Introduction
to
microsensors and microactuators

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Class Information

- Instructor: Wei-Chih Wang, Ph.D.
- Office: S606 (Phone: 206-543-2479)
- Grading: 3 credits
- Class Time: MTW 10:00-12:00 AM (S607)
- Course website: http://depts.washington.edu/mictech/optics/sensors/index.html
- Textbooks:
  - Fundamentals of Photonics, B. Saleh, John Wiley& Sons
  - Fiber optic Sensors, E. Udd, John Wiley& Sons
  - Selected papers in micro sensors, MEMS devices, smart materials and micro actuators.
  - EAP Handbook, SPIE

Class Information

- **Grading:**
- Homework assignments 60% (3 assignments)
- Final Project 40%.
- •**Final Project:**

  - Choose topics related to sensors and actuators.
  - Details of the project will be announced in mid quarter
  - Two people can work as a team on a project, but each person needs to turn in his/her own final report.
  - Oral presentation will be held in the end of the quarter on your final project

Objectives

- To introduce the student to some basic principles and techniques of micro sensors and actuators

Outline of the class

- Definition of sensor and actuator
- Methodology and materials commonly used in sensors and actuators
- Sensor and actuator examples of each underlying physical principle (including some of my research projects)
- Mainly mechanical sensors and actuators

Schedule

- Week 1. Introduction to basic principal of micro sensors and actuators
- Week 1 Electrostatic transducers – capacitive sensors, electrostatic actuators
- Week 1 Cantilever transducer - mechanical resonance, damping, and stress analysis
- Week 1 Composite structure
- Week 2 Magnetic transducers – typical and non-typical applications of magnetic sensors and actuators
- Week 2. Piezoelectric transducers – devices and applications using piezoelectric materials (i.e. PZT, PVDF, ZnO and PTF)
- Week 3 Thermal transducers – resistive sensors and actuators (i.e. strain gage, anemometer, bubble jet, SMA, optothermal actuator, etc.)
- Week 3 Electrostrictive and Magnetostrictive transducers
- Week 4. Optical Transducers – optical techniques in devices and applications. (Intensity modulation, phase modulation, and other optical techniques)
- Week 4 Smart Materials –electro active polymers (dielectric actuator, ionic polymers, etc.)
- Week 5 Introduction to Biosensors – materials and applications.
- Week 5 Final project presentation

Sensor Definition

A device that responds to a physical stimulus, such as thermal energy, electromagnetic energy, acoustic energy, pressure, magnetism, or motion, by producing a signal, usually electrical.

My sensor definition

- Sensors imitating after the five human senses: gustatory (taste), olfactory (smell), tactile, auditory, and visual.

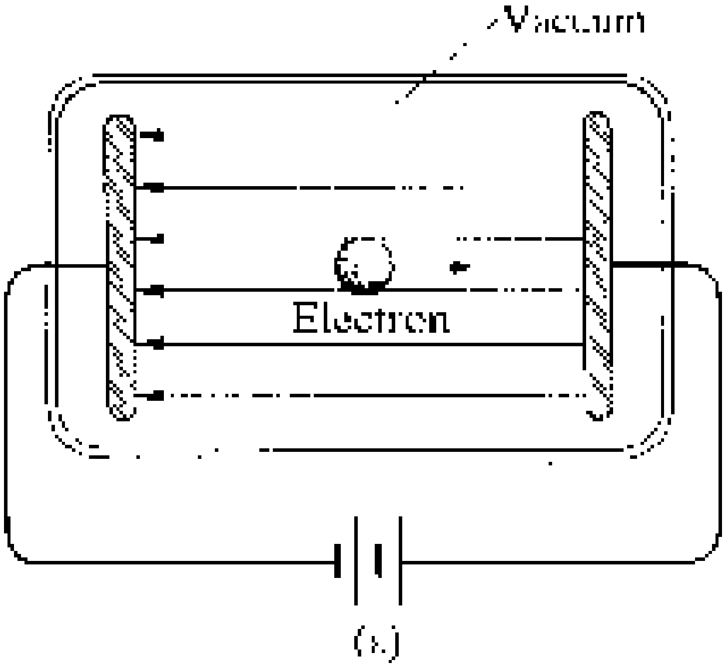
Actuator definition

- A mechanism that puts something into automatic action

Method for sensing and actuation

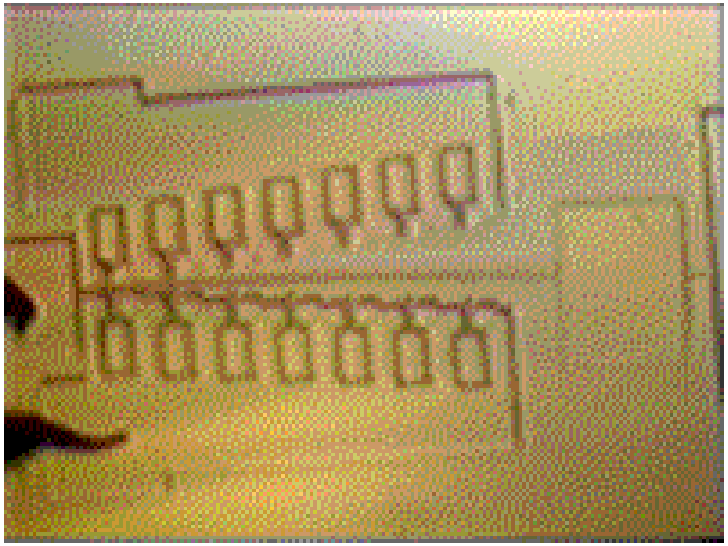
- Optical
- electrostatic
- magnetic
- Piezoelectric
- thermal

