Air Force Institute of Technology

U.S. AIR FORCE

MEMS Variable Area Capacitor for Room Temperature Electrometry

2d Lt George Underwood

Educating the World's Best Air Force

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 1.9E-6 electrons [1]
  - However, the sensing temperature was 4.2 Kelvin

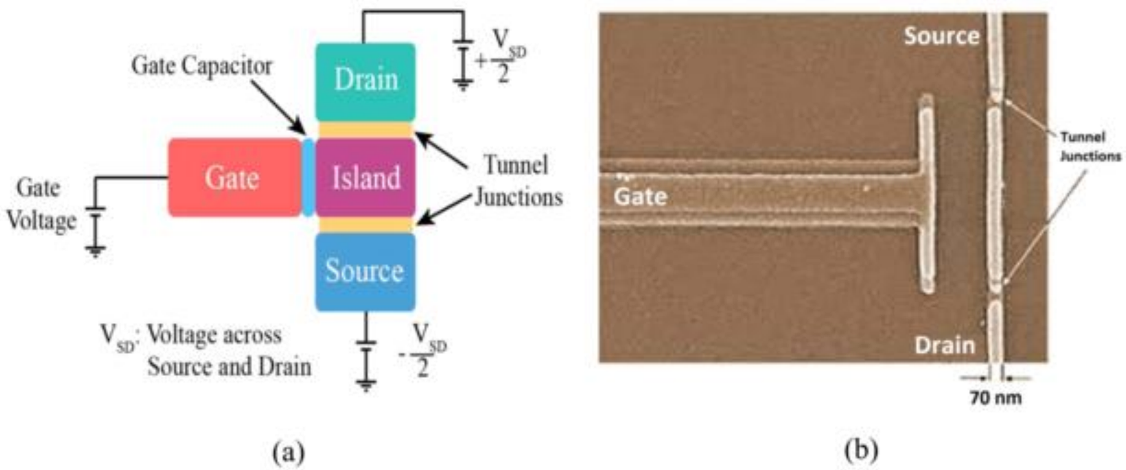


Figure 1: (a) Schematic diagram of SET as a charge sensor electrometer. (b) scanning electron micrograph an SET. This image was taken from [1]

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%

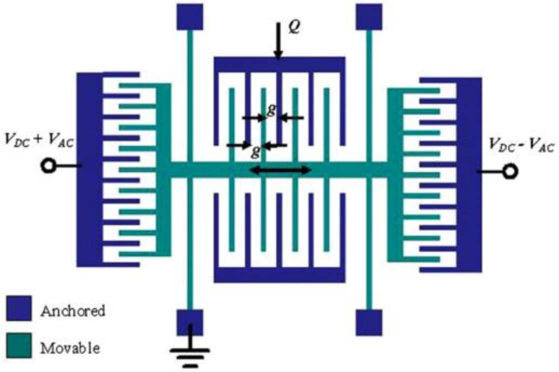


Figure 2: Top view of a variable gap capacitor (borrowed from [3]).

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

Ross Gunn 1897-1966

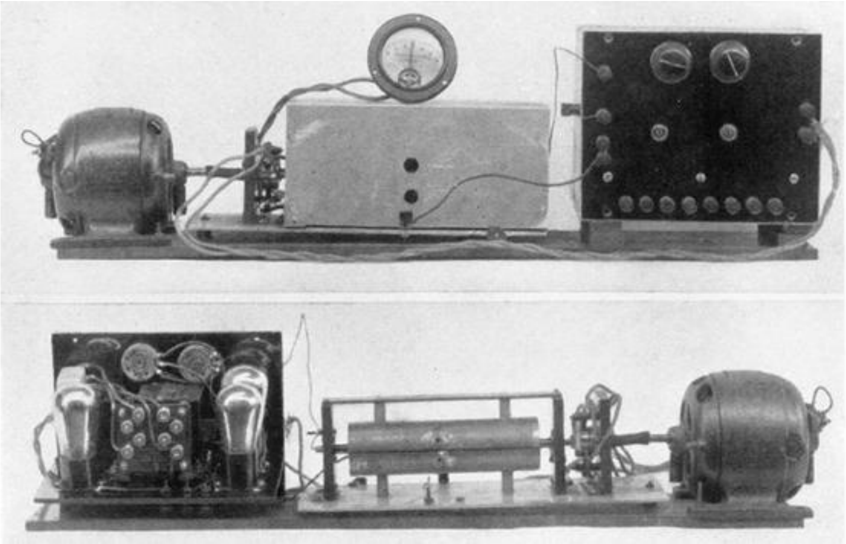
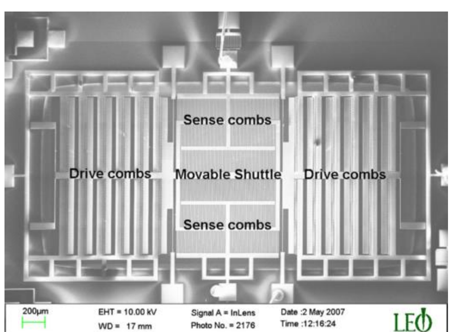


