Distributed dielectric charging and its impact on RF MEMS devices

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***Abstract* — This paper gives a new insight into the problem of RF MEMS irreversible stiction due to dielectric charging. Previous reported works describing the phenomenon only account for a drift of the actuation characteristics as a whole as they consider uniform charge densities. We demonstrate how the spatial charge distribution in the dielectric layer can result in the failure of the devices. We emphasize the role of the variance of the distribution, a parameter neglected in the literature. Our model can account for a shift of the C-V actuation characteristics but also for a change in its profile. In particular, the pull-out window can be narrowed and even made to disappear as a result of the non-zero variance of the charge distribution. We identify the processing, the contact conditions and the distributed charge depths as variance- and thus failure-enhancer parameters.**

I. INTRODUCTION

The dielectric-charging phenomenon is widely accepted as a major yield and reliability issue for electrostatically actuated RF MEMS switches [1]-[7]. Charges trapped or displaced during the processing and/or the actuation of the electrostatic devices can result in their latching or their self-biasing. Indeed, a uniform charge distribution built in the dielectric layer of a device as shown in Fig. 1 results in a shift of the whole C-V curve as shown in Fig. 2, measured and described thoroughly in [6]-[8].

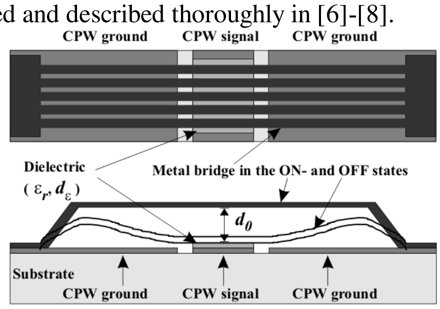

Fig. 1. Standard RF MEMS capacitive shunt switch

Besides lowering the actuation voltage in an attempt to minimize the stress on the dielectric layer and the resulting built-in charges, other complex actuation schemes like shaped actuation-pulses [3] and bi-polar actuation voltages [5] have been proposed. These techniques keep the C-V characteristics more centered on the bias origin at 0V, preserving the normal actuation of the switches.

Nevertheless, RF MEMS devices still fail due to dielectric charging. The shift of the C-V curve does not succeed to explain the narrowing of the pull-out window and the resulting vanishing of the pull-out bias that leads to an irreversible stiction as shown in Fig. 3.

This paper gives a new insight into the stiction of RF MEMS devices due to dielectric charging. We use remarkably simple formalism and concepts to take a 3D charge distribution into account and to explain the shift and the deformation of the C-V curves leading to a failure.

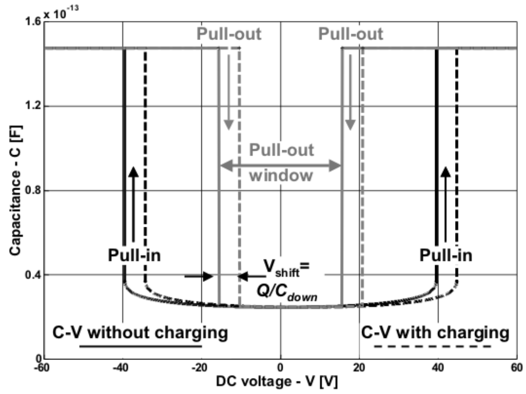

Fig. 2. C-V curve with a uniform charging (i.e. zero-variance)

