DESIGN AND FABRICATION OF MEMS BASED AC VOLTAGE REFERENCE

A. Bounouh[1], H. Camon[2], R. Plana[2], D. Bélières[1], Q. Wang[1], F. Blard[2], F. Ziadé[1], A. Poletaeff[1], D. Allal[1] and C. Pisella[3]

[1]LNE – 29 avenue Roger Hennequin, 78197 Trappes, France
[2]LAAS/CNRS – Université de Toulouse - av du colonel Roche, 31077 Toulouse cedex 4, France
[3]Tronic's Microsystems – 55 rue du Pré de l'Horme, 38926 Crolles cedex, France
alexandre.bounouh@lne.fr

Abstract – This work explores the MEMS potentialities to fabricate flexible AC voltage references through mechanical-electrical transduction that could be used for high precision electrical metrology or for applications in miniaturized instrumentation. The design presented allows the generation of AC voltage reference ranging from 1V to 60 V using the same Epitaxial Silicon On Insulator (SOI) Surface Micromachining process that permits an accurate control of both dimensions and material properties. Different tests structures have been designed and fabricated. First results show a good agreement between the calculated and the measured characteristics of the devices and the performance, stability and reliability of these systems is still under investigation.

I. Introduction

MEMS technologies and devices are used nowadays in widespread applications thanks to the development of microelectronics technologies and processes. Besides, MEMS are for some applications in a production phase with dedicated factories. However, fundamental problems of physics remain unsolved as mesoscopic flows in the micropumps, damping phenomenon and adhesion at nanoscale, mechanics of small constraints... In electrical metrology, works undertaken since 1995 allowed to demonstrate the validity of MEMS approach to realize electrical references. Indeed, from MEMS devices made up of membranes, beams or seesaw structures, several applications in electrical metrology are possible as AC and DC voltage references, RF-DC converters, current reference, low frequency voltage divider and RF and microwaves power sensors [1-3]. Such devices are made of micro-machined electrodes of which one at least is movable thanks to the application of an electrostatic force between the two electrodes, inversely proportional to the square of the gap (Fig.1 left).

For voltage references, one uses the pull-in effect of a electro-mechanical microsystem having a movable electrodes. The stable displacement named x of the movable electrode is limited to the third of the gap named d. Figure 1 (right) shows the characteristic voltage-displacement where the pull-in voltage V_{pi} corresponds to the maximum voltage applied to the capacitive MEMS beyond which the two electrodes are put in contact.
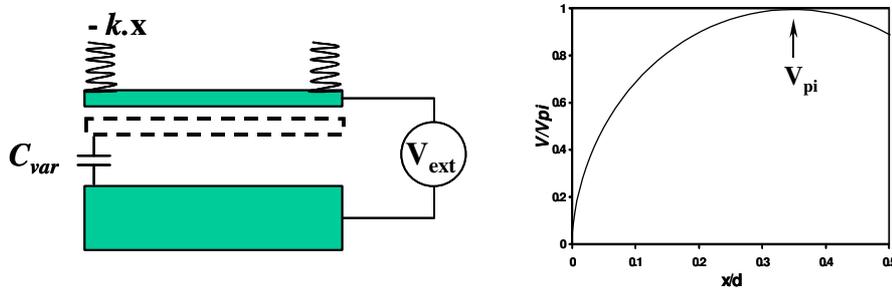

Figure 1. Capacitive MEMS and its voltage-displacement characteristic

If the structure of figure 1 is now biased with a AC sinusoidal current of amplitude I_{RMS} and frequency ω, the AC voltage presents, according to the current I_{RMS}, a maximum (Fig.2):

$$V_{AC}^{\max} = V_{pi} = \sqrt{8kd^2 / 27C_0} \qquad (1)$$

(C_0 is the capacitance at x = 0 and k the spring constant), which can be used as a stable AC voltage reference, since its relative variation in this point depends only on the square of that of the current.
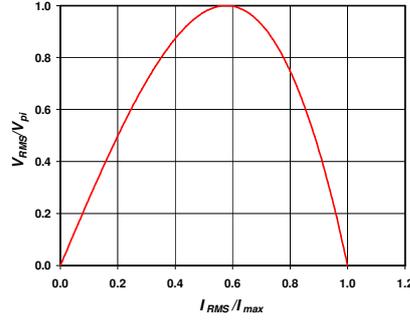

Figure 2. MEMS Voltage versus I_{RMS} biasing current

Thus, results of such experiments presented in [3] showed a stability of 2 ppm over three weeks (after ambient humidity, pressure and temperature corrections) of a 9 V MEMS AC voltage reference obtained with a commercial accelerometer. In order to have the required stability performance for primary and secondary metrology fields and precision instrumentation (some parts in 10^7 per year), special designs and architectures featuring low sensitivity with respect to strain and geometrical dispersion have to be investigated, as well as technological processes featuring low residual stress and high repeatability.