electrostatic actuator

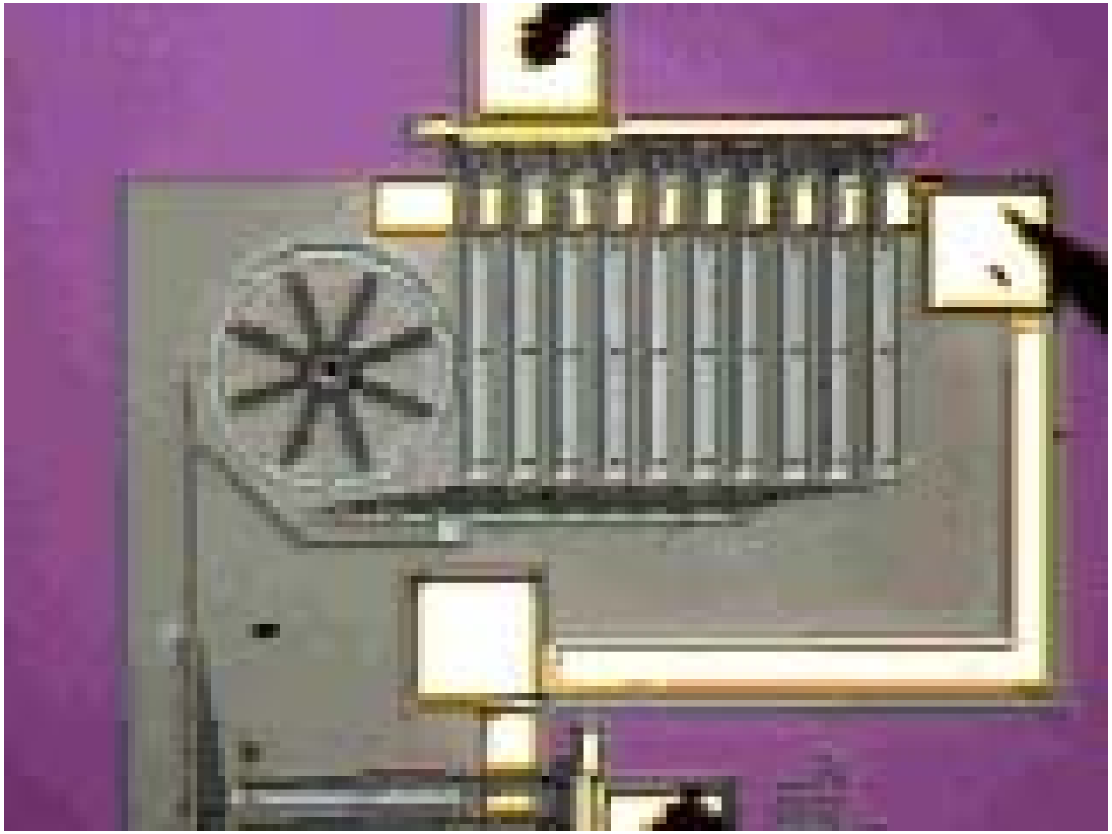


F=qE

Electrostatic actuator



Comb Drive MEMS motor



electrostatic

In estimating the force generated by an electrostatic actuator, One can begin with Coulomb’s law, which give the force Between two point charge,

$$F_{elec} = \frac{1}{4\pi\varepsilon_r\varepsilon_o}\frac{q_1 q_2}{x^2}$$

Where x distance separation between two charge q_1 $q_{2.}$ For most realistic electrostatic actuators, the model becomes quite complex, the method most be solved by numerical methods.

First-order approximation

For first order approximation, sometimes one can start with a Parallel-plate capacitor approximation.

For parallel-plate capacitor with plate area, A (neglecting fringe effect), the energy stored at a given voltage, V is given by

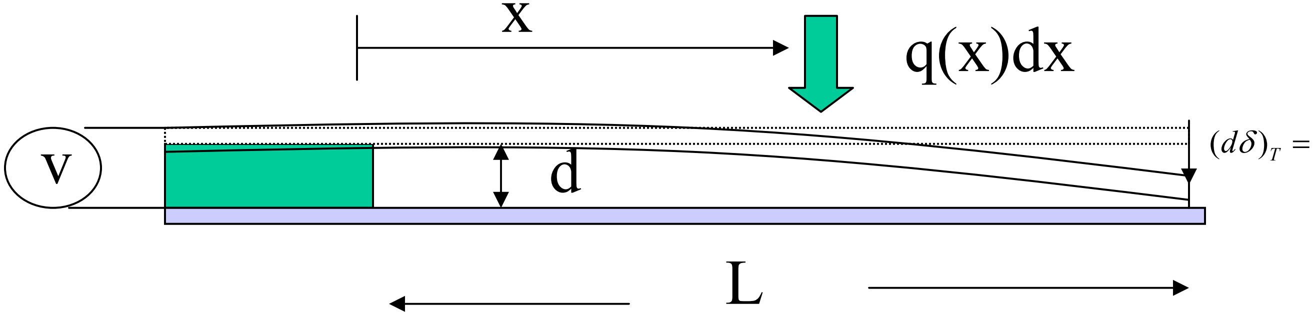
$$W = -\frac{1}{2}CV^2 = -\frac{1}{2}\frac{\varepsilon_r \varepsilon_o \mathrm{AV}^2}{x}$$

And force between the plates is

$$F = \frac{\partial W}{\partial x}$$

Electrostatic cantilever actuators

An analysis of relationship of applied voltage and deflection in a Micro machined cantilever beam



Based on simple beam deflection equation having electrostatic Force q applied at position x on a beam with length L and width W and tip deflection δ_t is given by

