PUBLICATION III

MEMS-Based AC Voltage Reference

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MEMS-Based AC Voltage Reference

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***Abstract*—An ac root-mean-square (RMS) voltage reference based on a microelectromechanical system (MEMS) component is presented. The device stability is investigated in various experiments. A time stability at a level of a few $\mu V/V$ in 24 h was measured using an accelerometer MEMS component at an operating frequency of 100 kHz.**

***Index Terms*—AC voltage reference, capacitive sensors, microelectromechanical systems.**

I. INTRODUCTION

PROPOSALS for an ac voltage reference based on a capacitive microelectromechanical system (MEMS) were first published in 1998 [1], [2]. The MEMS ac voltage reference is based on the characteristic pull-in point of the MEMS component. This pull-in point depends only on the component geometry and material properties of single crystal silicon. The benefits of MEMS components in reference applications are good stability [3], low $1/f$ noise, large operation voltage range, small size, and low power consumption.

The electronics of a stable ac voltage reference is easier to realize than the electronics of a dc voltage reference. Indeed, while the dc reference requires a feedback circuit [3], only an ac current drive is needed for the ac voltage reference to bias the component to the pull-in position. In addition, electrode charging effects are negligible when using an ac signal for the actuation of the moving electrode [4].

II. PRINCIPLE OF OPERATION

If a sinusoidal current with an RMS amplitude I_{RMS} and angular frequency ω is driven through a spring suspended moving plate capacitor, the amplitude of the ac voltage across the plates is given by

$$V_{\mathrm{RMS}}=\frac{I_{\mathrm{RMS}}}{\omega C_0}\left[1-\frac{4}{27}\left(\frac{I_{\mathrm{RMS}}}{\omega C_0 V_{\mathrm{pi}}}\right)^2-\frac{F_{\mathrm{m}}}{kd}+\varepsilon'(x-x_0)\right] \quad (1)$$

where C_0 is the capacitance at zero voltage, k is the spring constant, and d the gap between the plates. ε' describes the second-order terms due to mechanical movement of the plate and x is the plate deflection from the rest position x_0. The pull-in voltage is

$$V_{\mathrm{pi}}=\sqrt{\frac{8kd^2}{27C_0}}\left[1-\frac{F_{\mathrm{m}}}{kd}+\frac{4}{9}\left(\frac{\omega_0}{\omega}\right)^2+\varepsilon''(C_{\mathrm{s}},Q,R,\ldots)\right] \quad (2)$$

where F_{m} describes all external mechanical forces effecting the component such as vibrations, tensions, and ambient gravity. Again, ε'' describes second-order terms, which depend on parasitic capacitance C_{s}, component mechanical Q value, parallel resistance R, etc. The device is operated at a frequency higher than its resonant frequency, $f=\omega_0/2\pi$, to minimize the influence of the mechanical forces.

The amplitude V_{RMS} has a maximum $V_{\mathrm{RMS,max}}$, which can be used as an ac voltage reference since a small change ΔI_{RMS} in the current near the pull-in point has only a minor effect on V_{RMS}.

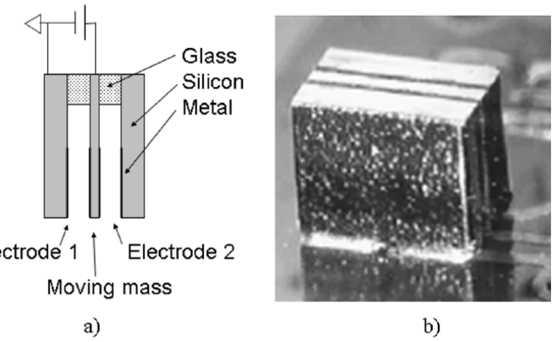

Fig. 1. (a) Photograph of the component and (b) a schematic diagram of the structure of the component.

III. COMPONENT STABILITY

If the external mechanical forces exerting on the MEMS component are small, the stability of the component depends only on the material, the geometry and the manufacturing process selections, which are discussed below.