II. Design methodology and calculations

The stability and the reproducibility of the MEMS based AC voltage standard V_{pi} relates mainly on the stability of the spring constant k and the geometrical properties of the device (i.e the gap distance and the C_0 capacitance). The dispersion of the AC voltage reference is mainly caused by the residual and gradient of mechanical stress and the charging effects [4] that could turn out to a limitation in the stability of the MEMS based voltage references. It is therefore, important to deeply investigate these limitations in order to be able to overcome them either through technological developments or through appropriate architectures. The structures that are under discussion in this paper are based on a silicon disk plate featuring different configuration of the suspending springs to ensure a controlled piston mode motion. The structures have been designed using a Coventorware CAD platform and the design kit of a commercially available MEMS process developed by TRONIC's Microsystems. Figure 3 shows the layouts of the movable part of the structures that have been designed and that will be used for the tests. The first device (1) is a 500 µm-radius disk plate with three curved 1300 µm-long springs of 3 µm width. Device (2) is very similar to (1) design and has the same dimensions, only the curved part of the springs in (2) are attached together forming a ring of 3 µm width, which slightly increases the stiffness of the structure and then V_{pi}. The aim of this design is to improve the vertical guidance of the movable plate. The same disk plate as previously (r =500 µm) is used for forming the last design (3) having four straight springs (360 µm $\times$ 3 µm). The whole structures have been designed to have a capacitance C_0 in the range of 4 pF and resonance frequencies less than 50 kHz ($\omega_0 = \sqrt{k/m}$).
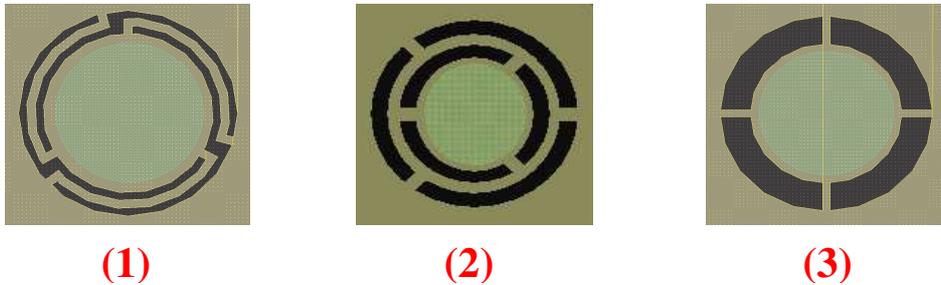

(1)   **(2)**   **(3)**

Figure 3. Design of several shapes of electrostatic test structures.

The design of the structures is carried out following 3 steps: *i*) definition of deposit type, etching and thickness of the layers; *ii*) drawing of the masks; *iii*) Mesh of the different regions. The calculations have been performed with the electromechanical formulation of Coventor software. For each structure,

the displacement x of the movable electrode is calculated by varying the DC voltage applied between the movable electrode and the silicon substrate. Figure 4 shows for the structure (1) the simulations and the calculated displacement according to the DC voltage, which gives a simulated pull-in voltage at $x=0.66$ µm corresponding to 1/3 of the gap of 2 µm defined by the thickness of the SOI silicon dioxide.
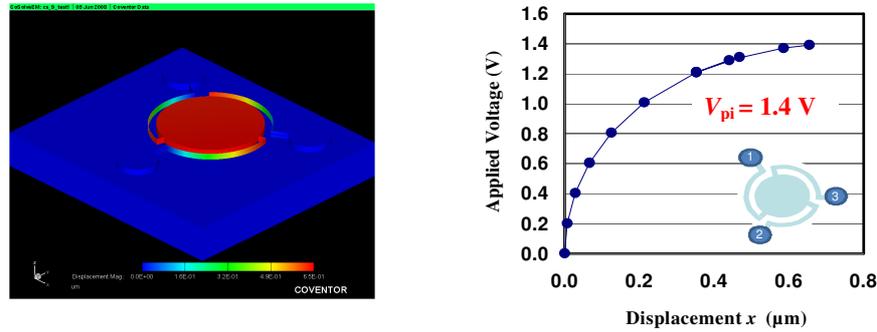

Figure 4. Coventor modelling of structure (1) and pull-in voltage calculation.

