PUBLICATION II

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STABLE SOI MICROMACHINED ELECTROSTATIC AC VOLTAGE REFERENCE

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ABSTRACT

We have designed and manufactured a micromachined moving plate capacitor to be used as an AC voltage reference in electrical metrology. The reference is based on the characteristic AC current – voltage curve of the component having a maximum, the value of which depends on the geometry of the component and material properties of single crystalline silicon. The electrode surface stability is essential in this application and hence a new fabrication process has been developed to metallize both surfaces of an electrostatically actuated micromachined structure. The stability of the AC reference voltage at a frequency of 100 kHz and an RMS voltage value 6.4 V was measured to be ± 60 ppm over 14 hours.

1. INTRODUCTION

Electrostatically actuated capacitive MEMS components can be used as electrical references. Examples of a MEMS DC voltage reference [1], an AC voltage RMS converter [2], and a true RMS-to-DC converter [3] have been published. The targeted benefits of using MEMS components as references are improved stability compared to conventional devices (Zener diodes, for example), low 1/f noise, large operation voltage range, small size and small power consumption. The major difficulty is to achieve the excellent long term stability required for metrological applications.

Electrostatic surface phenomena cause instability in capacitive MEMS components. A silicon semiconductor surface is unstable, hence metal electrodes are needed. However, metal surfaces can charge if they are covered with a native oxide layer, as is typical. Electrode charging effects are negligible when an AC signal is used for actuation of the moving electrode [4]. Also, the built-in voltage of the device, which originates from the surface potential difference of the metal electrode and silicon spring, is temperature dependent and a potential source of instability. Slowly changing surface potentials due to, e.g., adsorption and desorption of gas molecules, also contribute to electrical instability.

2. PRINCIPLE OF OPERATION

A parallel-plate capacitor with a spring-suspended moving plate exhibits a well-known pull-in phenomenon [1]. The pull-in voltage is given by

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

where k is the spring constant, d and C_0 are respectively the air gap and the capacitance at zero voltage.

If a sinusoidal current with an RMS amplitude I_{RMS} and angular frequency ω is driven through the capacitor, the amplitude of the AC voltage across the plates is given by [1]

$$V_{ac} = \frac{I_{RMS}}{\omega C_0}\left[1-\frac{4}{27}\left(\frac{I_{RMS}}{\omega C_0 V_{pi}}\right)^2\right], \qquad (2)$$

where we assume that the device is operated at a frequency much higher than its mechanical resonance frequency, f_0. This avoids movement of the plate due to electromechanical coupling. The amplitude V_{ac} reaches a maximum value $V_{ac,\max} = V_{pi}$ at $I_{RMS,\max} = (3/2)\omega C_0 V_{pi}$. This amplitude can be used as an AC voltage reference since a small change in the current I_{RMS} has a negligible effect on $V_{\mathrm{ac,max}}$ near the pull-in point. The eigencurve of the component is shown in Fig.1 as a function of the moving plate deflection x from the centre position ($V_{ac} = 0$).

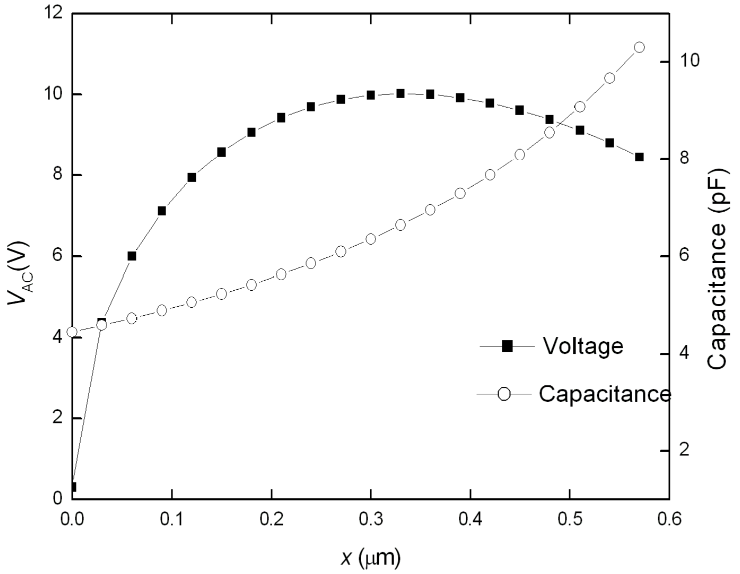

Fig.1. Calculated eigencurve for the component shown in Fig.2. (d=1μm and C0 = 4.45 pF).

