AMN- 606

MEMS/NEMS Technology and Devices

Lecture 5/6:

Industrial and Automobile Applications

Dr. Hassan Mostafa

hmostafa@uwaterloo.ca

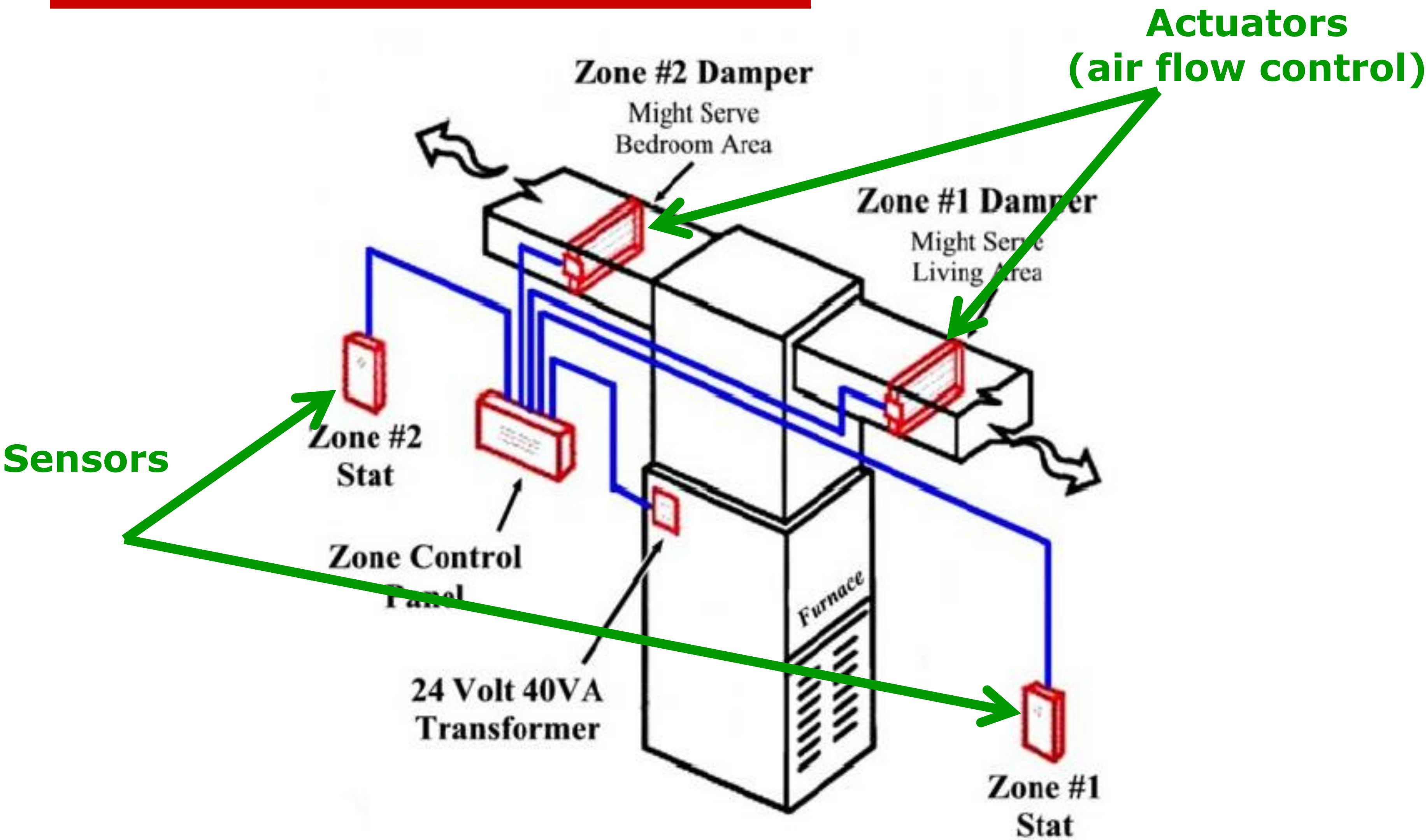
Cairo University

Fall 2018

Sensors and Actuators

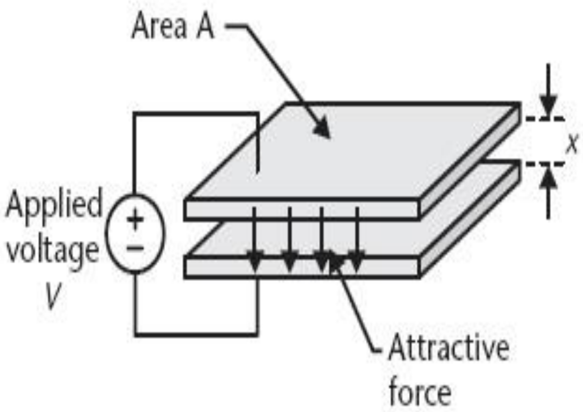
- **Sensor**
  - A device that converts an environmental condition into an electrical signal
- **Actuator**
  - A device that converts a control signal (usually electrical) into mechanical action (motion)
- **Basic components of a control system**
  - Sensor
  - Actuator
  - Power supply
  - Controller