The calculated parameters of the three structures are summarized in table 1 where the capacitance C_0 at $x=0$, the spring constant k, the resonance frequency and the pull-in voltage are given.

Structures	C_0 (pF)	k (N/m)	f_0 (kHz)	V_{pi} (V)
(1)	26.7	5.75	1.15	1.4
(2)	21.0	814	9.86	12
(3)	27.0	8993	45.73	55

Table1. Calculated characteristics of the test structures.

III. MEMS Technology Description and fabrication

The choice of the technology has been driven by the theoretical calculations made in the previous section where it has been shown that it was very important to have a technology which minimizes the gradient of stress and that allows a good control of dimensions. This is why we have chosen a SOI process and an industrial foundry to make sure that the process will be repeatable. It consists of a Silicon On Insulator (SOI) surface micromachining process. The SOI top layer is a 60 µm thick monocrystalline silicon layer used for the mechanically active layer, exhibiting excellent mechanical characteristics (it can tolerate up to 10^{10} cycles without any crack or fatigue [5]). The silicon dioxide layer acting as insulator and spacer defines the gap of 2 µm height and the silicon substrate features 450 µm thick acting as the fixed electrode. Silicon wafers resistivity is in the range of 0.02 Ω.cm obtained by a high boron p-type doping of 2.10^{18} cm^{-3}.

Figure 5 illustrates the process flow used for the realizations of our structures. The top layer is firstly etched in order to realize the disk plate suspended with springs and then gold contact pads are realized. After the partial selective etching of the silicon dioxide, the plate and springs are released from the substrate.

1 - SOI wafer – Si et SiO$_2$ Etching

3 - Etching of the microstructures

2 - Epitaxy – Implant – Passivation - Metallisation
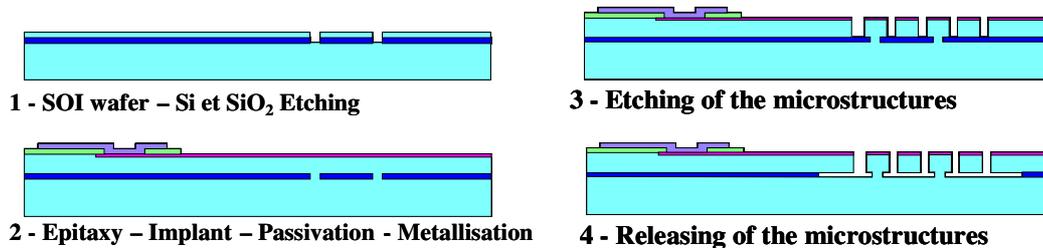
4 - Releasing of the microstructures

Figure 5. Process flow of MPW of Tronics

o ensure the stability of the MEMS, the die is protected by a vacuum hermetic silicon wafer level packaging. The final structure is composed by the assembly of the SOI wafer where the MEMS is

realized and a silicon wafer acting as a cap for protecting the MEMS (Fig.6). The non-sealed areas are defined by partial etch of a silicon dioxide initially realized and the metallization define the sealing areas for assembly. After assembly, via holes are realized to allow electrical contact to pads.