$$d\delta_T = \frac{x^2}{6EI}(3L - x)wq(x)dx$$

Total beam deflection is $\delta_T = \int d\delta_T$

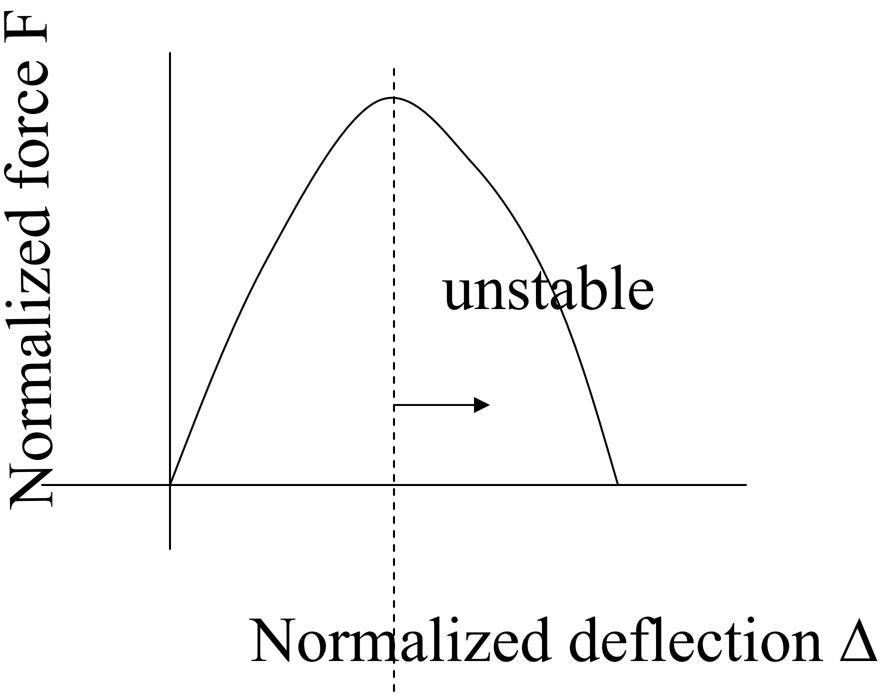
To make the solution of the integral possible, one can assume a square-law curvature of the beam at any point along its length

$$\delta(x) \approx \left(\frac{x}{L}\right)^2 \delta_T$$

This in turn yields a normalized load, F, required to produce a Specified tip deflection,

$$F \equiv \frac{\varepsilon_o w L^4 V^3}{2EId^3} = 4\Delta^2 \left(\frac{2}{3(1-\Delta)} - \frac{\tanh^{-1}\sqrt{\Delta}}{\sqrt{\Delta}} - \frac{\ln(1-\Delta)}{3\mathrm{H}}\right)^{-1}$$

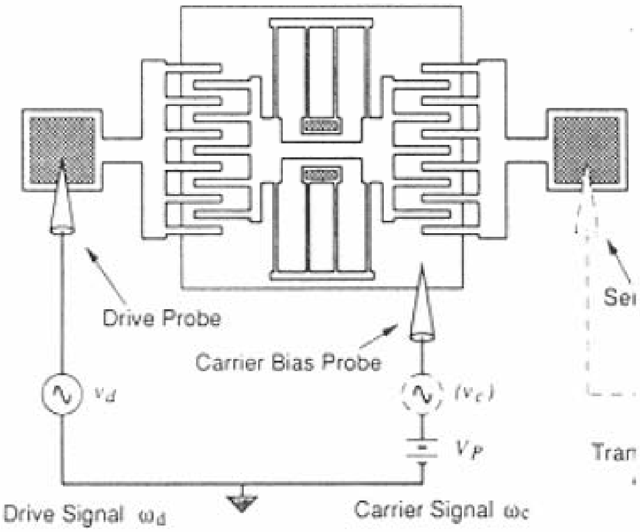
Where $\Delta = \delta_T/d$ (normalized deflection at tip)



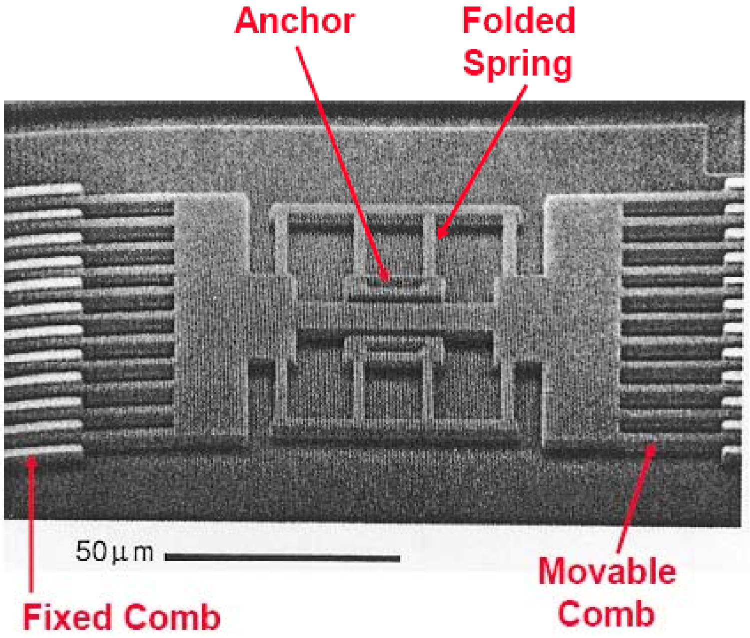
Based on the normalized force equation, the above curve
Shows that at once deflection exceeds a threshold voltage,
The position of the tip is unstable and the beam spontaneously
Deflects all the way down. The threshold voltage is approximately
Given by

$$V_{th} \approx \sqrt{\frac{18EId^3}{5\varepsilon_o L^4 w}}$$

Comb Drive Actuators

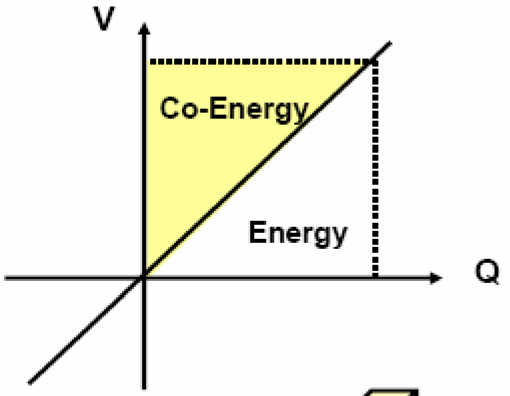


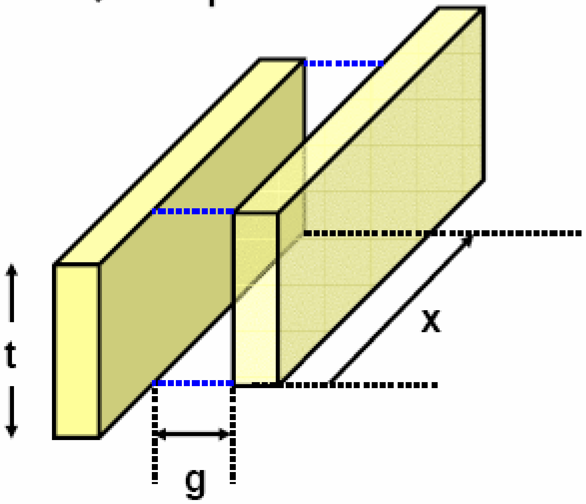
Schematic



Scanning Electron Micrograph (SEM)