Home heating example



Actuation methods

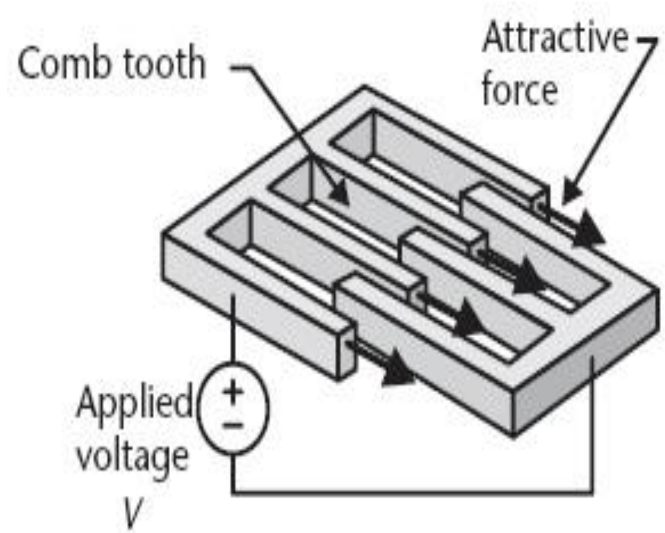
- **Electrostatic actuation**
  - It relies on the attractive force between two conductive plates
  - An applied voltage results in an attractive electrostatic force between the two plates
  - If *C is the capacitance between two* parallel plates, *x is the spacing between them, and V is an* externally applied voltage, the electrostatic force is then $(0.5 * C * V^2)/x$
  - *The square term* ensures that the force is always positive and attractive due to the opposite charges polarity on the plates



Actuation methods

Electrostatic actuation

- Electrostatic comb actuators are a variant that includes two comb sets of inter-digitated “teeth” that are offset relative to each other
- An applied voltage brings the two combs together such that the teeth become alternating
- Designers have favored comb actuators over parallel-plate actuators because they allow a larger displacement (tens of micrometers are feasible)



Actuation methods

Piezoelectric Actuation

- **Piezoelectricity** is the ability of some crystals to create mechanical stress, or motion by expanding or contracting in response to an applied voltage
- Piezoelectric actuation can provide significantly large forces, especially if thick piezoelectric films are used

Actuation methods

- **Thermal Actuation**
  - It consumes more power than electrostatic or piezoelectric actuation
  - **First approach (Two-layers)**
    - The difference in the thermal expansion coefficients between two joined layers of dissimilar materials cause bending with temperature
    - One layer expands more than the other as temperature increases
    - This results in stresses at the interface and consequently bending of the stack
    - The amount of bending depends on the difference in coefficients of thermal expansion and absolute temperature

Actuation methods

- **Thermal Actuation**
  - **Second approach (thermo-pneumatic)**
    - A liquid is heated inside a sealed cavity
    - Pressure from expansion exerts a force on the cavity walls, which can bend
    - This method also depends on the absolute temperature of the actuator
  - **Third approach (Suspended beam)**
    - A suspended beam of a same homogeneous material with one end anchored to a supporting frame of the same material
    - Heating the beam to a temperature above that of the frame causes a differential expansion of the beam's free end with respect to the frame
    - Force-displacement trade-off
    - It relies on the difference in temperature between the beam and the supporting frame