1 - fabrication of the MEMS structure

2 - fabrication of the cap

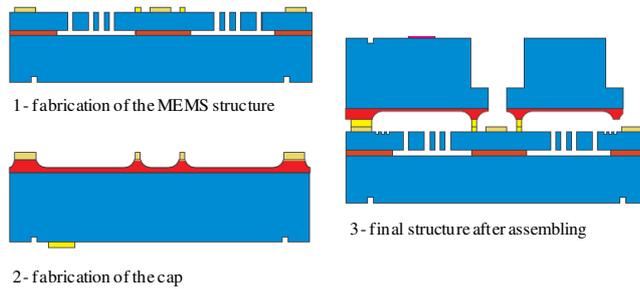3 - final structure after assembling

Figure 6. Silicon cap realization and MEMS assembly

The previous layouts have been used for elaborating the MEMS structures. Figure 7 shows photos of the three fabricated MEMS. Let us note that on the same die there are 3 MEMS hermetically packaged and 3 other MEMS in a no hermetic packaging. This configuration makes it possible to assess the packaging effect on the stability of the AC voltage references.
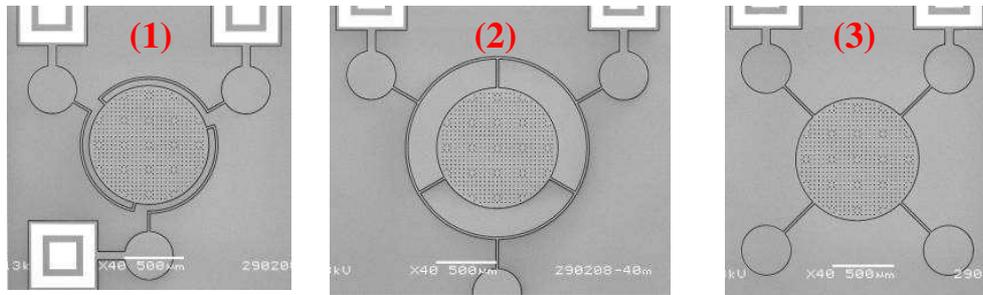

Figure 7. MPW MEMS structures fabrication

IV. First measurement results

The multi-physic characterization platform has been set up in order to verify the model parameters and to perform the appropriate characterization to determine the stability coefficient of the MEMS based AC voltage. First C-V curves have been carried out on the MEMS of structure (1) by using a RLC-meter. An external DC bias voltage was applied to the MEMS and the capacitance was measured with an AC voltage of 0.1 V at a frequency of 100 kHz.
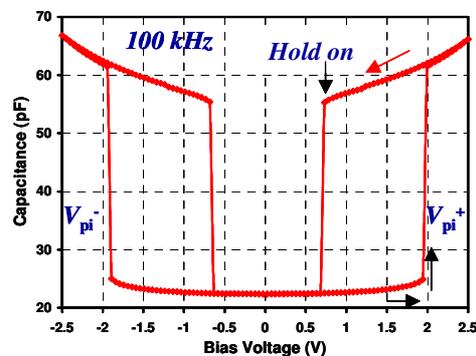

Figure 8. C-V characteristic of the MEMS of structure (1) at 100 kHz signal frequency

As shown in figure 8, the MEMS exhibits a pull-in effect at Vpi = 1.9 V which is in a very good agreement with the calculated Vpi of 1.4 V. Furthermore, a hold on effect is observed at 0.65 V

translating the difference in variation between both electrical and mechanical forces with the displacement *x*. The same C-V curves have also been realized by changing the frequency of the ac signal from 1 kHz to 200 kHz (Fig.9). The pull-in point remains the same whatever the frequency of the ac voltage (for clarity the hold on effect is not represented on these C-V curves).
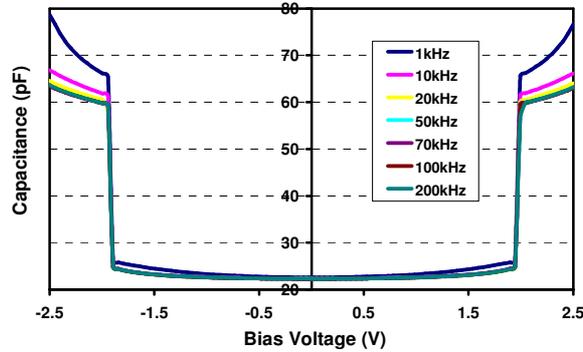

