Voltage Sensing using MEMS Parallel-Plate Actuation

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Abstract

Microelectromechanical systems (MEMS) have been proposed as DC electrical metrology references. The design reported here is the first to enhance the qualities of a MEMS DC reference with potential tuning and sensing via an isolated and monolithically integrated MEMS technology and, thereby, convert a stable parallel-plate voltage reference to a simple, sensitive, low-burden voltage sensor. This on-chip system reliably measures unknown potentials ranging from -60 V to 60 V with sampling times less than 10 msec. In the initial design, the system is used to measure atto-amp leakage current though 10 PΩ, suspended, MEMS isolation.

Keywords: electrometer, pull-in, MEMS, parallel-plate, voltage reference, metrology, isolation

1 Introduction

Quantitative electromechanical measurement of charge and potential was most famously demonstrated by Millikan [1] and simplified in later spring based systems [2]. In the literature, low temperature MEMS electrometers using resonance tuning caused by moving the input charge through a known external magnetic field have recently been demonstrated and studied [3]. General discussion of electrometer design including that of mechanical, spring-balanced electrometers can be found in older literature [4, 5].

Current proposals utilize the stability and precision of MEMS systems for DC and AC electrical metrology references [6, 7, 8]. For voltage sensing, the DC reference characteristics are most relevant. For voltages near 10 V, Rocha and Kärkkäinen found MEMS references based on parallel-plate pull-in can provide 500 μV accuracy, -1 mV/K temperature sensitivity [6], and voltage drift less than 100 μV/V per hour [7].

As is well known, an electrostatic parallel-plate actuator with a linear spring and an initial gap, -gap, will pull-in (collapse) when actuated quasistatically at a critical voltage, -Vcrit, where the gap has been reduced to 2/3 -gap. A device combining such an actuator with a displacement or contact sensor and a means to vary the potential on one side of the actuator can be used to accurately measure an unknown potential on the other parallel-plate with minimal disruption of the system being measured. Parallel-plate pull-in time rather than voltage has been used for pressure sensing [9, 10], and one time use of pull-in coupled with stiction has been used for in situ potential measurement in plasmas [11].

In this paper, the following (Figure 1) single-crystal-silicon (SCS) MEMS electrometer is presented and analyzed as an example of on-chip potential sensing using parallel-plate pull-in to measure voltage. To our knowledge, this device is the first reported design to use pull-in as a voltage comparison technique for charge and potential measurement. An adjacent 45 deg mirror has been milled with a focused-ion-beam to provide means for in-plane vibrometer based confirmation of the device motion.

![Figure 1: On-chip electrometer](image)

2 Pull-In Potential Sensing

The pull-in voltage of parallel-plate actuators is used as voltage sensor by varying the potential on one side of the actuator and monitoring pull-in with an integrated or external sensor. Pull-in need not
correspond to complete collapse of the actuator; indeed, bump-stops within the unstable region, limiting the minimum gap, are used to reduce friction, lower to release voltage after pull-in, minimize parasitic leakage across the collapsed actuator, and increase $Q$ (quality factor) by reducing squeeze film damping.

A circuit symbol (Figure 2) for this class of pull-in, parallel-plate voltage sensor is introduced below to simplify later circuit diagrams. The symbol resembles a variable capacitor because of its electrostatic actuator component; while, the arrows indicate not only variable capacitance but the direction of motion of the moving plate (the other plate is assumed to be fixed). A means of detecting pull-in is represented by a third terminal between the capacitor plates.

![Figure 2: Pull-in sensor symbol](image)

The potential of the non-moving plate is measured by finding the smallest magnitude voltage needed on the opposite side to close the actuator. The closing action of a typical pull-in actuator design is shown in Figure 3 where the spring and moving plate are formed by a simple cantilever.

![Figure 3: Sensor collapse](image)

The procedure used in measurement is to deterministically vary the input voltage, $V_{in}$, on one side of the actuator and monitor the displacement sensor to determine when the potential difference reaches the critical voltage of the sensor:

$$V_{fix} - V_{in} = V_{crit}$$

Various methods of detecting actuator pull-in have been used including bringing an integrated heater into contact with a forward biased diode and optical coupling of reflected light into an adjacent structure containing a reversed biased diode. The pull-in sensing method used for the data presented here is optical monitoring through a microscope of the reflectance where actuator will stop after pull-in. As seen in Figure 3, the reflectance of the top of the aluminum coated structures is much higher than the reflectance in the gap between the actuator plates. This mid-gap reflectance is particularly low because of sidewall roughness of the high-aspect-ratio (30:1) SCS MEMS and the release curvature of the silicon surface 40 $\mu$m below the top of the structure. The diagram below illustrates this configuration:

![Figure 4: Optical pull-in monitor](image)

In collecting more than 10,000 data points, this sensing system never produced a false positive event and did not require adjustment during the longest data collection period of 5.5 hours.