A. Material and Geometry

Fundamental factors affecting the pull-in voltage stability, according to [2], are the spring constant k, the gap d, the permittivity ε, and the electrode area A of the component. A stable spring constant is achieved by using single crystal silicon springs. Although single crystal silicon is mechanically an extremely stable material, the spring constant has a temperature coefficient arising mainly from the temperature coefficient of the modulus of elasticity, on the order of -6×10^{-5} /°K [5]. However, the temperature coefficient of the device, usually 10–20 times higher, is dominated by the component mounting.

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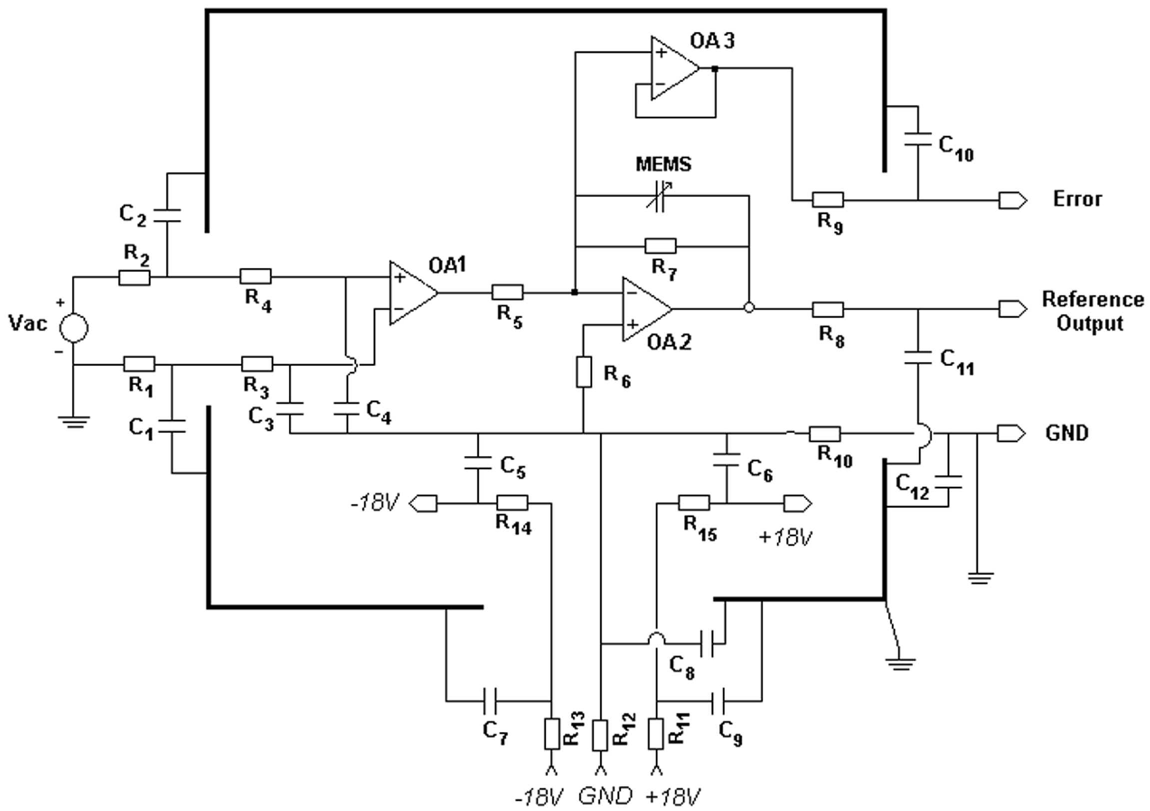

Fig. 2. Readout electronic used in MEMS component characterization.

Consequently, the device needs to be stabilized for temperature or temperature compensated.

Mechanical deformations of the electrode plates can change the distance d between the plates. Residual stress, inherent for epi-poly process [6], strongly influences time and temperature stability of the component. Hence stress-free substrate material, such as silicon-on-insulator (SOI), is essential. Rigid mounting of components can also cause stress and, hence, should be avoided.

B. Mechanics

When the component is operated close to the mechanical resonance frequency, mechanical forces, related to the inertia of the moving plate, will also influence the stability of the pull-in value. In addition, second-order forces due to temperature, humidity, or any dc voltage that may exist across the component, can also effect the device stability.