3. COMPONENT DESIGN

The component is a large (r = 400 μm) round silicon plate suspended with three 260 μm-long springs, as shown in Fig. 2. The upper moving plate and lower fixed plate form a capacitor, which moves in a piston mode. The bottom of the moving plate is coated with sputtered aluminum, and the top of the fixed lower plate is coated with sputtered molybdenum. The metal thicknesses are 100 nm and 50 nm correspondingly. The component was designed for a 10 V pull-in voltage and as low a resonance frequency (about 60 kHz) as feasible, which can be achieved by fabricating the device as large as the manufacturing process allows. A large component is beneficial also for the readout electronics since the work capacitance value increases. The ambient gravity decreases the pull-in voltage by 2.2 mV (calculated).

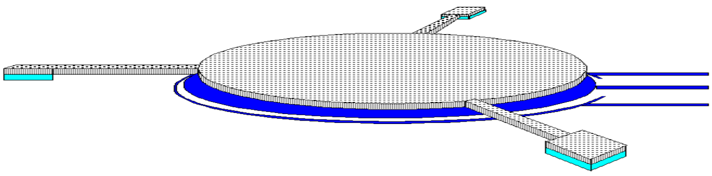

Fig.2. AC reference MEMS component

A SOI wafer was selected as the starting point of the design because of single crystal silicon springs and well defined device layer thickness. The device layer of the SOI forms the moving plate. Although the handle layer is removed during the process, this manufacturing scheme is expected to give the best results. A 20 µm-thick SOI is easily available and thick enough to withstand stress arising from the different thermal expansion coefficients of silicon and deposited metal layer.

Parasitic capacitances are a nuisance in capacitive sensors. They cause loss of sensitivity since the relative change of capacitance vs. displacement decreases. In addition, they limit the actuation range of the moving-plate capacitive actuator under charge control. Hence parasitic capacitances, mainly originating from the spring attachment areas, are minimized in the sensor design. A guard also surrounds the bottom electrode.

4. FABRICATION

A new fabrication process has been developed in order to realize the metallization on both capacitor surfaces. The approach chosen is based on aligned direct bonding of separately metallized and patterned wafers. The device wafer was a SOI with 20 µm thick device layer and 1 µm buried oxide layer and the substrate wafer was a 380 µm thick double side polished Si wafer. Both of the wafers were Boron doped and the resistivity was 0.015 - 0.02 Ωcm. The metal electrodes are placed in wells to avoid problems in wafer bonding. The well depth and oxide thickness of the substrate wafer define the gap height, which is 1 µm.

To enable bonding of the metallized wafers low temperature wafer bonding is utilized. After wafer bonding the handle layer of the SOI wafer and the buried oxide are removed by etching. Then the upper component surface is metallized and patterned and finally the device is formed with ICP etching. The process consists of three parts: 1) processing of the device (moving part) wafer, 2) processing of the substrate wafer, and 3) processing of the bonded pair as shown in Fig.3. The final component is step 4 in Fig. 3. The process requires 10 lithography steps.