Electrostatic Comb-Drive Actuator
-- Voltage Control





$$C = \frac{\varepsilon A}{g} = \frac{\varepsilon t x}{g}$$

$$W(V,g) = \frac{1}{2} C V^2$$

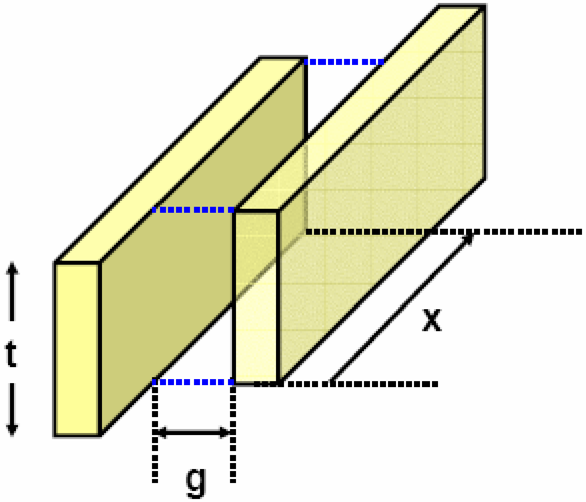
$$W^*(V,g) = QV - W(Q,g) = \frac{1}{2} C V^2$$

Force per Gap: $$\boxed{F_x = \left.\frac{\partial W^*(V,g)}{\partial x}\right|_V = \frac{\varepsilon V^2 t}{2g}}$$

Total Force: Multiply by the number of gaps

Electrostatic force with voltage control is
- proportional to V^2
- inversely proportional to g
- independent of x
  - → Constant force along motion direction
  - → No bistability

Typical Electrostatic Force in Microscale



For t = g

$$\boxed{F_x = \frac{\varepsilon V^2}{2}}$$

Direction of Force:
Increasing Overlap

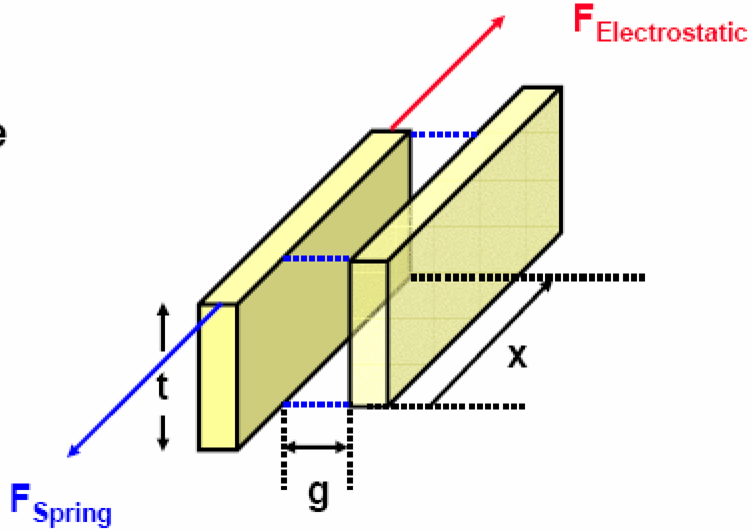
$$\varepsilon_0 = 8.854 \times 10^{-12} \frac{Farad}{meter}$$

E.g., V = 15 Volt

F_x = 1 nN

Stability Analysis

- **An equilibrium point is unstable if in the presence of small perturbation, the net force does not tend to return it back to equilibrium position**
- **For stable point, the variation of the net force should be of opposite sign with the perturbation.**



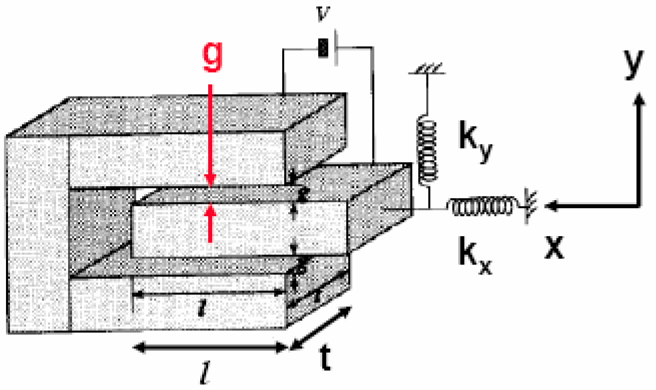
$$F_{net} = \frac{\varepsilon V^2 t}{2g} - k(x - x_0)$$

$$x \rightarrow x + \delta x$$

$$\delta F_{net} = \left.\frac{\partial F_{net}}{\partial x}\right|_V \delta x = -k\delta x$$

Always Stable

Lateral Instability



- To increase the lateral stability
  - Design a spring with large lateral stiffness (or large K_y/K_x ratio)
  - Reduce overlap at V = 0 (small l)
- Lateral stability becomes more critical for comb drives with

$$F_{net} = \frac{\varepsilon V^2 tl}{2(g-y)^2} - \frac{\varepsilon V^2 tl}{2(g+y)^2} - k_y y$$

$$y \rightarrow y + \delta y$$

$$\delta F_{net} = \left.\frac{\partial F_{net}}{\partial y}\right|_{y=0} \delta y = \left(\frac{2\varepsilon tlV^2}{g^3} - k_y\right)\delta y$$

$$\Downarrow$$

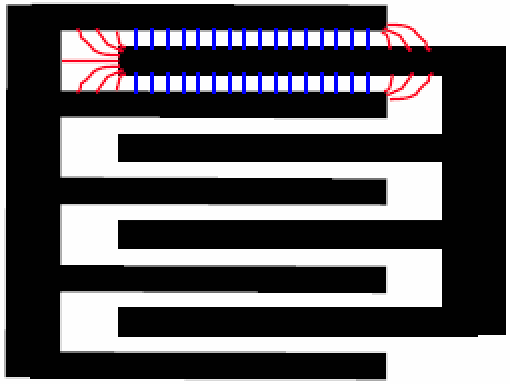
$$\frac{2\varepsilon tlV^2}{g^3} - k_y < 0$$