C. Electrical Charging

Various electrode surface phenomena are potential sources of instability. Charging can be reduced by metallizing the electrode surfaces. But, also, metal electrode surfaces can oxidize. The charged oxide can be observed as an effective gap reduction.

IV. Component Characteristics

All the measurements were performed using bulk micromachined accelerometers. The accelerometer is a cantilever attached at one end as shown in Fig. 1(a). A single component comprises of two identical capacitors, i.e., between the moving mass and the side electrodes. Only one capacitor was monitored at a time while the other one was grounded. The component was either flip-chipped on a printed circuit board or attached to a TO-8 can with bond wires. The component was enclosed in gas atmosphere and was over damped. A photograph of the component is shown in Fig. 1(b). The component was sensitive to inclination changes, which is characteristic for an accelerometer, and it had an influence on the repeatability of the measurements.

V. Electronics

The requirements for the ac voltage reference electronics are high slew rate and high open loop gain. A schematic of the experimental set-up is shown in Fig. 2. 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. The output of OA2 is the ac reference voltage. The output of the unity gain buffer amplifier OA3 corresponds to the voltage at the inverting input of OA2. Monitoring this voltage gives information about any variations of the gain of the operational amplifier OA2. The actual error depends also on the phase shift between the output and input signal. The instrumentation amplifier OA1 isolates the ac source from the electronics. Filtering of the power supply and also input and output voltages suppresses EM interference. In addition, shielding techniques are employed to prevent changes

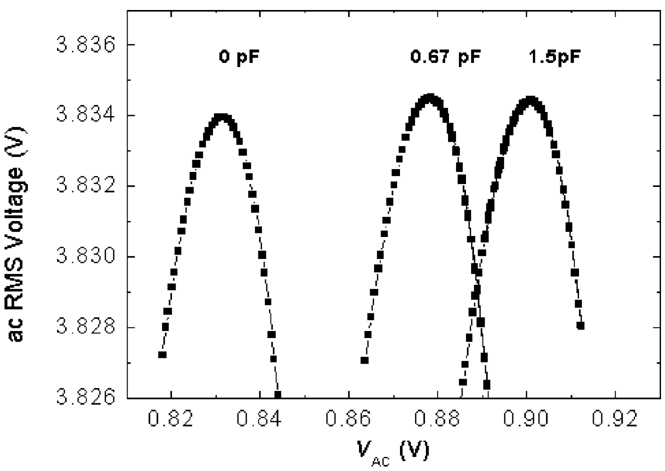

Fig. 3. AC reference voltage curves for stray capacitance values 0, 0.67, and 1.5 pF. AC RMS voltage value change was 143 $\mu V/V$ and 122 $\mu V/V$, accordingly.

in stray capacitances. The MEMS capacitor is measured in a four terminal configuration (not shown in Fig. 2).

VI. Measurement Results

The ac voltage reference was characterized in various experiments. First, we examined the device as an ideal voltage source, which is immune to stray capacitance and to parallel resistance changes. Then, we studied the frequency response, and the sensitivity to environmental parameters such as temperature and humidity. Finally, the stability of the ac voltage amplitude was studied over time. All the measurements were performed at room temperature, which varied from 21 °C to 24 °C, and at a 100 kHz frequency unless otherwise mentioned.

A. The Device as a Voltage Source

1) Stray Capacitance: The effect of stray capacitance was experimentally analyzed by inserting a discrete capacitor in parallel with the MEMS component. For each capacitor being inserted, the signal generator voltage was scanned near the pull-in point and the RMS value of the reference output voltage was measured using a multimeter. The pull-in point, about 4.65 V, was determined from the maximum of the curve. The nominal capacitance of the component was 10 pF. The parallel capacitance values were 0.67 pF and 1.5 pF, about 10% of the nominal value and well above the expected stray capacitance values. The results are shown in Fig. 3. The voltage maximum change for the 0.67 pF capacitor was 143 $\mu V/V$ and for the 1.5 pF capacitor 122 $\mu V/V$. However, these changes are due to component inclination change, which was inevitable when applying a capacitor to the electronics, rather than due to capacitor value changes. This was demonstrated by inserting and removing the same capacitor into the electronics. We could not observe an ac reference voltage change due to stray capacitance within the measurement repeatability.