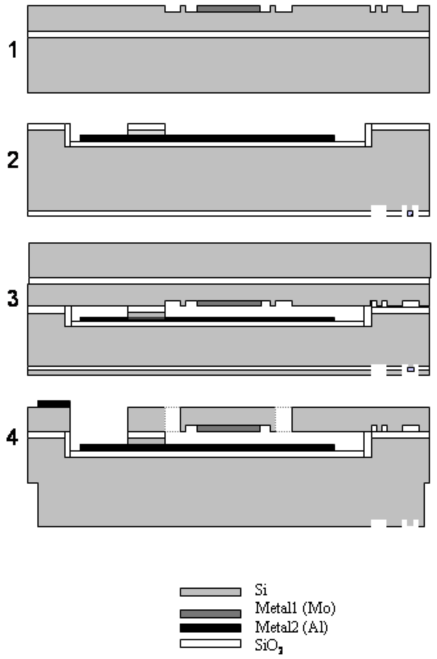

Fig.3. Major process steps.

The most critical step in the process is the wafer bonding. If the bonding surface quality is not sufficient, large non-bonded areas can be observed in optical or acoustical measurements. In the worst case, the wafers will not bond at all. To keep the surfaces in bondable condition, careful process planning and frequent cleaning procedures are demanded throughout the process. Because metallizations are needed on the capacitor surfaces, metal residues have to be removed from bonding surfaces with great care. Also, trapped gas bubbles between the bonded wafers can cause large non-bonded areas, as experienced in our process. The component yield from the successfully bonded areas was very good.

A photograph of the final component is shown in Fig. 4. The three small contact pads at the end of the springs are connected to the capacitor moving plate (only two of them are used) and the two middlemost large contact pads on the right are connected to the bottom plate. This enables a four terminal point capacitance measurement. The two remaining large contact pads on the right are connected to the guard (grounded).

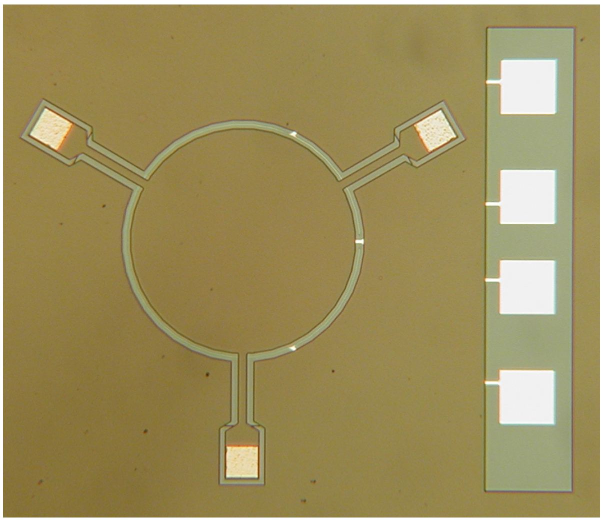

Fig.4. Final component.

5. PACKAGING

Open capacitive structures are very sensitive to changes in temperature, pressure, humidity, etc. Hence the sensor needs to be encapsulated in vacuum or in protective gas. A high gas pressure was chosen as it works as a mechanical damper. The component was encapsulated into a hermetically sealed TO-8 can containing 1 atm nitrogen gas. Fig 5. shows a component glued in a TO-8 can and a hermetically encapsulated component .

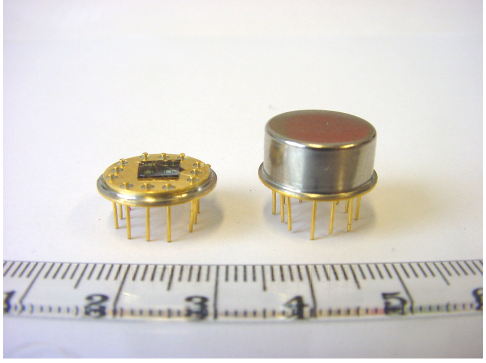

Fig.5. Component glued in TO-8 can and hermetically encapsulated component.