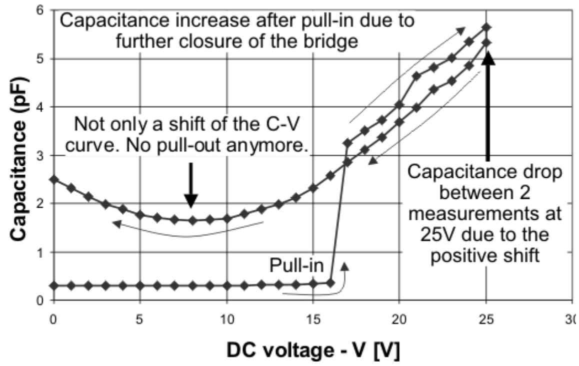

Fig. 3. C-V curve showing the stiction of a shunt switch

II. NON-UNIFORM DIELECTRIC CHARGING

A. *Thought experiment*

Consider the setup sketched in Fig. 4. A fixed metal plate is covered with a dielectric layer split in two parts with equal areas. The two dielectric islands have uniform fixed surface charges of opposite sign (*+/-Q*). A movable metal plate is fastened with a spring above the dielectric layer. A DC voltage source is applied to the two plates. The *+/-Q* charges shift the voltage-force characteristics by *+/-*V_{shift}, opposite for the 2 dielectric islands.

It is striking to observe that although the net dielectric charge is zero, the resulting electrostatic force F_{el} is not zero, even at 0 applied voltage.

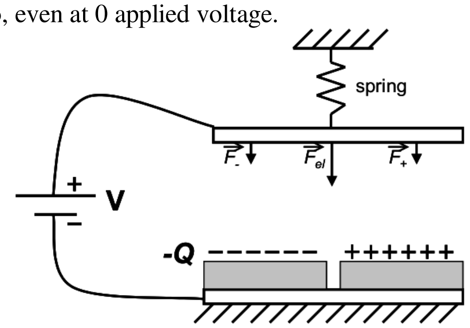

Fig. 4. Stiction thought experiment

B. Mathematic description

In this section, we develop a 3D model taking into account the volume charge distribution and demonstrate that the unrealistic charging situation used in the thought experiment is not needed to produce the same effects.

Consider the setup in Fig. 5, generalizing the model presented in [8]. A fixed metal plate of area A is covered with a dielectric layer of thickness d_ε, dielectric constant ε_r and volume charge density $\psi(x,y,z)$. A rigid movable metal plate is fastened with a spring k to a fixed wall above the dielectric layer at a rest position d_0. A DC voltage source of amplitude V is applied to the two plates. The setup is placed in vacuum.

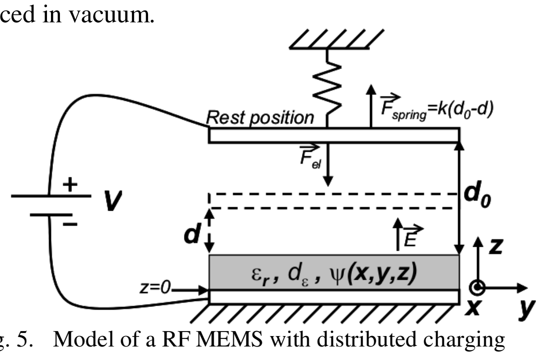

Fig. 5. Model of a RF MEMS with distributed charging

Using Gauss' law and assuming the electric field is everywhere aligned with the z-axis, F_{el} is given by

$$F_{el}(d)=\frac{\varepsilon_0}{2}\int_{Area}\left[\frac{V-\dfrac{\psi_{eq}(x,y)\ d_\varepsilon}{\varepsilon_0\varepsilon_r}}{d+\dfrac{d_\varepsilon}{\varepsilon_r}}\right]^2 dx\ dy \qquad (1)$$

where d is the gap spacing and

$$\psi_{eq}(x,y)=\int_0^{d_\varepsilon}\int_\alpha^{d_\varepsilon}\frac{\psi(x,y,z)}{d_\varepsilon}\ dz\ d\alpha \qquad (2)$$

is the equivalent surface charge distribution defined as the surface charge distribution placed at $z=d_\varepsilon$ which produces the same electrostatic force as the actual $\psi(x,y,z)$. Note that a charge Q placed at the surface of the dielectric has an equivalent $Q_{eq}=Q$ while the same charge Q placed at the bottom of the dielectric has an equivalent $Q_{eq}=0$.