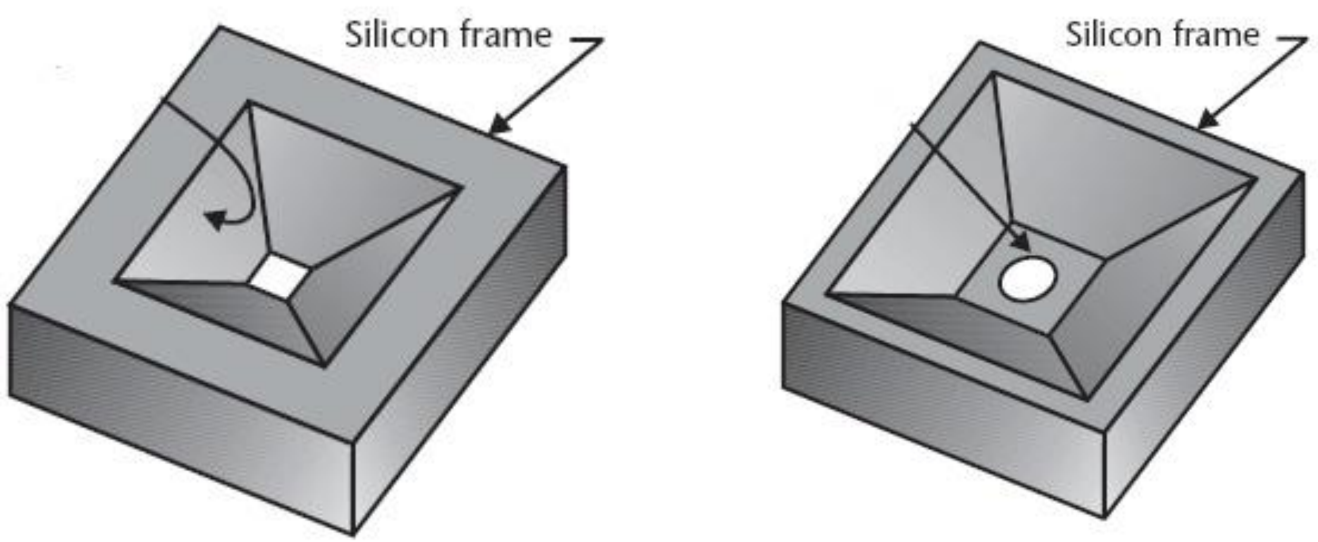
Actuation methods

- **Magnetic Actuation**
  - Electrical current in a conductive element that is located within a magnetic field gives rise to an electromagnetic force (called the Lorentz force) in a direction perpendicular to the current and magnetic field
  - This force is proportional to the current, magnetic flux density, and length of the element

Passive Micro-machined Mechanical Structures

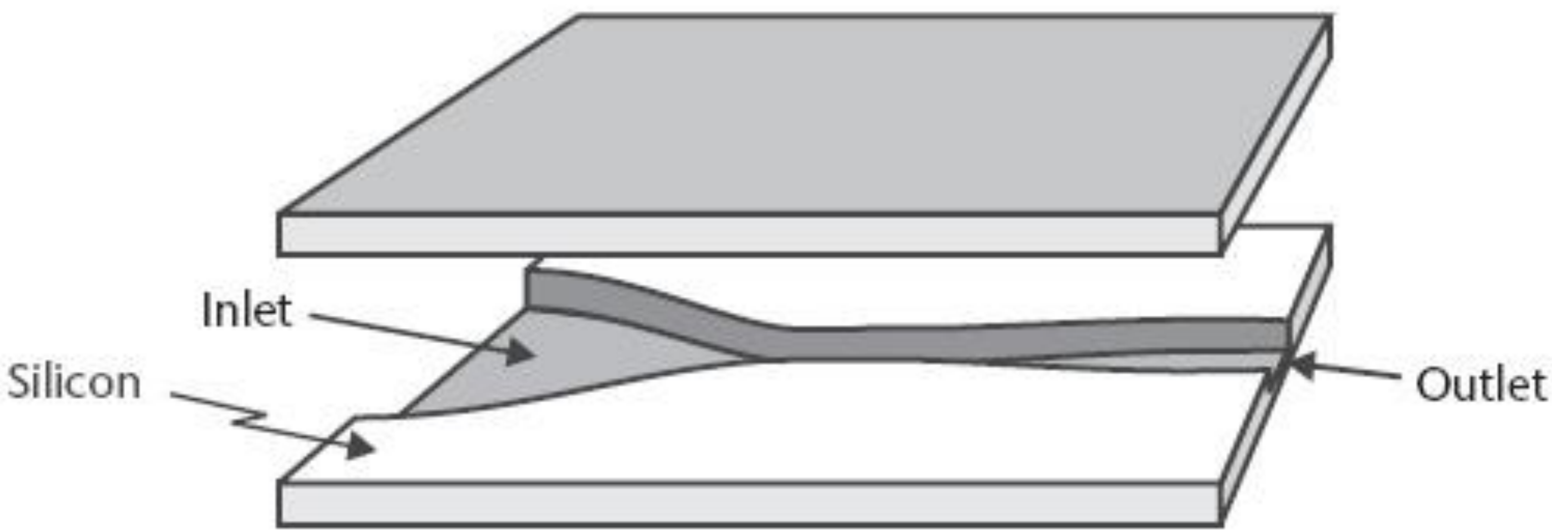
Fluid Nozzles

- Nozzles are among the simplest microstructures to fabricate using anisotropic etching of silicon, electroforming, or laser drilling of a metal sheet
- Forming nozzles of circular or arbitrary shape in silicon involves additional fabrication steps