2) Parallel Resistance: Similarly, a resistor was added in parallel with the MEMS component and the voltage-current curves were recorded in an identical measurement setup as previously. A 90 kΩ additional resistance in parallel with the 1 MΩ resistance changed the ac reference voltage by 7.9 $\mu V/V$.

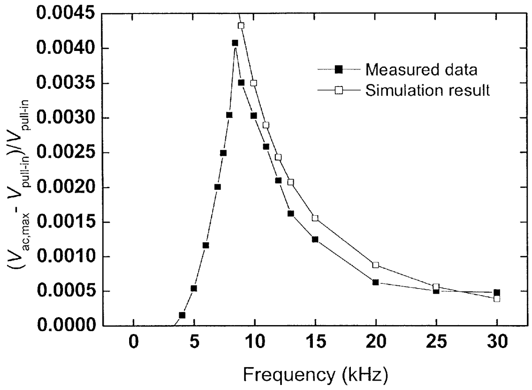

Fig. 4. Dependence of the ac voltage reference with the operating frequency.

The same order of magnitude change was also observed with a parallel resistance of 300 kΩ.

3) Conclusion: The stray capacitance and parallel resistance variations were not observed to effect the value of the ac voltage reference within the measurement accuracy. However, they do effect the input current at which the pull-in point is reached. Therefore, the electronics driving the ac voltage reference should be able to track the maximum of the voltage amplitude even if the stray capacitance and parallel resistance change.

B. Frequency Dependence

The frequency dependence of the ac voltage amplitude was measured by varying the frequency of the input current near the component mechanical resonance frequency (about 10 kHz). The results are plotted in Fig. 4. The results show two phenomena. For frequencies higher than 10 kHz, the voltage exhibits a $(\omega_0/\omega)^2$ frequency behavior. This effect was also verified by simulating a current driven and viscously damped moving plate capacitor, which had a resistor and a capacitor in parallel, using the Runge-Kutta method. The simulation agrees well with the measured data. Below the resonance frequency, the frequency behavior is different because mechanical damping due to residual gas pressure is frequency dependent. The device should be operated at frequencies well above the component mechanical resonance frequency in order to minimize the influence of the mechanical forces.

C. Environmental Changes

1) Temperature Coefficient: The temperature coefficient of the ac voltage reference was measured by cycling the temperature of the component between $32.05 \pm 0.05\,°C$ and $34.4 \pm 0.05\,°C$ in approximately two hour periods. The mechanical stress arising from the component mounting was minimized by attaching the component only from the bond wires in a TO-8 can. Two 390 kΩ resistors were attached in parallel on top of the TO-8 can lid and the temperature was controlled by changing the voltage across the resistors. The temperature was monitored with a Pt100 thermometer, which was attached on the side of the TO-8 can. The ac RMS voltage values were determined from the maxima of the curves when the signal generator amplitude was scanned near the pull-in point as in previous measurements. Fig. 5 shows the ac reference voltage as a function of time during

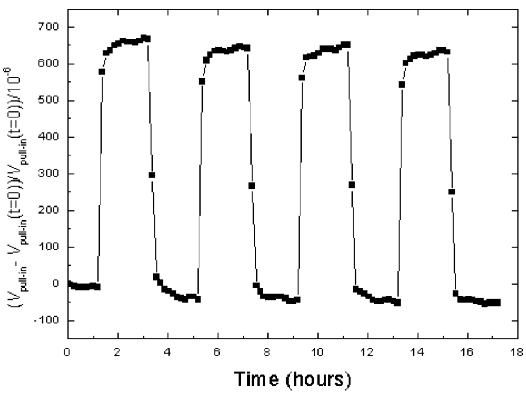

Fig. 5. Variations of the pull-in voltage as a function of temperature.