or

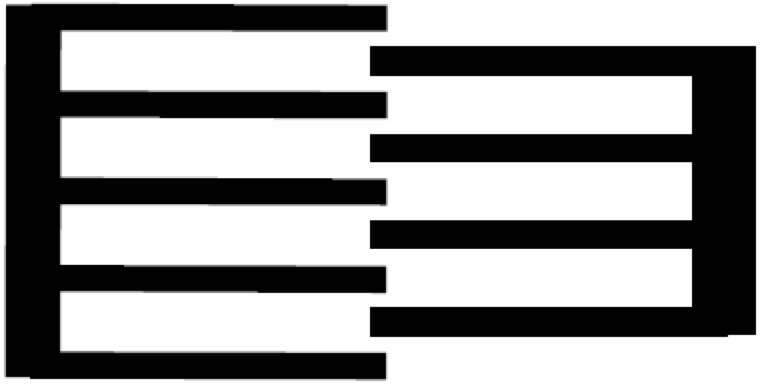
$$V_{Critical} < \sqrt{\frac{k_y g^3}{2\varepsilon tl}}$$

Optimum Comb Drive Geometry

These 2 comb drives have the same electrostatic force along the finger direction



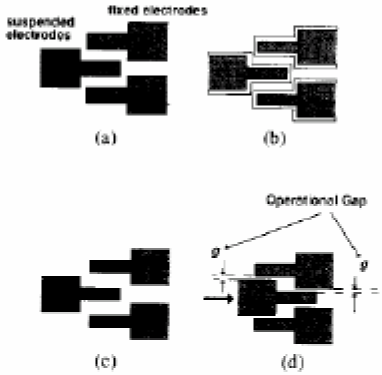
Poor lateral instability

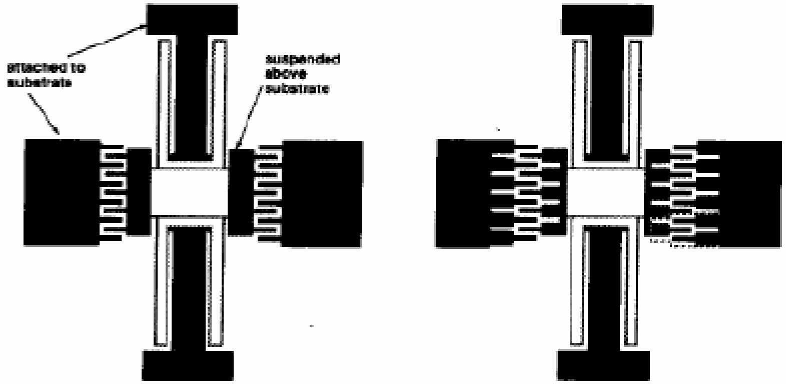


Better lateral instability

How to Create Comb Drive Actuators with Small Gaps?

- Smaller gap produces larger force
  - Force of comb drive is inversely proportional to the gap spacing between adjacent combs
  - High force, high resonant frequency
- Sub-micron gap requires expensive lithography (e-beam writing, ..)
- Innovative approach to produce sub-micron fingers
- Lateral stability become more critical
  - Optimize spring design