Passive Micro-machined Mechanical Structures

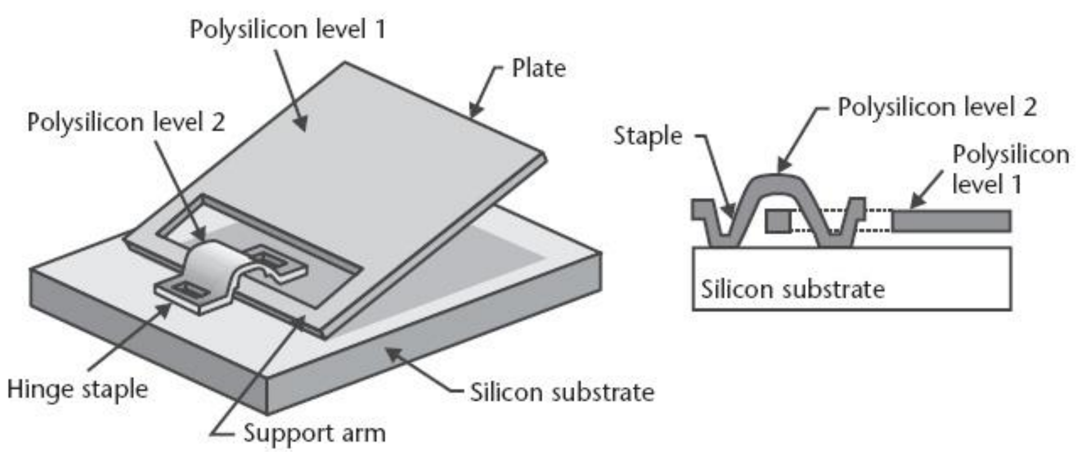
- **Fluid Nozzles**
  - Nozzles types:
    - ***Top shooters****: they are* oriented perpendicular to the surface of the wafer as *in the inkjet field*
    - ***Side shooters****: they are oriented parallel* to the wafer surface as in the fluid flow field



