Overview

• Intro
• Variable Capacitors
• Variable Area Capacitor
• Comparison
• Designs
• Future Research
Introduction

• Microelectromechanical systems (MEMS) show potential for creating extremely sensitive charge sensors
• These sensors or electrometers are used in [1]:
  • mass spectrometry
  • detection of bio-analyte and aerosol particles
  • measurement of ionization radiation
  • space exploration
  • quantum computing
  • Scanning tunneling microscopy
• Commercially, electrometers can sense a minimum equivalent charge of 5000 electrons [2]
  • Keithley 6517 electrometer
• MEMS have demonstrated detection of 6 electrons at room temperature and atmospheric pressure [3]
Introduction

- Other technologies have been used to detect charges smaller than one electron such as the single electron tunneling transistor (SET)
  - One such transistor detected an equivalent charge of $1.9 \times 10^{-6}$ electrons [1]
  - However, the sensing temperature was 4.2 Kelvin

Figure 1: (a) Schematic diagram of SET as a charge sensor electrometer. (b) scanning electron micrograph of an SET. This image was taken from [1]
Introduction

• There exists a demand for more sensitive, more accurate charge detection at room temperature
  • Charge-detection electrometers are used to measure the charge on large particles such as viruses [2]
    • With the capability of detecting 15 electrons, these charge-detection electrometers could be used for DNA analysis
  • Gas-detector electrometers could be used for car exhaust monitoring with a 500-electron resolution [2]
  • A high-resolution voltmeter could be used in satellites to monitor the charging of electrical components due to bombardment by high-energy particles [2]
Introduction

• Previously reported MEMS electrometers are vibrating reed, variable gap capacitors [2-3]
• These devices suffer from high damping due to squeeze-film damping [2]
• They also suffer from limited conversion gain which directly relates to charge resolution
• This research proposes a different sensing scheme that eliminates the effects of squeeze-film damping and increases the maximum possible conversion gain by more than 70%
Variable Capacitors

• First variable capacitor electrometer was described in 1932 by Ross Gunn at Naval Research Laboratory [4]
• Gunn obtained a charge resolution of 4 fC (24,000 electrons)
• Variable capacitance was the main method of measuring charge until the advancement of solid state sensors

Figure 3: picture of first variable capacitor electrometer [4]
Variable Capacitors

- MEMS variable capacitor electrometers were first introduced by Riehl et al. in 2002 [2]
- The output voltage was measured at the second harmonic of the drive voltage to eliminate the effects of feed through noise
- The charge conversion gain (the increase in RMS voltage per coulomb) was calculated to be [2]:

\[
\frac{d\bar{v}_i}{dQ} = \frac{\dot{x}^2}{g^2} \frac{C_0}{2\sqrt{2}(C_0 + C_p)^2}
\]

Figure 4: SEM image of Lee et al. Electrometer (left). Simple model of the electrometer (right) borrowed from [3].
Variable Capacitors

- This scheme of sensing introduces a lot of damping from varying gaps between surfaces.
- The electrometer from this research will eliminate this type of damping by creating a variable mems capacitance with a sensing scheme of a harmonically changing area.

\[ c_{\text{Couette}} = \mu_p \rho \frac{A}{y} \]
\[ c_{\text{Squeeze}} = \mu_p \rho \frac{7A z_0^2}{y^3} \]

Figure 5: Illustration of slide-film damping (top) and squeeze film damping (bottom).
Variable Area Capacitor

![Diagram of Variable Area Capacitor](image)