The stable and unstable electromechanical equilibrium positions of the movable plate are obtained by balancing $F_{el}(d)$ with the spring force $F_{spring}=k(d_0-d)$ and are thus expressed by

$$V=\frac{\overline{\psi_{eq}}d_\varepsilon}{\varepsilon_0\varepsilon_r}\pm\sqrt{\frac{2k}{\varepsilon_0 A}(d_0-d)\left(d+\frac{d_\varepsilon}{\varepsilon_r}\right)^2-\frac{d_\varepsilon^2\sigma^2(\psi_{eq})}{\varepsilon_0^2\varepsilon_r^2}} \qquad (3)$$

where $\overline{\psi_{eq}}$ and $\sigma^2(\psi_{eq})$ are the mean and variance of the equivalent surface charge distribution $\psi_{eq}(x,y)$.

On the one hand, the mean equivalent charge results in a shift of the *d-V* and C-V curves equivalent to the Q/C_{down} shift obtained for a uniform charging [8]. On the other hand, the variance of $\psi_{eq}(x,y)$ affects the shape of the actuation characteristics. The non-zero variance has the effect of a permanent force offset. Note for example that a non-zero variance forbids the rest position of the spring $d=d_0$ as an equilibrium position for the system. This is a manifestation of the never vanishing F_{el} in our thought experiment.

C. Failure due to the disappearance of the pull-out bias

The pull-out voltage V_{PO}, obtained from (3) with d=0, is a parabolic function of the charge variance, given by

$$V_{PO}=\frac{\overline{\psi_{eq}}d_\varepsilon}{\varepsilon_0\varepsilon_r}\pm\sqrt{\frac{2kd_0d_\varepsilon^2}{\varepsilon_0\varepsilon_r^2A}-\frac{d_\varepsilon^2\sigma^2(\psi_{eq})}{\varepsilon_0^2\varepsilon_r^2}} \qquad (4)$$

Increasing the variance, the 2 symmetric V_{PO} shift towards each other, as shown in Fig. 6(a) and (b) in the case of a zero mean charge. The pull-out window narrows, as measured and reported in [4], and vanishes for a variance of $\psi_{eq}(x,y)$ independent of the dielectric layer parameters and given by

$$\sigma^2_{no\_PO}=\frac{2kd_0\varepsilon_0}{A} \qquad (5)$$

As the movable plate can not be released anymore, the structure fails by stiction on the dielectric due only to the variance of $\psi_{eq}(x,y)$. Note that the pull-in voltage V_{PI} is hardly changed in comparison to V_{PO}.

(a)

(b)

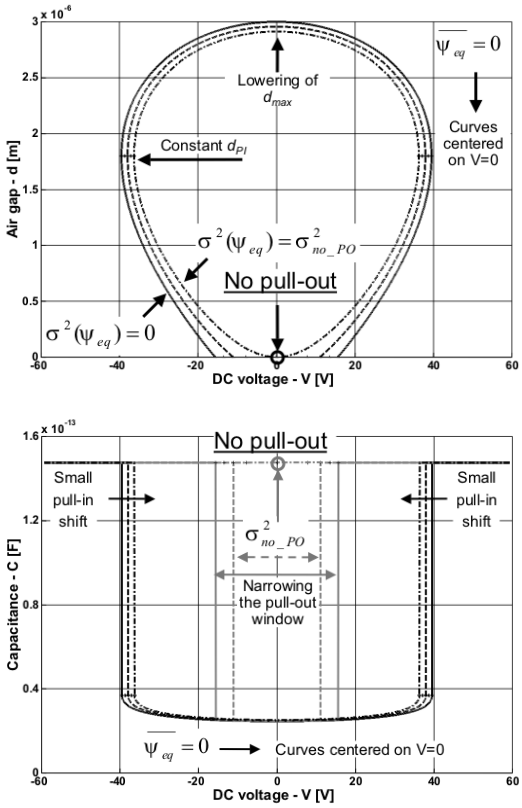

Fig. 6. Simulated narrowing of (a) the full *d-V* and (b) the stable C-V curve of the system sketched in Fig. 5 increasing $\sigma^2(\psi_{eq})$ until $\sigma^2_{no\_PO}$; $k=10N/m$, $A=10^4\mu m^2$, $d_o=3\mu m$, $\varepsilon_r=5$ and $d_\varepsilon = 3\mu m$.