Passive Micro-machined Mechanical Structures

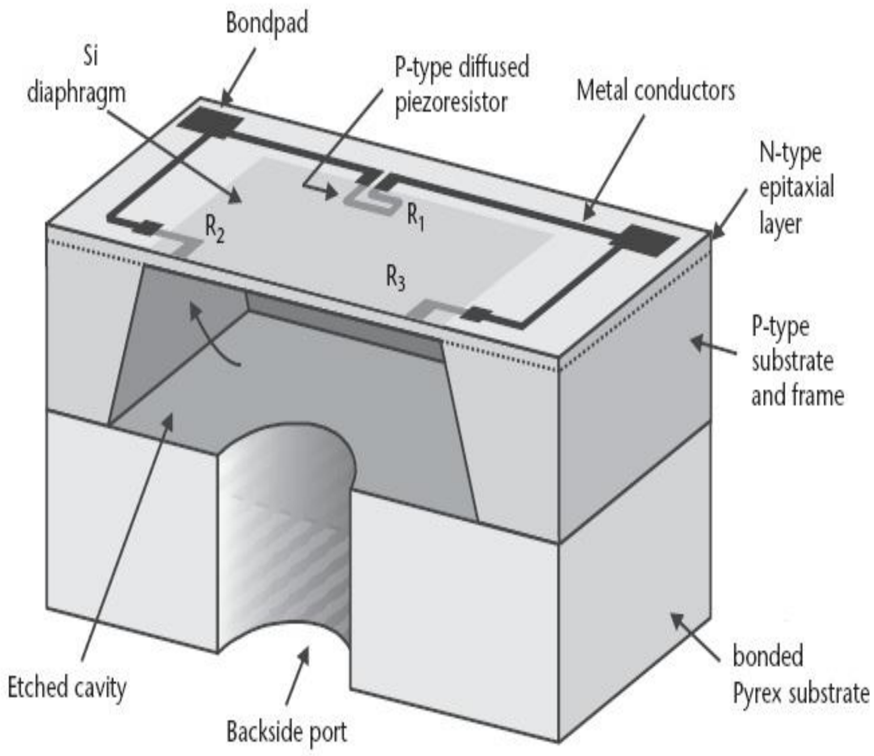
Hinge Mechanisms

- At the microscopic scale, hinges extend the utility of the 2D surface micromachining technology into the 3D
- The hinge structure is simple, consisting of a plate and a support arm made of a first polysilicon layer
- A staple made of a second polysilicon layer captures the plate support arm
- The staple is anchored directly to the substrate
- The fabrication utilizes the polysilicon surface micro-machining process



Sensors and Analysis Systems

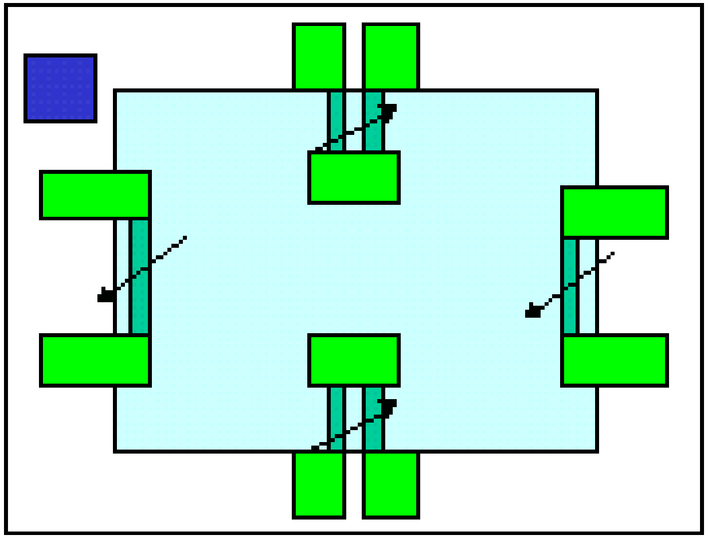
- **Pressure Sensor:**
  - The vast majority use piezoresistive sense elements to detect stress in a thin silicon diaphragm in response to a pressure load
  - The basic structure of a piezoresistive pressure sensor consists of four sense elements in a Wheatstone bridge configuration that measure stress within a thin silicon membrane

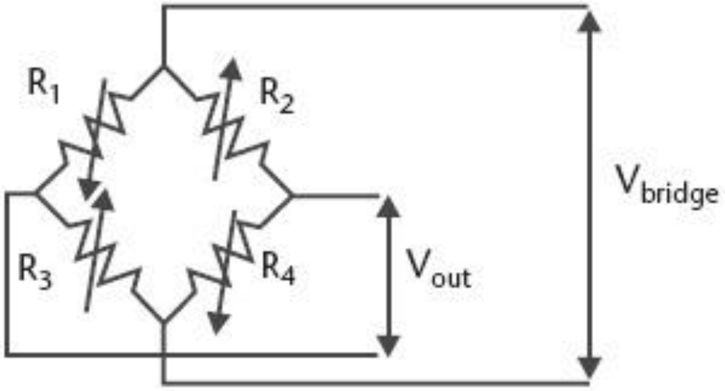


Sensors and Analysis Systems

Pressure Sensor:

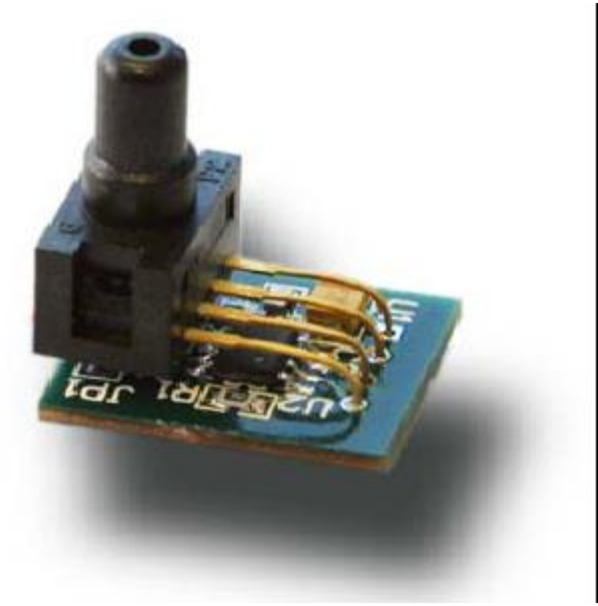
- The stress is a direct consequence of the membrane deflecting in response to an applied differential pressure across the front and back sides of the sensor
- The membrane deflection is typically less than one micrometer
- Four diffused *p-type* piezoresistors at the points of highest stress, which occur at the center edges of the membrane
- The four resistors should be identical under zero applied pressure



