in the leakage current would exhibit a sharp increase and vanish at pull-out as shown above.

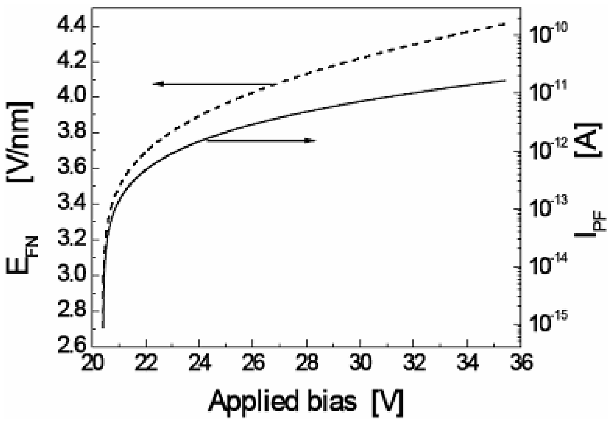


Fig. 3. Dependence on Poole-Frenkel current and corresponding Fowler-Nordheim electric field intensity of the applied bias to device terminals.

In conclusion, it has been demonstrated that in floating electrode MEMS capacitive switches the operation is different with respect to conventional ones. Although the transition to pull-in state is electrostatically controlled in the conventional way, the pull-in is sustained through current flow that allows the development of electrostatic force between the floating electrode and the moving armature. This process appears to control the pull-out voltage since the electric field in the gap vanishes as soon as the diminishing of the current through the dielectric cannot be sustained. Finally we should like to emphasize that this mechanism is promising because it can lead to new devices with properly engineered dielectric films that will efficiently mask the charging and produce a new generation of MEMS capacitive switches.

References

[1] G.M. REBEIZ, *RF MEMS: Theory, Design, and Technology*, Hoboken, NJ: Wiley, 2003.

[2] G. REBEIZ, K. ENTESARI, I.C. REINES, S.-J. PARK, M. EL-TANANI, A. GRICHENER and A.R. BROWN, IEEE Microwave Magazine **10**, 55, 2009.

[3] C.L. GOLDSMITH, J. EHMKE, A. MALCZEWSKI, B. PILLANS, S. ESHELMAN, Z. YAO, J. BRANK and M EBERLY, IEEE MTT-S Int. Microwave Symp. Digest, Long Beach, CA, 227, (2001)

[4] J.B. MULDAVIN, R. BOISVERT, C. BOZLER, S. RABE and C. KEAST, IEEE MTT-S Int. Microwave Symp. Dig., pp. 1915, Philadelphia, PA, June 2003.

[5] S. MELLE, D. De CONTO, D. DUBUC, K. GRENIER, O. VENDIER, J.-L. MURARO, J.-L. CAZAUX and R. PLANA, IEEE Trans. on Microwave Theory and Techniques MTT-**53**, 3482, 2005.

[6] H.M.R. SUY, R.W. HERFST, P.G. STENEKEEN, J. STULEMEIGER and J.A. BIELEN, NIST Proc. Nanotech, 1-5 June, Boston, 2008.

[7] Jae Y. PARK, Geun H. KIM, Ki W. CHUNG, Jong U. BU, Sensors and Actuators A **89(**88), 2001.

[8] X. ROTTENBERG, H. JANSEN, B. NAUWELAERS, P. FIORINI, W. De RAEDT, H.A.C. TILMANS, *Boosted RF-MEMS capacitive shunt switches*, Proceedings of Workshop on Semiconductor Sensor and Actuator, pp. 667–671, SeSens, Veldhoven, Nov. 2003, The Netherlands.

[9] C. CALAZA, B. MARGESIN, F. GIACOMOZZI, K. RANGRA and V. MULLONI, Microelectronic Engineering **84**, 1358, 2007.

[10] W. Merlijn van SPENGEN, Robert PUERS, Robert MERTENS and Ingrid de WOLF, J. Micromechanics Microengineering **14**, 514, 2004.

[11] X. ROTTENBERG, I. DE WOLF, B.K.J.C. NAUWELAERS, W. De RAEDT, H.A.C. TILMANS, W. De RAEDT and Harrie A.C. TILMANS, IEEE Journal of Microelectromechanical Systems **16**, 1243, 2007.

[12] H.J. De Los SANTOS, G. FISCHER, H.A.C. TILMANS and J.T.M. van BEEK, IEEE Microwave Magazine, pp. 36–49, Dev. 2004.