Figure 3: picture of first variable capacitor electrometer [4]

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]:

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



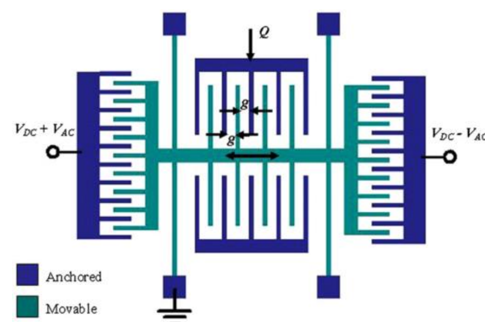


Figure 4: SEM image of Lee *et al.* Electrometer (left). Simple model of the electrometer (right) borrowed from [3].

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

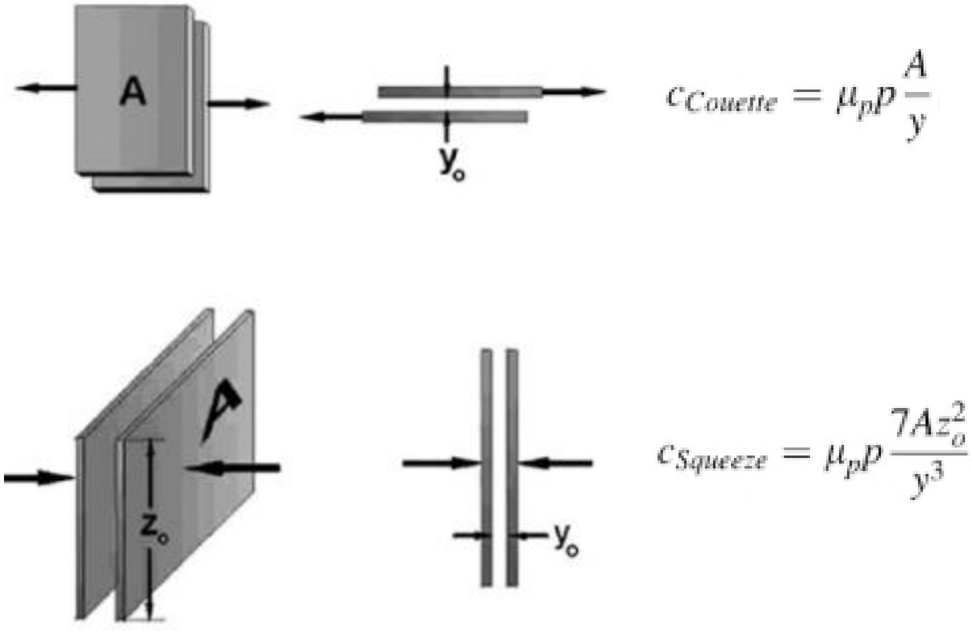
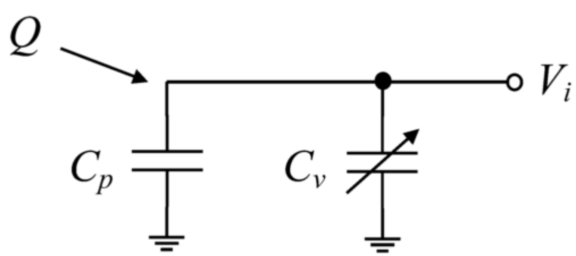
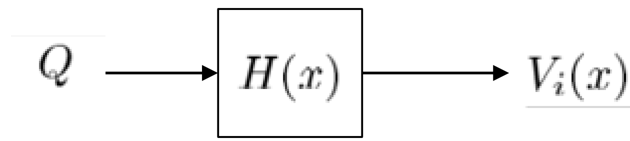