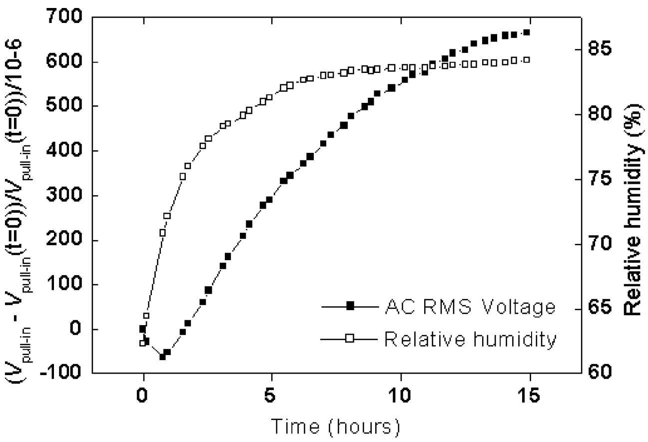

Fig. 6. AC voltage reference response to relative humidity change.

the temperature cycling. The temperature coefficient of the device was measured to be 240 $\mu\text{V}/\text{V}/^{\circ}\text{C}$, which is about four times higher that the temperature coefficient of the modulus of elasticity. Since the mechanical stress arising from the component mounting was minimized, it is assumed that the temperature coefficient is dominated by the component bending due to different temperature expansion coefficients of silicon and glass. In addition, a transient of about 200 min was observed in the beginning of the measurement. A similar transient is also present in the time stability experiment.

2) Humidity: The ac voltage reference sensitivity to humidity was measured by inserting a moist cotton pad in a cup inside the electronics enclosure. Relative humidity inside the enclosure progressively increased from about 60% to about 85%. As previously, the ac RMS voltage was determined from the maxima of the voltage curves, when the input voltage was scanned near the pull-in point. The results are shown in Fig. 6. A 25% change in relative humidity resulted in a 700-$\mu\text{V}/\text{V}$ increase in the ac RMS voltage. Since neither stray capacitance nor parallel resistance have an effect on the ac voltage, it is assumed that humidity is absorbed by the glue and/or the ceramic printed circuit board where the component was mounted and, hence, caused the component inclination change.

D. Stability With Time

Preliminary time stability measurement of the ac voltage reference is shown in Fig. 7. The device was closed in a temperature-stabilized chamber, which was mounted on a stone table. The temperature was $23.51 \pm 0.012\,^{\circ}\text{C}$ during the 18 h measurement. The amplitude of the excitation voltage was varied near the pull-in point, and the RMS value of the reference output voltage was measured using a multimeter. A second-order polynomial fit was made to the parabolas similar to those of Fig. 3, and the voltage at the maximum was determined. The values are plotted in Fig. 7. After a transient of about 200 min, the reference output voltage stays constant within the scatter of the data with a standard deviation of about 8 μV (1.7 $\mu\text{V}/\text{V}$). The scatter is mainly caused by the multimeter, which is not an ideal device for voltage measurements at 100 kHz.

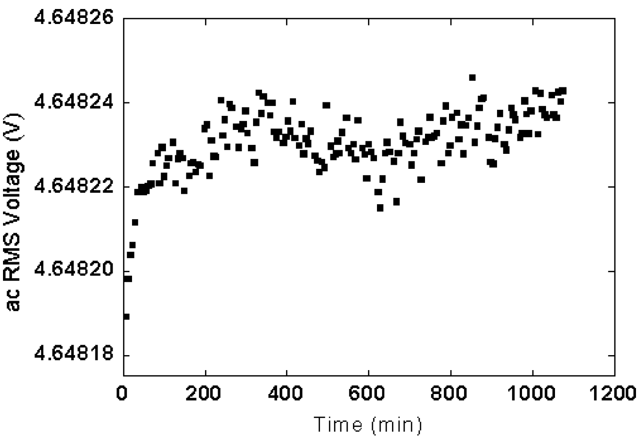

Fig. 7. Time stability of the ac voltage reference.

VII. Conclusion

We have demonstrated that a moving plate MEMS capacitor can be used as an ac RMS voltage reference. The voltage reference should be operated well above the mechanical resonance frequency. Ac voltage amplitude stability of a few $\mu\text{V}/\text{V}$ in 24 h has been measured using a MEMS accelerometer as a test component. VTT has designed and manufactured a MEMS component optimized for the ac voltage reference use and it is currently being evaluated. Temperature control or compensation for the ac voltage reference is needed as well as a hermetic package, which should eliminate effects of humidity and pressure on the stability of the ac voltage reference.

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