3 Electrometer Design

An on-chip electrometer was designed and tested to characterize the electrical characteristics of a suspended, thermal-oxide, isolation technology for SCS MEMS [12, 13]. The isolation resistances were found to be too high for confident off-chip measurement; while, on-chip, pull-in potential sensing provided accurate, simple, and low burden sensing. A micrograph of the device with integrated potential sensing is shown in Figure 1; while, the circuit corresponding to the measurement setup is shown in Figure 5.
The swept voltage used to vary the potential across the actuator is $V_{in}$.

To use parallel-plate instability in a sensor application, it is important to have a well-defined, stable closing voltage. Fringing fields and spring non-linearities will cause the instability point to differ from two thirds the starting plate separation but will not impact its usefulness as a sensor under the quasi-static actuation used here. Device asymmetries arise mainly from the use of bump-stops which cause fringing field asymmetries, leading to each plate having a different effective contribution to the potential across the actuator. Defining the normal closing voltage, $V_{crit}$, to be the input voltage needed to close the actuator with the voltage on the fixed plate being the same potential as the wafer, the following formula relates the input voltage, $V_{in}$, and reference voltage, $V_{fix}$, to the normal closing voltage:

$$V_{crit} = V_{in} - \Gamma V_{fix},$$

where $\Gamma$ represents the influence of $V_{fix}$ relative to $V_{in}$. Ideally $\Gamma = 1$, but it is more important to determine its value for a particular design by stepping $V_{fix}$ and measuring its effect on the closing voltage by sweeping $V_{in}$. Such a sweep is shown below for the extremely asymmetric design of Figure 1 for which $\Gamma = 0.6345$; further accuracy can be obtained by adding a cubic term, but the correction provided by this term is less than 1% for voltages between -20 V and 20 V.

Particularly when using a probe station, measured $V_{crit}$ can drift by up to 10 mV per hour. This drift is likely do to variations in probe contact resistance since after the first hour the drift rate decreases to less than 2 mV per hour.

Once the parallel-plate actuator is closed the potential across the actuator must be reduced to release the plate. A large contact area can result in surface forces capable of holding the actuator closed with no applied voltage. To avoid this stiction, small protrusions (called bump stops or simply stops) are used which contact before the full plate area. These stops serve to increase the minimum releasing voltage by reducing surface interactions and increasing the minimum plate separation which reduces the force between the plates for a given voltage and minimize the current spike caused by the capacitor’s collapse [14]. The simplest design is to locate the stops on one side of the parallel-plate. A better arrangement is to design a separate stop, either grounded or electrically connected to the moving plate. Because the moving plate will contact this stop, the moving plate is usually used to carry the known voltage leaving the unknown and possibly sensitive potential isolated by an air-gap.

This sensor system needs to approach instability quasistatically, so its maximum operating frequency must be significantly below its natural frequency. The cantilever based systems studied have a resonant frequency of ~50 kHz and are capable of measuring potentials with the range ±60 V with 5 mV precision at a sampling rate of >30 Hz. Because the device is tested in air, its Q is fairly low (around 20); coupled with its high resonant frequency this means that the system will effectively reach equilibrium in less than 2 msec at which point its energy will have damped to 67% ($1/e^2$) of the initial energy.

The dynamics of the closing and opening of a threshold actuator are shown in Figure 7. The data was collected using a commercial vibrometer after cutting a 45 degree mirror (Figure 1) using a focused ion beam. The recorded instability point is greater than one half the total movement because the motion is limited by a bump-stop (the designed gap between actuator plates is 4 µm in this design).
4 Operation and Results
The sensor in Figure 5 has several unknown characteristics which must be determined before calibrated measurements can be made:

a. $V_{\text{crit}}$, the normal pull-in potential of actuator.
b. $\Gamma$, the relative effectiveness of $V_{\text{fix}}$ on the potential difference.
c. $C_{\text{fix}}$, the capacitance of the reference.
d. $R_{\text{fix}}$, the parasitic resistance of the reference.

$V_{\text{crit}}$ is determined by setting $V_{\text{fix}} = 0$ and sweeping $V_{\text{in}}$ until pull-in occurs. $\Gamma$ is determined as described in Section 3. Since $C_{\text{fix}}$ is fairly large for this application, it is measured with a commercial LCR meter (HP-4274A). $R_{\text{fix}}$ is difficult to measure because the capacitor is a MOS structure with a thermal oxide guard ring minimizing leakage. Conveniently, $R_{\text{fix}}$ is the last unknown in an electrometer design so the device itself can be used to measure $R_{\text{fix}}$ serving as a demonstration of the device’s usefulness. Once $R_{\text{fix}}$ is known, small currents applied to $C_{\text{fix}}$ from other sources can be measured by the voltage change at $V_{\text{fix}}$.