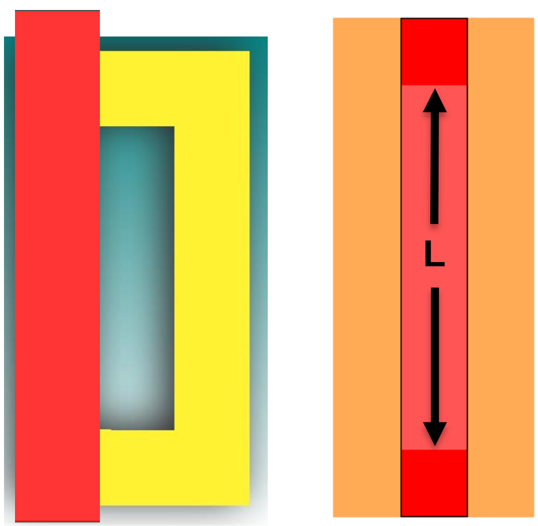
Figure 5: Illustration of **slide-film damping** (top) and squeeze film damping (bottom).

Variable Area Capacitor





$$\frac{V_i(x)}{Q} = H(x) = \frac{1}{C(x)}$$



(a) (b)

Figure 6: Depiction of variable area capacitance

$$C(x) = \frac{\epsilon_o L\, x(t)}{g} + C_o + C_p \qquad x(t) = |\hat{x} \sin \omega t|$$

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

$$= C_{max}(|\sin \omega t| + \alpha) \qquad \alpha = \frac{C_{po}}{C_{max}}$$

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

Variable Area Capacitor

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

$$a_n = \frac{2}{P} \int_{x_0}^{x_0+P} s(x) \cdot \cos\left(\frac{2\pi n x}{P}\right) dx \qquad s(x) = H(t) = \frac{1}{C_{max}(|\sin \omega t| + \alpha)} \qquad P = 2\pi/\omega$$

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

$$\boxed{= \frac{2}{\pi C_{max}} \left(2\alpha\pi - 4 - \frac{(4\alpha^2 - 2)\tan^{-1}(\sqrt{\alpha^2 - 1})}{\sqrt{\alpha^2 - 1}} \right)} \qquad \alpha = \frac{C_{po}}{C_{max}}$$