Figure 6: Depiction of variable area capacitance

\[ H(t) = \frac{1}{C_{max}(|\sin \omega t| + \alpha)} \]

\[ C(x) = \frac{\varepsilon_o L x(t)}{g} + C_o + C_p \quad x(t) = |\hat{x}\sin \omega t| \]

\[ C(t) = \frac{\varepsilon_o L \hat{x}|\sin \omega t|}{g} + C_{po} = \frac{\varepsilon_o L \hat{x}}{g} \left( |\sin \omega t| + \frac{C_{po} g}{\varepsilon_o L \hat{x}} \right) \]

\[ = C_{max}(|\sin \omega t| + \alpha) \quad \alpha = \frac{C_{po}}{C_{max}} \]
Variable Area Capacitor

\[ s(x) = \frac{a_0}{2} + \sum_{n=1}^{\infty} \left[ a_n \cos(nx) + b_n \sin(nx) \right] \]

\[ a_n = \frac{2}{P} \int_{x_0}^{x_0+P} s(x) \cdot \cos\left(\frac{2\pi nx}{P}\right) \, dx \]

\[ s(x) = H(t) = \frac{1}{C_{\text{max}}\left(|\sin \omega t| + \alpha\right)} \]

\[ P = \frac{2\pi}{\omega} \]

\[ a_2 = \frac{\omega}{\pi C_{\text{max}}} \int_{-\pi/\omega}^{\pi/\omega} \frac{\cos 2\omega t \, dt}{|\sin \omega t| + \alpha} = \frac{2\omega}{\pi C_{\text{max}}} \int_{0}^{\pi/\omega} \frac{\cos 2\omega t \, dt}{\sin \omega t + \alpha} = \frac{2}{\pi C_{\text{max}}} \int_{0}^{\pi} \frac{\cos 2\tau \, d\tau}{\sin \tau + \alpha} \]

\[ = \frac{2}{\pi C_{\text{max}}} \left(2\alpha \pi - 4 - \frac{(4\alpha^2 - 2) \tan^{-1}(\sqrt{\alpha^2 - 1})}{\sqrt{\alpha^2 - 1}}\right) \]

\[ \alpha = \frac{C_p}{C_{\text{max}}} \]

when \( \alpha = 1 \)

\[ a_2 = \frac{2}{\pi C_{\text{max}}} (2\alpha \pi - 6) \]
Comparison

- Conversion gain of variable area system peaks at $C_{\text{max}} = 2.6 \ C_{\text{po}}$

$$\frac{d\bar{v}_i}{dQ} = \frac{\sqrt{2}}{\pi C_{\text{max}}} \left(2\alpha \pi - 4 - \frac{(4\alpha^2 - 2) \tan^{-1}(\sqrt{\alpha^2 - 1})}{\sqrt{\alpha^2 - 1}}\right)$$

- Conversion gain of variable gap system peaks when $C_0 = C_p$

$$\frac{d\bar{v}_i}{dQ} = \frac{\dot{x}^2}{g^2} \frac{C_0}{2\sqrt{2}(C_0 + C_p)^2}$$

- Variable area capacitance can create a 70% larger conversion gain

Figure 7: Conversion gain comparison between two sensing schemes. Both plots are graphed assuming the same parasitic capacitance.
# Designs

## Variable Area Charge Resolution

<table>
<thead>
<tr>
<th>$C_p$ (pF)</th>
<th>Predicted Charge Conversion Gain (V/C)</th>
<th>Equivalent Charge ($# , e^-$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>155</td>
<td>$3.30 \times 10^7$</td>
<td>12,636</td>
</tr>
<tr>
<td>24</td>
<td>$1.33 \times 10^9$</td>
<td>313</td>
</tr>
<tr>
<td>6</td>
<td>$1.9 \times 10^{10}$</td>
<td>22</td>
</tr>
</tbody>
</table>

## Lee et al. Charge Resolution

<table>
<thead>
<tr>
<th>$C_3$ (pF)</th>
<th>$C_p$ (pF)</th>
<th>Predicted responsivity (V/C)</th>
<th>Measured responsivity (V/C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>0.372</td>
<td>155</td>
<td>$1.96 \times 10^6$</td>
</tr>
<tr>
<td>S2</td>
<td>0.744</td>
<td>155</td>
<td>$3.91 \times 10^6$</td>
</tr>
<tr>
<td>S3</td>
<td>0.744</td>
<td>24</td>
<td>$1.07 \times 10^8$</td>
</tr>
<tr>
<td>S4</td>
<td>0.51</td>
<td>6</td>
<td>$1.07 \times 10^9$</td>
</tr>
<tr>
<td>S5</td>
<td>1.28</td>
<td>6</td>
<td>$2.14 \times 10^9$</td>
</tr>
</tbody>
</table>