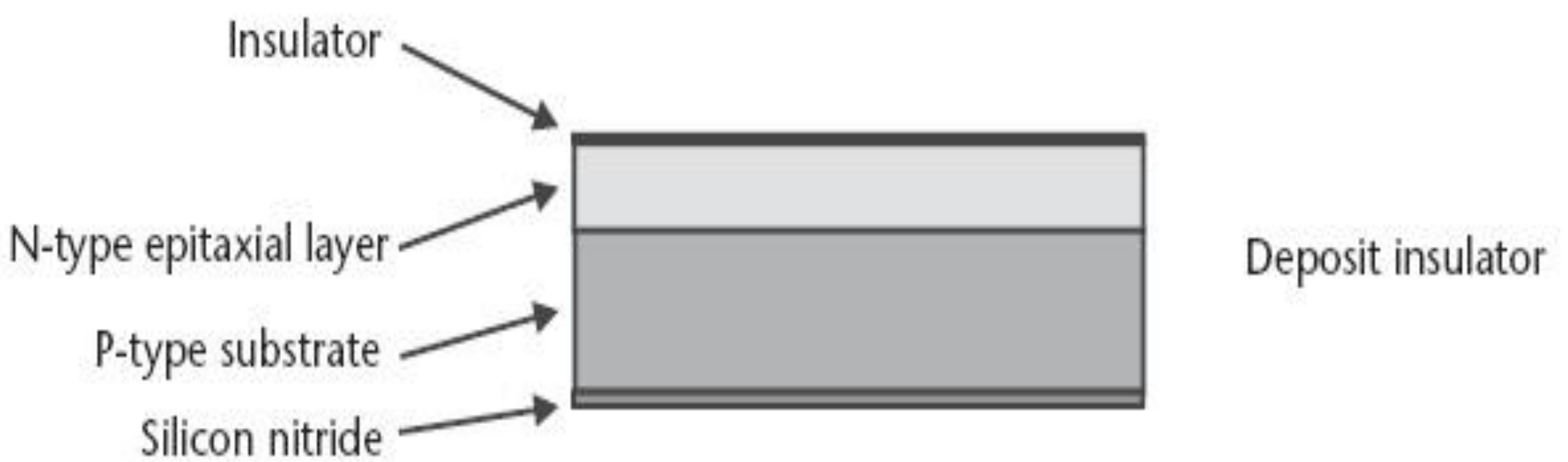


Sensors and Analysis Systems

- **Pressure Sensor:**
  - **Sensitivity:**
    - The ratio between the normalized output voltage (measured bridge voltage in mV divided by the bridge supply voltage in V) and the applied pressure in Pa
    - Units: (mV/V)/Pa
  - **Zero offset**
    - Offset voltage measured under zero applied pressure
    - This occurs due to mismatch in resistors or temperature variations
    - Desired to be Zero