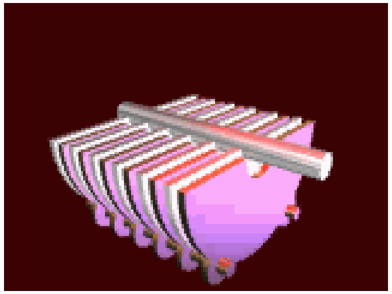


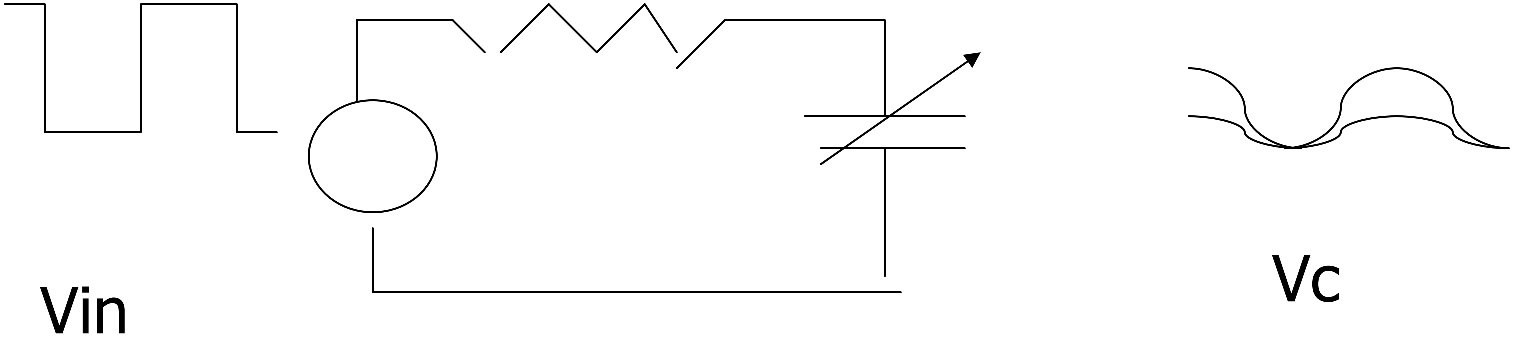


How capacitor works

$CV= q$

$C=\varepsilon A/d$

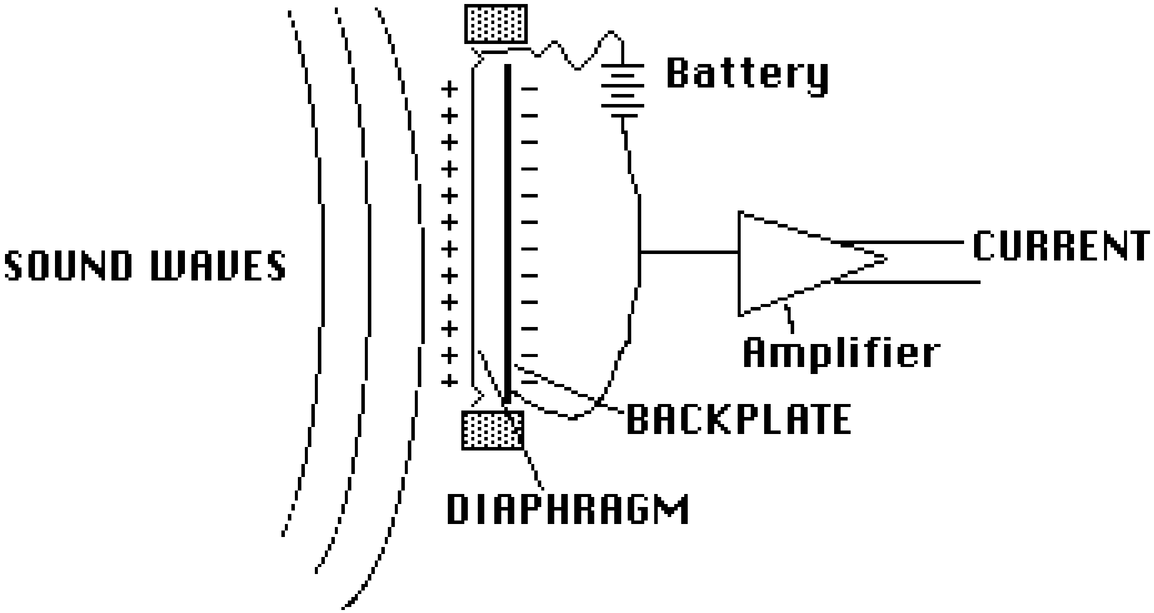




Condenser microphone

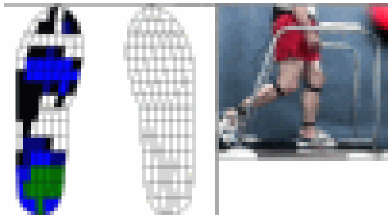
$CV = q$

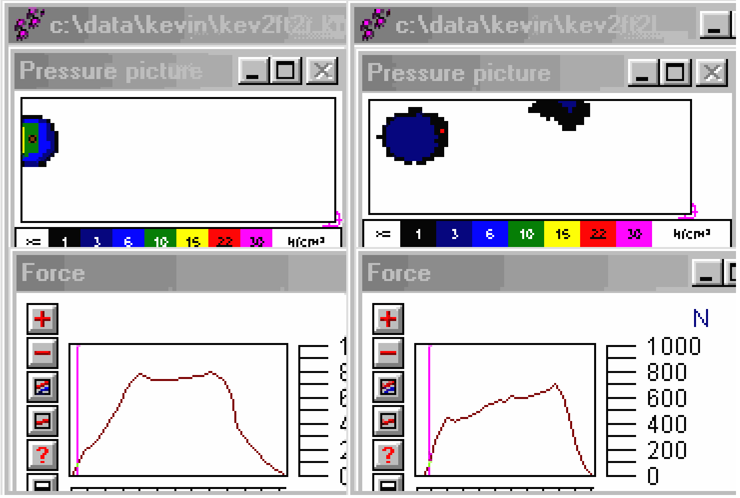
$C = \varepsilon A/d$



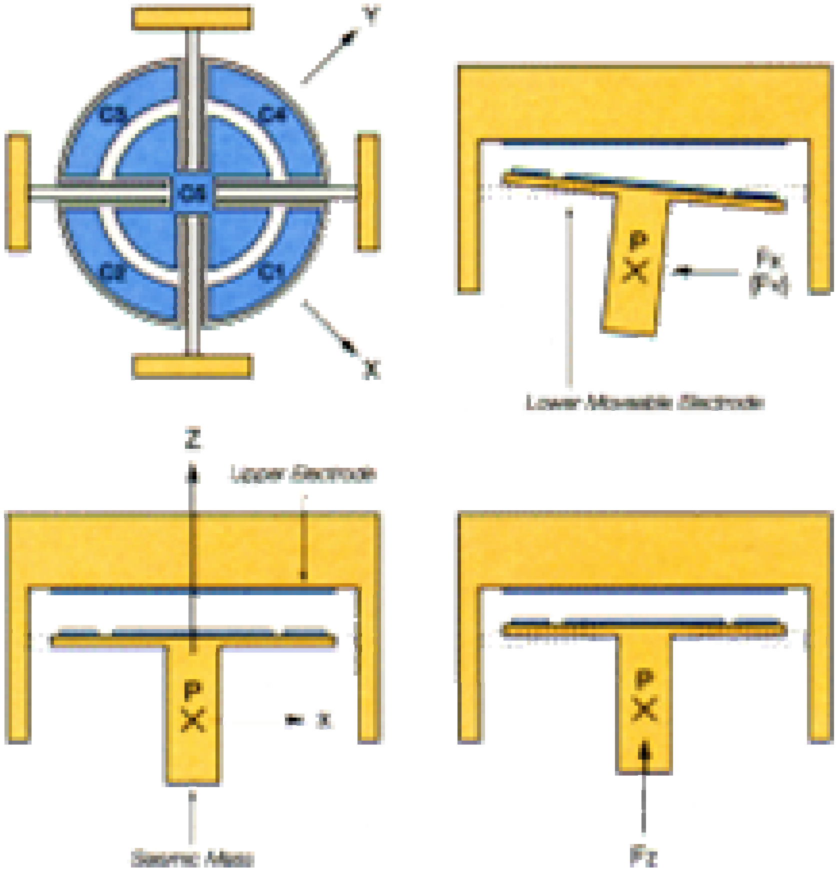
Distribute tactile sensor (capacitive)