## Comparison to Highest performance

<table>
<thead>
<tr>
<th>Input referred noise (nV/\sqrt{Hz})</th>
<th>$C_p$(pF)</th>
<th>Charge Conversion Gain (V/C)</th>
<th>Equivalent Charge ($# , e^-$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lee Variable Gap</td>
<td>29</td>
<td>2</td>
<td>$2.742 \times 10^{10}$</td>
</tr>
<tr>
<td>Variable Area</td>
<td>29</td>
<td>2</td>
<td>$1.303 \times 10^{11}$</td>
</tr>
</tbody>
</table>
Future Research

- Future research can be done to lower the parasitic capacitance for maximizing the charge resolution
  - This can be done by substrate removal or by implementing a CMOS, MEMS first fabrication process
- Also, the device can be incapsulated in a vacuum (using Stanford’s Epi-Seal process) to reduce damping and prevent bending due to shear stress
- Further research can be done to gather real world data for scientific applications.

**Figure 8:** Epi-Seal Process by Stanford University.
Summary

• Intro
• Variable Capacitors
• Variable Area Capacitor
• Comparison
• Designs
• Future Research
Questions?
References


Electrometry is a technique for measuring small electrical currents using an electrometer instrument. An electrometer can detect very low current, voltage, and charge. Electrometers are used in:
- mass spectrometry
- detection of bio-analyte and aerosol particles
- measurement of ionization radiation
- scanning tunneling microscopy

Figure 1: Secondary ion mass spectrometry (SIMS) instrumentation
A state of the art electrometer is the Keithley 6517 electrometer.

<table>
<thead>
<tr>
<th>MODE</th>
<th>RESOLUTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammeter</td>
<td>10 aA</td>
</tr>
<tr>
<td>Voltmeter</td>
<td>10 μV</td>
</tr>
<tr>
<td>Coulometer</td>
<td>800 aC (5000 electrons)</td>
</tr>
</tbody>
</table>
Feedthrough

- Feedthrough is present whenever actuation and sensing take place in the same vicinity.
- The drive electrode inevitably couples to the sense node.

\[ v_f = v_d \frac{C_{ss}}{C_{ss} + C_{x+}} - v_d \frac{C_{ss}}{C_{ss} + C_{x-}}. \]
\[ C_{x-} = C_{rs} (1 + \delta_i). \]
\[ |v_f| = |v_d| \frac{|\delta|C_s}{C_r}. \]

Fig. 2.9: Generic sense circuit with feedthrough capacitance

Fig. 2.10: Differential sense circuit with feedthrough capacitors

- A technique to reduce the effects of feedthrough is differential sensing.
Feedthrough

- An analogous technique to reduce feedthrough is to use differential actuation
  - This refers to driving the structure using antisymmetric waveforms, one on each side
- If the feedthrough capacitors all match within 1%, the resultant feedthrough signal at the output is reduced by 10,000 with respect to the single-ended case (Fig. 2.9)
Feedthrough can be further reduced through harmonic sensing:

- The sensing signal can be measured at twice the frequency of the driving voltage.
- The driving voltage will be filtered out.

In real systems, the drive signal can be stepped up to the second harmonic:

- The second harmonic distortion is defined as:

\[
HD_2 = \frac{|\hat{v}_d(2f)|}{|\hat{v}_d(f)|}.
\]

Applying this to the differential drive and sense from before gives:

\[
|v_f| = |v_d| \frac{C_4}{C_1} |\delta_1| |\delta_2| \cdot HD_2.
\]

It is not difficult to achieve HD values less than .001 with a function generator:

- This method can therefore reduce feedthrough by a factor of over 1000.
- Combining all three techniques, we can expect to attenuate a 1-mV feedthrough signal to 100 pV.