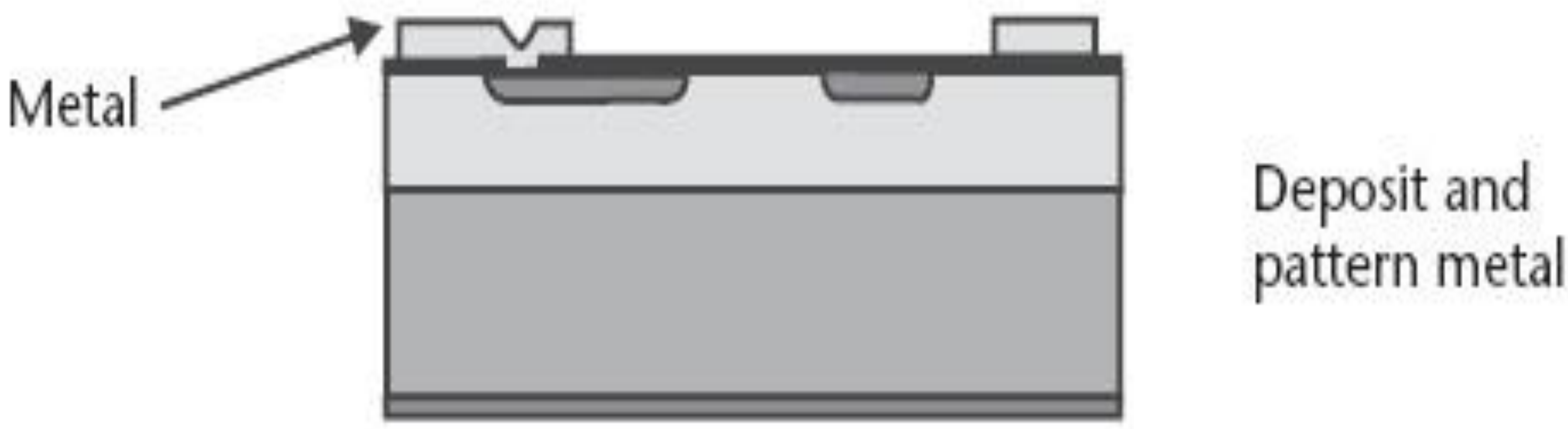


- **Pressure Sensor:** ***(Self-Reading)***
  - **Fabrication**
    - An *n-type epitaxial layer* of silicon is grown on a *p-type wafer*
    - *A thin insulating* layer is deposited on the front side of the wafer, and a protective silicon nitride film is deposited on the back side



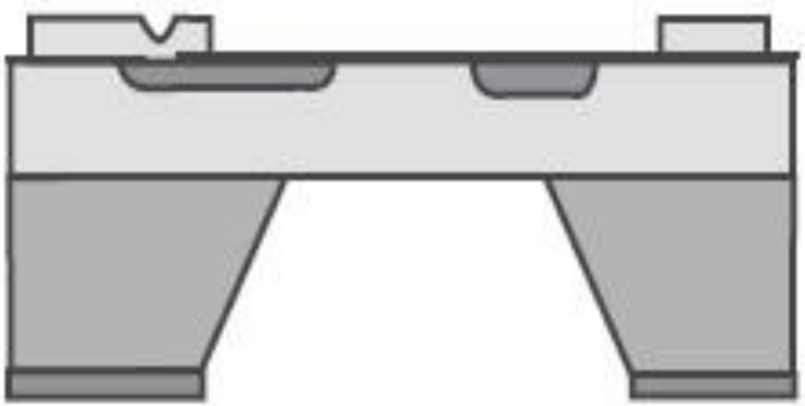
- **Pressure Sensor:** ***(Self-Reading)***
  - **Fabrication**
    - The piezoresistive sense elements are formed by locally doping the silicon *p-type*

- **Pressure Sensor:** ***(Self-Reading)***
  - **Fabrication**
    - Etching of the insulator on the front side provides contact openings to the underlying piezoresistors
    - A metal layer, typically aluminum, is then sputter deposited and patterned in the shape of electrical conductors



Sensors and Analysis Systems

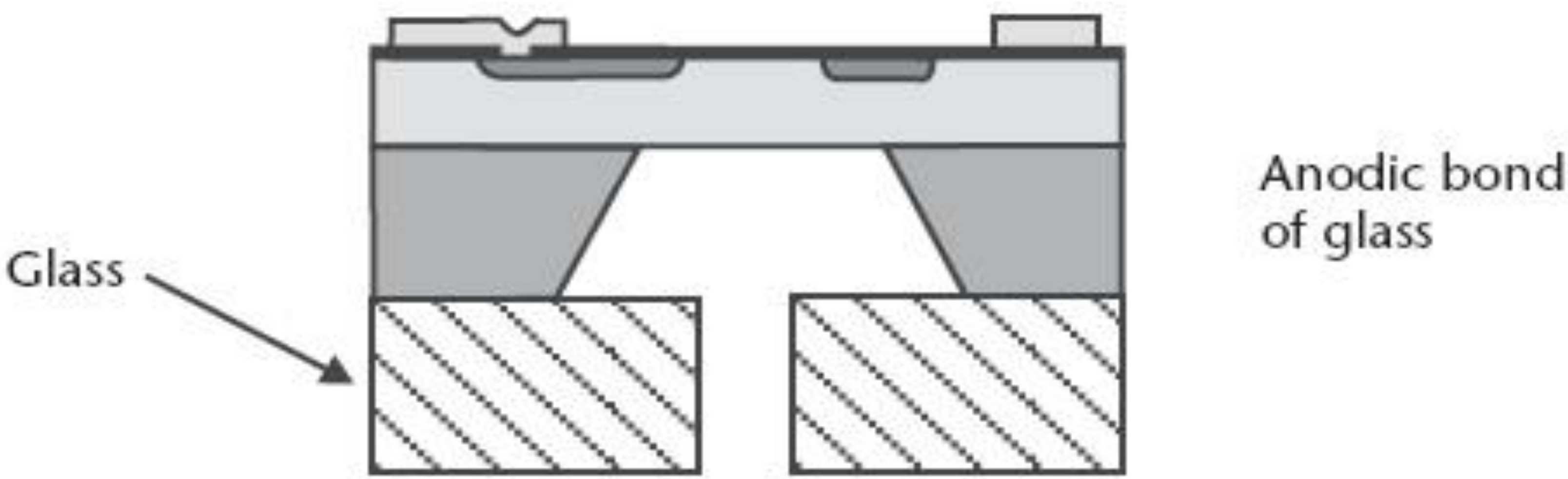
- **Pressure Sensor:** ***(Self-Reading)***
  - **Fabrication**
    - A square opening is patterned and etched in the silicon nitride layer on the back side
    - Double-sided lithography ensures that the backside square is precisely aligned to the sense elements on the front side