Noval PEDAR distribute pressure sensor



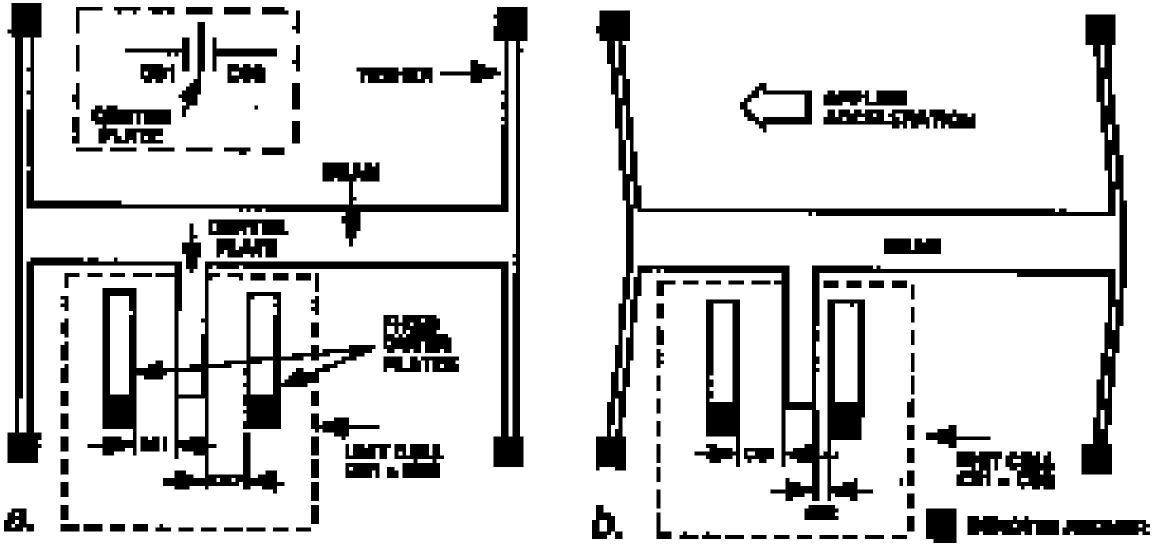


3 axis capacitive Accelerometer



British aerospace system and equipment model C3A-02

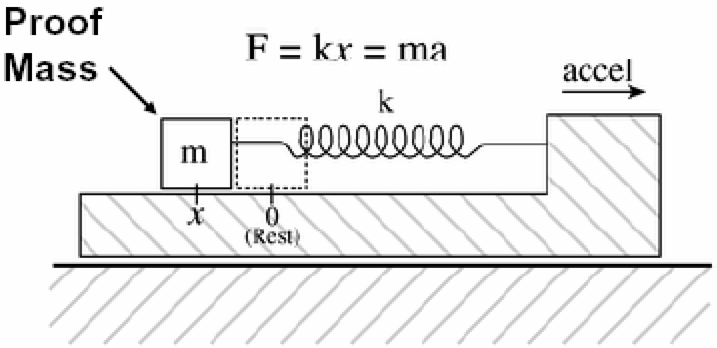
Analog device accelerometer



ADXL50 accelerometer

Basic Concept

Quasi-Static Accelerometers:



$$\boxed{F = kx = ma}$$

$$a = \frac{k}{m}x$$

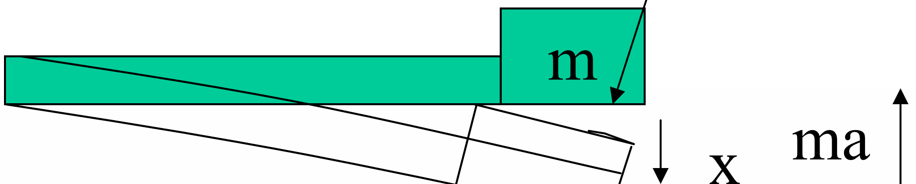
$$\omega_0 = \sqrt{\frac{k}{m}}$$

$$\boxed{a = \omega_0^2 \cdot x}$$

- Sense acceleration by sensing position
- High sensitivity (sensitive to low g)
  Low resonant frequency
  - Large proof mass
  - Compliant spring

Acceleration is detected
Based on the displacement
On the capacitor sensor

ucla



Sensitivity

- Sensitivity is limited by noises, including fluidic damping, circuit noise, shot noise

Damping force noise spectral Density: $S = 4k_B Tb$

$k_B T$: thermal energy
b: damping coefficient

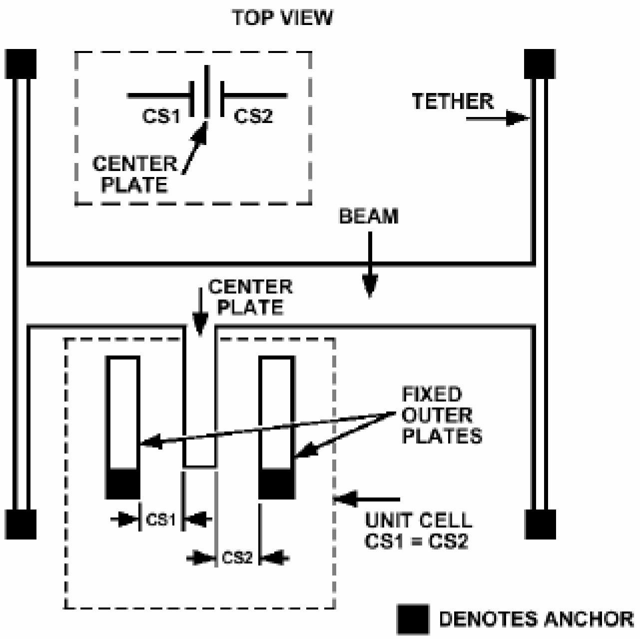
Mean-square force noise in 1 Hz: $f_{n,rms} = \sqrt{4k_B Tb}$