The procedure for determining $R_{\text{fix}}$ is defined below:

1. Determine $V_{\text{crit}}$, $\Gamma$, and $C_{\text{fix}}$.
2. Apply a known potential, $V_{\text{known}}$, to $V_{\text{fix}}$.
3. Begin recording the $V_{\text{fix}}$ needed to satisfy equation (1) by sweeping $V_{\text{in}}$.
4. Remove the known potential from $V_{\text{fix}}$ and allow $C_{\text{fix}}$ to self-discharge through $R_{\text{fix}}$.

Using the determined values of $V_{\text{crit}}=39.293$ V (note accurate knowledge of $V_{\text{crit}}$ is never used), $\Gamma=0.6345$, and $C_{\text{fix}}=2.98$ pF, the measured change in $V_{\text{fix}}$ is graphed in Figure 8 when $V_{\text{known}} = 20$ V.

![Figure 8: Discharge of $C_{\text{fix}}$](image)

By comparing the closing voltage to the known relationship between capacitor voltage and closing voltage, the corresponding capacitor voltage is determined. Comparing this voltage with a previous measurement is used to determine the average current between the measurements:

$$R = \frac{V_{\text{avg}}}{I_{\text{avg}}} = \frac{V_{\text{avg}}(t_2-t_1)}{C\Delta V}$$

![Figure 9: Measured parasitic resistance, $R_{\text{fix}}$](image)

From this analysis, the parasitic resistance of our charge accumulation capacitor is found to be greater than 1.5 $\Omega$ for voltages below 20 V allowing the system to directly measure averaged currents in the atto-amp range.

Smaller input currents can be measured if $R_{\text{fix}}$ is included in the charging model. To illustrate this process, a charging current was generated by applying voltage, $V_{\text{in}} = 100$ V, to a single suspended MEMS isolation of resistance $R_{\text{iso}}$. The charging equation for such a system is

$$V_{\text{fix}} = \frac{V_{\text{iso}}R_{\text{fix}}}{R_{\text{iso}} + R_{\text{fix}}} \left(1 - e^{-\frac{t}{C_{\text{fix}}(R_{\text{iso}} + R_{\text{fix}})}}\right).$$

The measured 1700 data points and Mathematica curve fit with residuals always below 1 V are shown below. The system charges slightly faster in the beginning than predicted by the model which is due to the higher parasitic resistance in the capacitor at small voltages (as can be seen in Figure 9) not represented in the model. The curve fit puts both $R_{\text{iso}}$ and $R_{\text{fix}}$ within 2% of 10 $\Omega$.

![Figure 10: Charging via atto-amp current](image)

The fit indicates an internal resistance of 10 $\Omega$ for the capacitor, comparable to the value measured by
monitoring the capacitor discharge directly. Taking this value as a reasonable approximation and presumably an accurate value for some voltage between 0 and 50 V, the resistance of the isolation segment can be evaluated, using the same incremental method used above to determine the guarded anchor resistance, by adding the current drained away by the internal leakage of the capacitor to the measured current since the isolation leakage is also supplying current to make up for the self-discharge of the capacitor. The result of this analysis is shown Figure 11 with error bands and indicates that a resistance of 10 Ω is reasonable.

![Graph showing incremental isolation resistance](image)

**Figure 11: Incremental isolation resistance**

As described in Sze [15], the conduction, in steady-state, through oxide at low field strength (i.e. far from breakdown) is ohmic, essentially independent of oxide thickness for a given field strength, and results from thermally excited electrons hopping between isolated states. For this 2 μm thick oxide isolation with an area of 20 μm² to have a 10 Ω resistance, the oxide resistivity is approximately 10¹³ Ωcm which falls in the range of measured for bulk oxide in the literature [16].

5 Conclusion and Extensions

This system is distinguished by its simplicity, attoamp sensitivity, PΩ isolation up to 20 V, and large voltage-sensing range. Sensing fA currents with PΩ input resistances is typical of relatively modern electrometers [17]. Unlike other configurations, since an air-gap is maintained between the sensing actuator and charge integrating capacitor, the sensor burden is relatively independent of sensing frequency.

Since this sensing system is monolithically integrated with a commercial grade MEMS technology (used in commercial production at Kionix, Inc. and Calient networks) with microfluidic capabilities [18], it opens many avenues for future investigation including:

a. Sensors for level triggering by biasing a sensor near pull-in.

b. Differential on-chip MEMS actuators and accelerometers applied to motion transduction.

c. Further exploration of on-chip sensing methods.

d. Low temperature detection of ultra-small charges.

e. Dynamics studies using shaped pulses to maximize sampling frequency.

f. Integration with on-chip relays for capacitive discharge allowing self-contained calibrated potential measurement.

6 Acknowledgements

Many graduate students in the MEMS group at Cornell University have helped, directly and indirectly, to achieve the result reported here. This work was done at the Cornell Nanofabrication Facility whose staff makes so much research possible. Funding for this project was provided by DARPA.

7 References