6. CHARACTERIZATION

A schematic drawing of the readout electronics developed for the AC voltage reference is shown in Fig. 6. An AC voltage is fed to the inverting input of the main operational amplifier OA2, which acts as a voltage to current converter to drive the current through the MEMS capacitor. Capacitors C_1 and C_2 as well as the shunt resistor R_4 force the DC voltage offset, which originates from OA2, to be zero across the MEMS capacitor. C_1 and C_2 are both 100 nF, hence much greater than the initial value (V_{ac}=0) of the MEMS capacitor (4.5 pF). The difference amplifier OA1 isolates the AC source from the electronics. The output of the unity gain buffer amplifier, AD549LH, is the AC reference voltage equivalent to the pull-in voltage of the MEMS capacitor. Guarding techniques are employed to minimize the effects of parasitic capacitances. The measurement setup is housed in a temperature, pressure and humidity-controlled environment.

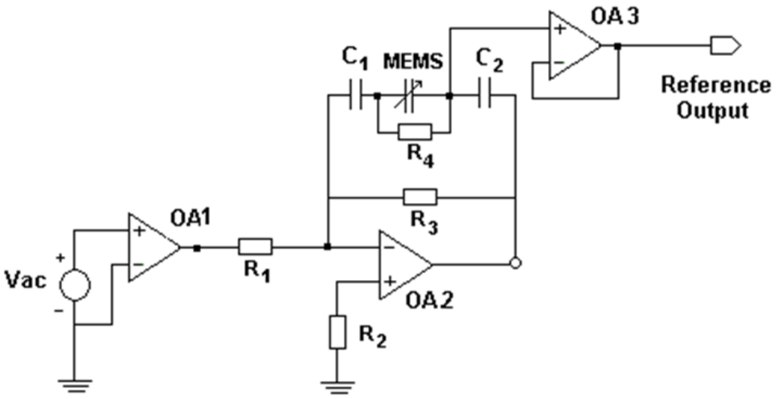

Fig. 6. Readout electronic used in MEMS component characterization.

7. RESULTS

A HP3324A signal generator was used to drive the MEMS capacitor to its pull-in point. The stability of the pull-in voltage 6.4 V was measured at 100 kHz. The stability for a period of 14 hours is shown in Fig. 7 and it is found to be within ± 30 ppm over 14 hours. The data is corrected versus the temperature changes of the input AC voltage source. The temperature inside the environment chamber was 28 ± 0.15 °C.

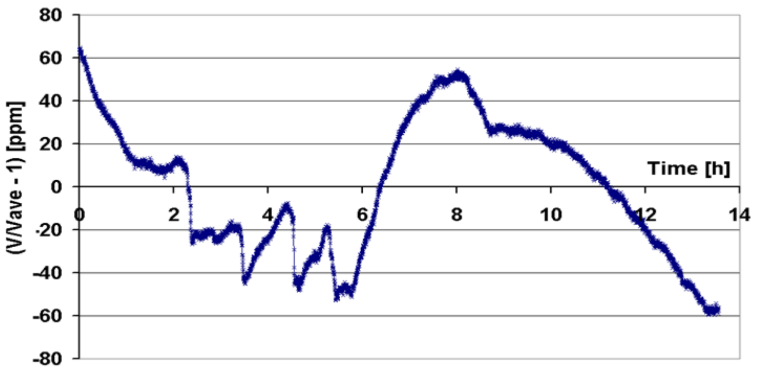

Fig. 7. Measurement results showing the stability of the MEMS component over 14 hours.

The characterization of the component has started only recently. More experiments are needed to find out reasons for the observed voltage behaviour in the measurement data. Potential sources for the slow voltage variation are charging of the MEMS component, instability of the readout electronics and changes in the environmental parameters. Although the component was hermetically packaged, the encapsulation was done at too low temperature (100 °C) to guarantee that there is no residual humidity inside the package that could influence the component stability.

8. CONCLUSIONS

A new MEMS process has been developed, which enables fabrication of moving plate capacitors having both capacitor surfaces metallized. The manufacturing is a straightforward, although lengthy, process. The wafer bonding at low temperature is challenging, especially since the wafers are exposed in many process steps.

The fabricated moving plate capacitors have been used as AC voltage references, which demonstrated rather good short-term stability. Long-term stability measurements have also started. The future work will focus on readout electronics improvement and component packaging. A LTCC package sealed in vacuum will be investigated next.

ACKNOWLEDGEMENTS

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