$$when\ \alpha = 1 \qquad a_2 = \frac{2}{\pi C_{max}} (2\alpha\pi - 6)$$

Comparison

- Conversion gain of variable area system peaks at Cmax = 2.6 Cpo

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

- Conversion gain of variable gap system peaks when Co = Cp

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

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

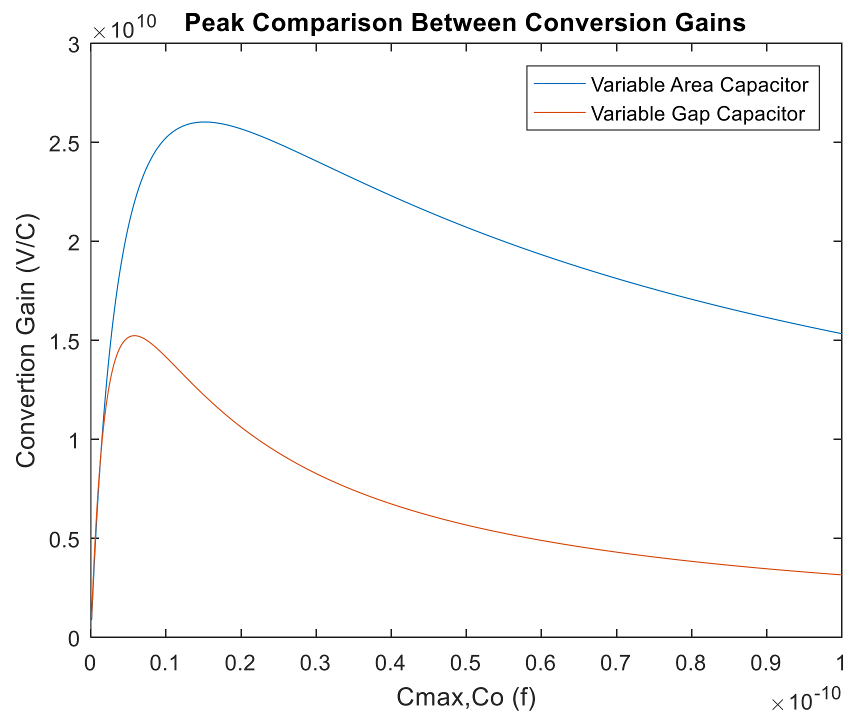
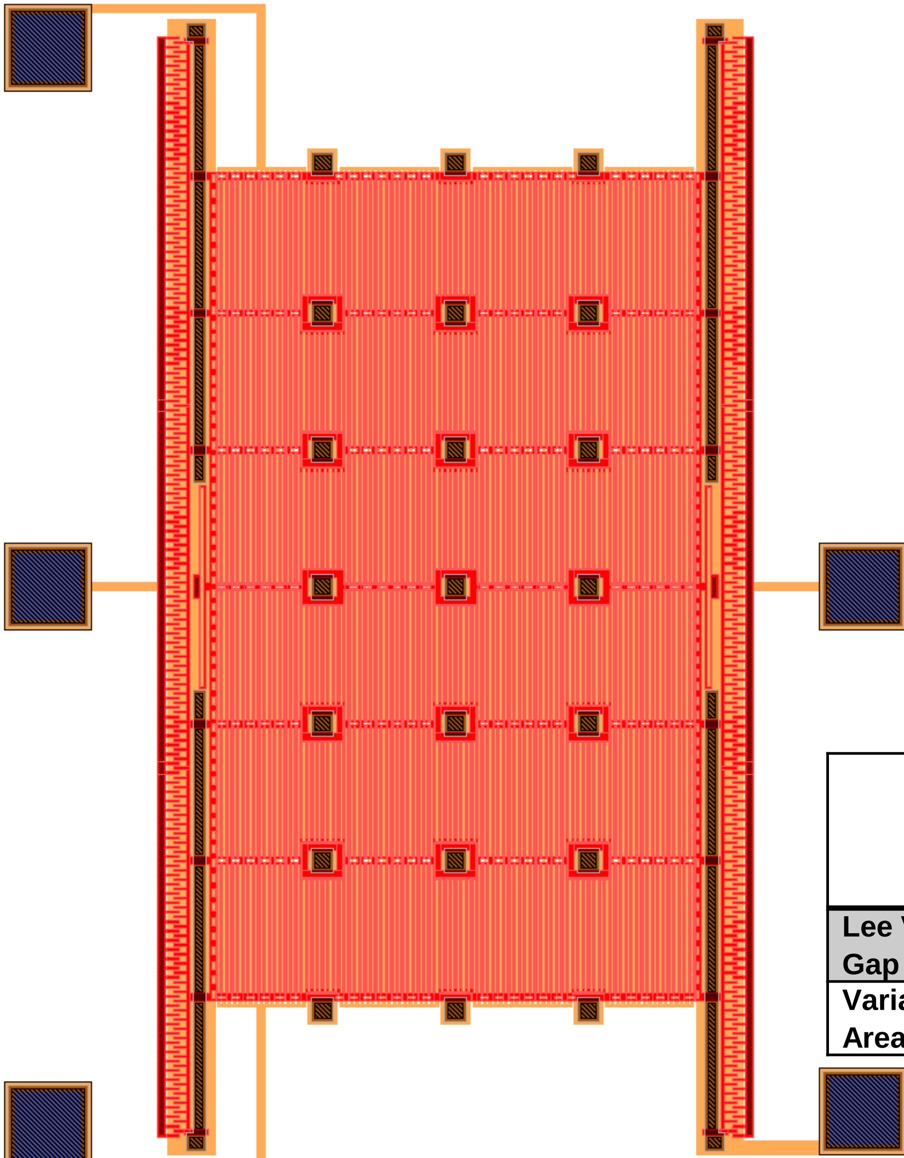


Figure 7: Conversion gain comparison between two sensing schemes. Both plots are graphed assuming the same parasitic capacitance.

Designs



Variable Area Charge Resolution

$C_p(pF)$	Predicted Charge Conversion Gain (V/C)	Equivalent Charge (# e-)
155	3.30 x 10^{7}	12,636
24	1.33 x 10^{9}	313
6	1.9 x 10^{10}	22

Lee *et al.* Charge Resolution

	C_S (pF)	C_P (pF)	Predicted responsivity (V/C)	Measured responsivity (V/C)
S1	0.372	155	1.96×10^6	2.02×10^6
S2	0.744	155	3.91×10^6	4.51×10^6
S3	0.744	24	1.07×10^8	1.02×10^8
S4	0.51	6	1.07×10^9	1.09×10^9
S5	1.28	6	2.14×10^9	2.09×10^9

Comparison to Highest performance

	Input referred noise (nV/$\sqrt{Hz}$)	$C_p(pF)$	Charge Conversion Gain (V/C)	Equivalent Charge (# e-)
Lee Variable Gap	29	2	2.742 x 10^{10}	6.6
Variable Area	29	2	1.303 x 10^{11}	1.4

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.