D. Failure due to the disappearance of the pull-in bias

From (3), we can easily show that the gap spacing at pull-in d_{PI} is not affected by the charging and is still given by $(2d_0-d_\varepsilon)/3$. V_{PI} is a function of the charging given by

$$V_{PI} = \frac{\overline{\psi_{eq}} d_\varepsilon}{\varepsilon_0 \varepsilon_r} \pm \sqrt{\frac{8k}{27\varepsilon_0 A}\left(d_0 + \frac{d_\varepsilon}{\varepsilon_r}\right)^3 - \frac{d_\varepsilon^2 \sigma^2(\psi_{eq})}{\varepsilon_0^2 \varepsilon_r^2}} \qquad (6)$$

V_{PI} can also disappear due to the variance of $\psi_{eq}(x,y)$. The critical variance for the pull-in is given by

$$\sigma^2_{no\_PI} = \frac{8k\varepsilon_0 d_\varepsilon}{27 A \varepsilon_r}\left(\frac{\varepsilon_r d_0}{d_\varepsilon} + 1\right)^3 \qquad (7)$$

Fig. 7(a) and (b) show simulations equivalent to Fig. 6(a) and (b), increasing the variance from $\sigma^2_{no\_PO}$ to $\sigma^2_{no\_PI}$. The whole *d-V* and C-V characteristics gradually vanish. As there is no more stable position for the movable armature, the device fails by self-actuation due only to the variance of the equivalent surface distribution.

(a)

(b)

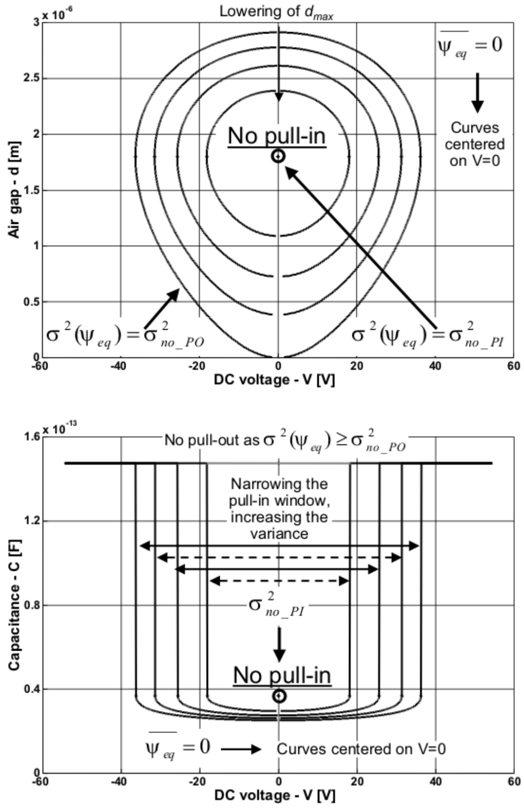

Fig. 7. Simulated complete closure of (a) the full *d-V* and (b) the stable C-V curves of the system already simulated in Fig. 6, this time increasing $\sigma^2(\psi_{eq})$ from $\sigma^2_{no\_PO}$ to $\sigma^2_{no\_PI}$

E. Influence of the physical parameters

Remarkably, only the variance of $\psi_{eq}(x,y)$ is needed to explain the irreversible stiction phenomenon. The dependency of the 2 branches of V_{PO} and V_{PI} vs. the charging variance is illustrated in Fig. 8 from (4) and (6).