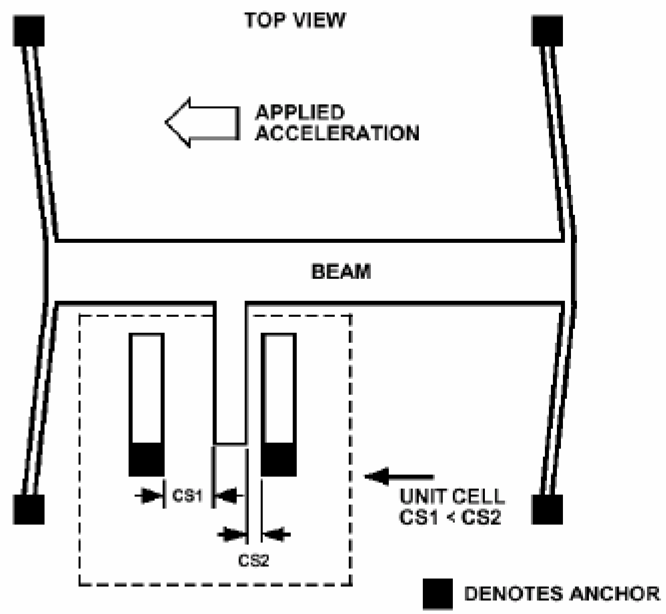
Mean-square equivalent acceleration noise:

$$a_{n,rms} = \frac{\sqrt{4k_B Tb}}{m} = \sqrt{\frac{4k_B T}{m^2}\left(\frac{m\omega_0}{Q}\right)} = \sqrt{\frac{4k_B T\omega_0}{mQ}}$$

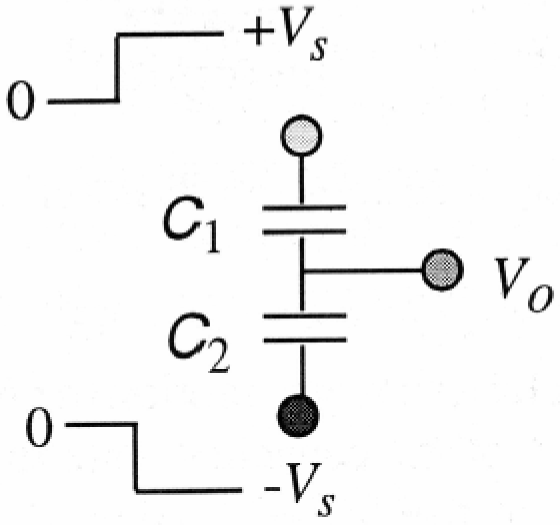
unit: $\frac{g}{\sqrt{Hz}}$

ADXL Differential Capacitive Sensor





Differential Capacitive Sensing



$$V_0 = -V_S + \frac{C_1}{C_1 + C_2} \cdot 2V_S$$

$$= \frac{C_1 - C_2}{C_1 + C_2} V_S$$

$$C_1 = C\frac{x_0}{x_0 + \delta x} \qquad C_2 = C\frac{x_0}{x_0 - \delta x}$$

For small displacement:

$$C_1 - C_2 = C\left(\frac{x_0}{x_0 + \delta x} - \frac{x_0}{x_0 - \delta x}\right)$$

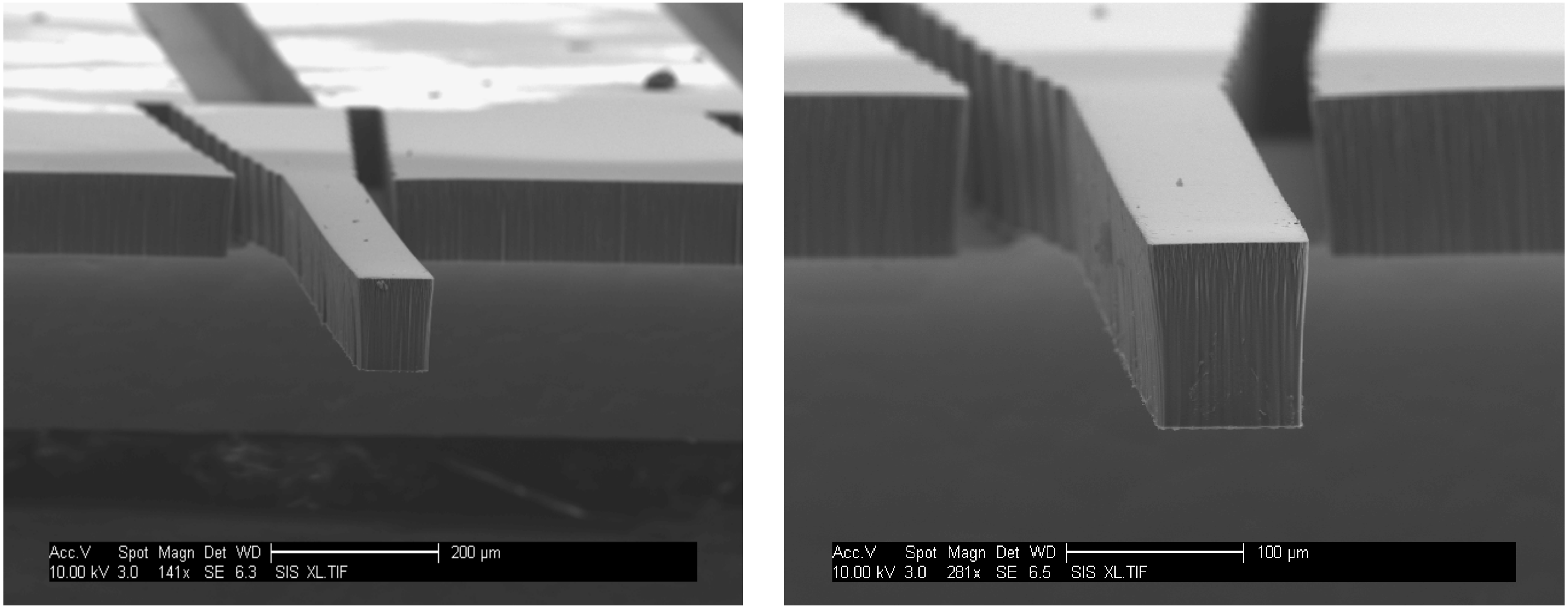
$$= C\frac{-2x_0\delta x}{x_0^2 - \delta x^2} \approx -C\frac{2}{x_0}\delta x$$

$$C_1 + C_2 \approx 2C$$

$$\boxed{V_0 \approx -\frac{\delta x}{x_0} V_S}$$

Output voltage is linearly proportional to the displacement

Microfabricated Beams



SU8 Beams

UWMictech