Figure 9. C-V curves of MEMS (1) at different frequencies

Measurements of the MEMS out-put RMS voltage in function of the current I_{RMS} flowing in the MEMS (U-I curve) have been carried out by using the voltage-to-converter read-out electronics developed at LNE. The measurements were realized at frequencies ranging from 10 kHz to 200 kHz. Figure 10 displays the characteristics MEMS out-put voltage of structure (1) versus the current I_{RMS} at two different frequencies of 100 kHz and 10 kHz. These curves show the same maximum of the out-put voltage corresponding exactly to the pull-in voltage Vpi = 1.9 V observed in the C-V curves.
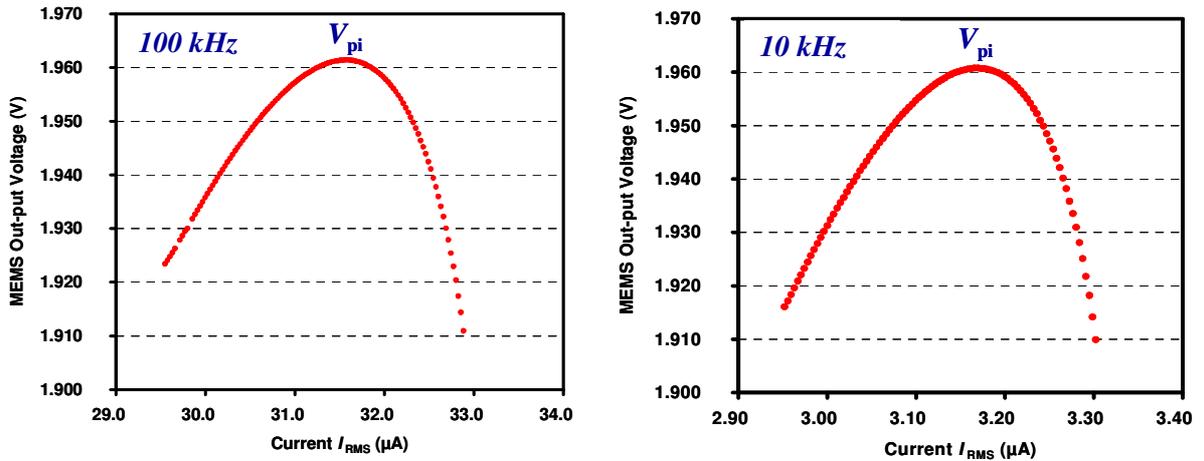

Figure 9. U-I curves of MEMS (1) at two different frequencies

The stability of the AC reference voltage corresponding to the maximum of these curves is under test by using a specific read-out electronics based on the amplitude modulation of the main biasing ac signal. The results will be presented at the time of the conference as well as the assessment of the whole MEMS fabrication. The results of this assessment will be used to validate the models, to understand the dispersions and to propose consolidated architectures more robust with respect to the dispersion in the MEMS fabrication.

IV. Conclusions

This paper is showing preliminary results concerning the potentialities of MEMS based technology for AC voltage references ranging from 1V up to 60 V. The objectives are to emphasize the capabilities of an industrial MEMS SOI process as well as specific architectures that are foreseeing to overcome the technological, mechanical and electrical drifts. The devices designed by finite element software have been fabricated using a MPW process. First results obtained on one of the structures show that the calculated and the measured pull-in voltage observed both with C-V and U-I curves are in a good

agreement. Further measurements are in progress on the stability of the AC voltage of this device in addition to the assessment of the characteristics of the whole run of MEMS fabrication. It has to be mentioned that specific cycling and reliability tests will also be performed. Moreover, a technological process for metallic membranes has been developed and used to manufacture MEMS devices in the shape of cantilevers and bridges on coplanar lines. On wafer measurements are in progress which will be used to compare the characteristics of both technological options (SOI and low stress metallic membrane).

References

[1] B.P. van Drieёnhuizen, "Integrated Electrostatic RMS to Converter", Thesis, 1996.

[2] M. Suhonen *et al*, "AC and DC Voltage Standards Based on Silicon Micromechanics, CPEM98, pp. 23-24, 1998.

[3] EMMA project report, Information Societies Technology, IST200028261EMMA, 2005.

[4] G. J. Papaioannou, J. Papapolymerou, P. Pons, R. Plana, "Dielectric charging in radio frequency microelectromechanical system capacitive switches : a study of material properties and device performance" Applied Physics Letters, Vol.90, pp.233507-1-233507-3, Juin 2007.

[5] H. Camon, C. Ganibal, "Advantages of alternative actuating signal for MEMS actuators", Sensors & Actuators A136 N°1, pp.299-303, 2007.