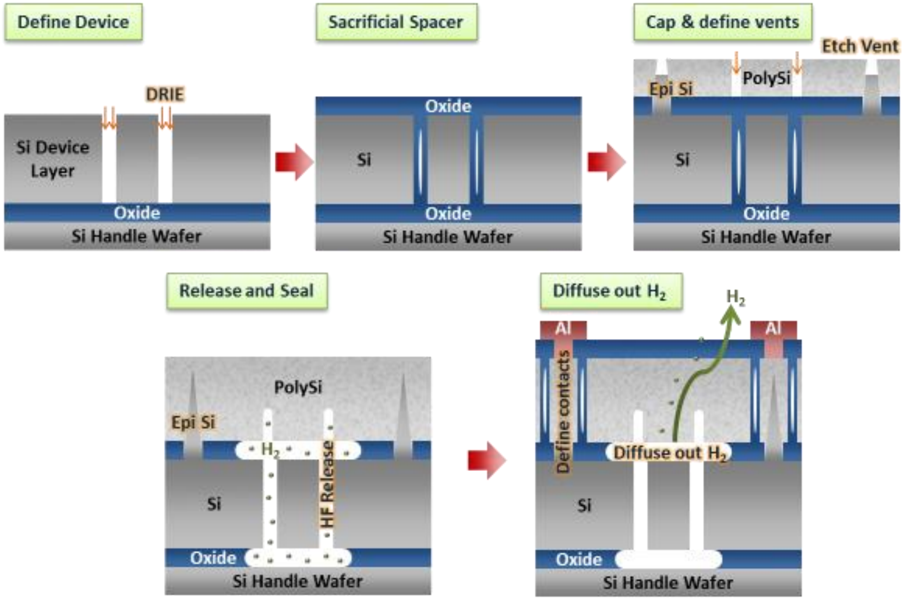


Figure 8: Epi-Seal Process by Stanford University.

Summary

- Intro
- Variable Capacitors
- Variable Area Capacitor
- Comparison
- Designs
- Future Research

Questions?

AFIT

References

AFIT

1. Jalil, Y.; Zhu, Y. Sensing of single electrons using micro and nano technologies: A review. Nanotechnology121 2017, 28.
2. Riehl, P.S.; Scott, K. High-Resolution Electrometer with Micromechanical Variable Capacitor. In Solid-State119 Sensor, Actuator and Microsystems Workshop 2002; pp. 305-308.
3. Lee, J.; Zhu, Y. Room temperature electrometry with SUB-10 electron charge resolution. J. Micromech.117 Microeng. 2008, 18.
4. Gunn, Ross. (1932). Principles of a New Portable Electrometer. Physical Review - PHYS REV X. 40. 307-312. 10.1103/PhysRev.40.307.

Electrometry

- 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

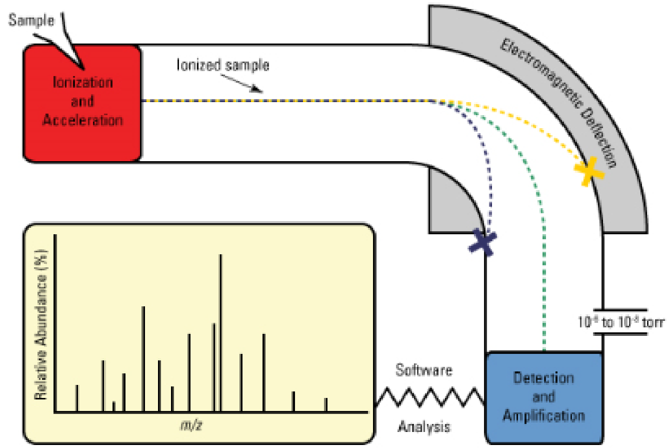


Figure 1: Secondary ion mass spectrometry (SIMS) instrumentation

Electrometry

- A state of the art electrometer is the Keithley 6517 electrometer

MODE	RESOLUTION
Ammeter	10 aA
Voltmeter	10 μV
Coulometer	800 aC (5000 electrons)