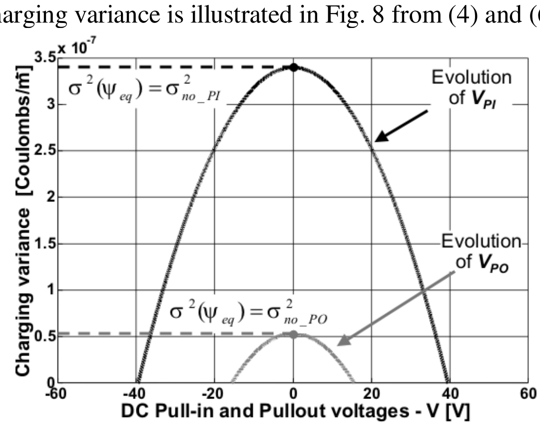

Fig. 8. Evolution of V_{PO} and V_{PI} vs. $\sigma^2(\psi_{eq})$.

As $V_{PO}<V_{PI}$ in absence of charge, V_{PO} disappears earlier than V_{PI}. Note that imposing $\sigma^2_{no\_PI}=\sigma^2_{no\_PO}$ implies $d_\varepsilon=2\varepsilon_r d_0$ using (5) and (7). This condition is equivalent to

$V_{PO}=V_{PI}$ and to the condition derived in [9] for a continuously stable actuation from $d=d_0$ to $d=0$.

All other things being equal, a larger spring constant per unit area k/A, a larger rest air gap d_0, a thinner dielectric layer d_ε and a higher dielectric constant ε_r make a switching device less sensitive to the variance and mean of $\psi_{eq}(x,y)$. In this view, assuming the equivalent surface charge distribution is independent of k, A, d_ε, ε_r, and d_0, large capacitance ratio $(\varepsilon_r d_0/d_\varepsilon)$ switches with large V_{PO} and V_{PI} are expected to be more reliable.

III. Sources of variance in dielectric charging

The *processing* is the first source of dielectric charging. The distributions of defects and traps imprinted in the dielectric layer during the processing are determining factors for the charging susceptibility and distribution.

The *parasitic air gap* [10] remaining upon closure of the device will lead to a distributed injection of charges and therefore a distributed charge in the dielectric.

The model presented in Fig. 5 assumed rigid plates. In practice however the movable plate deforms during its actuation so that d is also a function of (x,y) in (1).

The varying gap in the deformed state leads to a varying electric field, which results in a variation in the induced charges. For a shunt switch as shown in Fig. 1 the maximal deflection occurs in the center of the bridge. The middle of the dielectric area feels more electromechanical stress. The dielectric thus charges more in the center than at the edges.

The *charge depth* has an influence on its equivalent surface counterpart as expressed by (2). This induces an asymmetry of the charging effect for bias voltages of opposite signs in case of trapping. The equivalent surface charge distribution ψ_{eq} can as a consequence vary with (x,y) and lead to a failure even in the case of a uniformly nil charge density per unit area (i.e. $\int_0^{d_\varepsilon} \psi(x,y,z)dz = 0$).

IV. Conclusion

We have presented a model for the electrostatic actuation of MEM devices taking into account the volume distribution of charges in the dielectric layer. The 3D charging model covers all the phenomena that are explained by the uniform charging model. Further the 3D model explains the following:

- Even for a zero net dielectric charge but with a non-zero charge variance, an electrostatic force results.
- A non-zero charging variance forbids the rest position of the spring as an equilibrium position for the system.
- The pull-out and pull-in windows are narrowed by increasing the variance of the charge distribution.
- The pull-out phenomenon can disappear due to dielectric charging only, leading to permanent stiction.
- The pull-in phenomenon can disappear due to dielectric charging only, leading to permanent self-biasing and stiction.

Switches with a large capacitance ratio and large pull-out and pull-in voltages are less sensitive to a given dielectric charging condition. The processing, contact conditions and depth effects have been described to explain the origins of the variance of the equivalent surface charge distribution.

Acknowledgement

This project was supported by ESA-ESTEC under contracts 14627/00/NL/KW and 10435/02/NL/GS. Particular thanks go to F. Deborgies, L. Marchand and Juan Guijarro from ESTEC and M. van Spengen and I. De Wolf from IMEC for critic and fruitful discussions. We also thank the members of the L.E.T.

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