Feedthrough

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

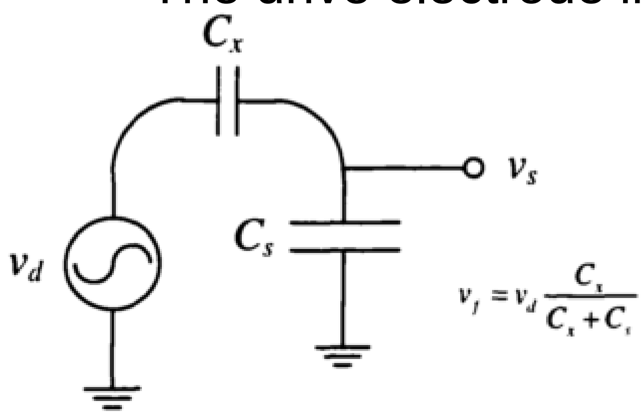


Fig. 2.9: Generic sense circuit with feedthrough capacitance

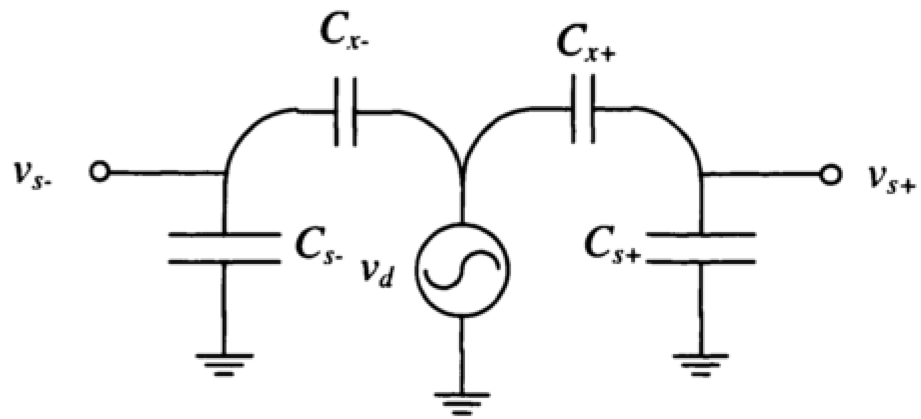


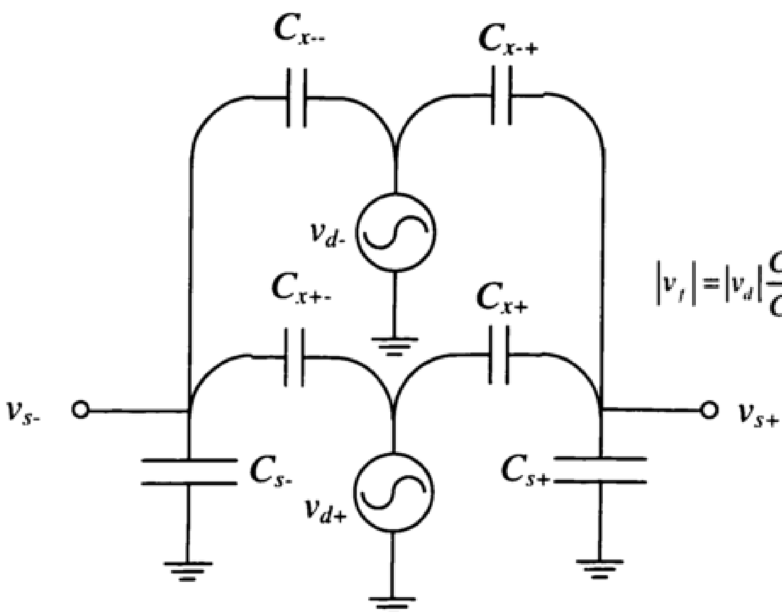
Fig. 2.10: Differential sense circuit with feedthrough capacitors

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

$$v_f = v_d \frac{C_{x+}}{C_{x+} + C_{s+}} - v_d \frac{C_{x-}}{C_{s-} + C_{x-}}. \qquad C_{x-} = C_{x+}(1+\delta_1). \qquad |v_f| = |v_d| \frac{|\delta_1| C_x}{C_s}$$

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)



$$|v_f| = |v_d| \frac{C_x}{C_s} |\delta_1| |\delta_2|$$

Fig. 2.11: Feedthrough model with differential drive and differential sense

Feedthrough

- Feedthrough can be further reduced through harmonic sensing
  - The sensing signal can be measured at twice the frequency of the driving voltage
  - The Diving 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:

$$|v_f| = |v_d| \frac{C_s}{C_s} |\delta_1||\delta_2| \cdot HD_2$$

- 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