Electrochemical etch of backside cavity

Sensors and Analysis Systems

- **Pressure Sensor:** ***(Self-Reading)***
  - **Fabrication**
    - The process forms a membrane with precise thickness defined by the epitaxial layer
    - Anodic bonding in vacuum of a Pyrex glass wafer on the back side produces an absolute pressure sensor that measures the pressure on the front side in reference to the cavity pressure



Accelerometers

- A sensor that detects change in velocity
- Most common application for MEMS accelerometers
  - Air bag deployment.

Accelerometers

- Accelerometers widely used for monitoring vibrations in industrial machinery

- Automotive applications: Brake sensor and bounce sensor

Accelerometers

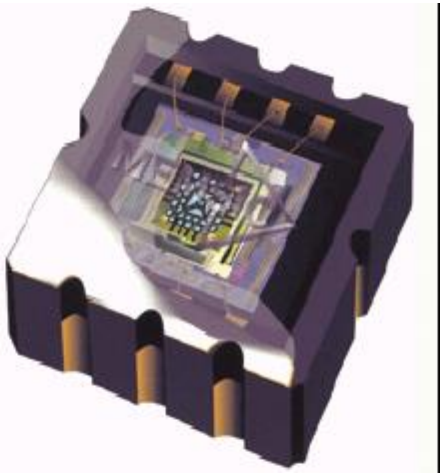
- The first demonstration of a micromachined accelerometer took place in 1979 at Stanford University
- **Basic structure**
  - Inertial mass suspended from a spring
  - They differ in the sensing of the relative position of the inertial mass as it displaces under the effect of an externally applied acceleration
  - Sensing methods such as capacitive or piezoelectric
- **Specifications**
  - Full-scale range (in G) <G=9.81 m/sec^2>
  - Sensitivity (in V/G)
  - Resolution (in G)
  - Bandwidth (in Hz) <acceleration reading times/sec>
  - Cross-axis sensitivity
  - Immunity to shock

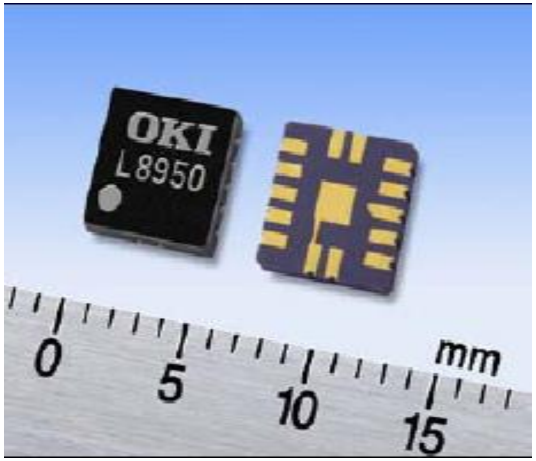
Accelerometers

- Accelerometers for airbag crash sensing are rated for a full range of ±50G and a bandwidth of about 1.0 kHz
- Accelerometers for engine vibration have a range of ±1G, but must resolve small accelerations (<100 µG) over a large bandwidth (>10 kHz)
- Accelerometers for pacemakers
  - Incorporate multi-axis accelerometers to monitor the level of human activity, and correspondingly adjust the stimulation frequency
    - Full scale range of ±2G and a bandwidth of less than 50 Hz, but they require extremely low power consumption for battery longevity
- Accelerometers for military applications can exceed a rating of ±1,000G

Accelerometers

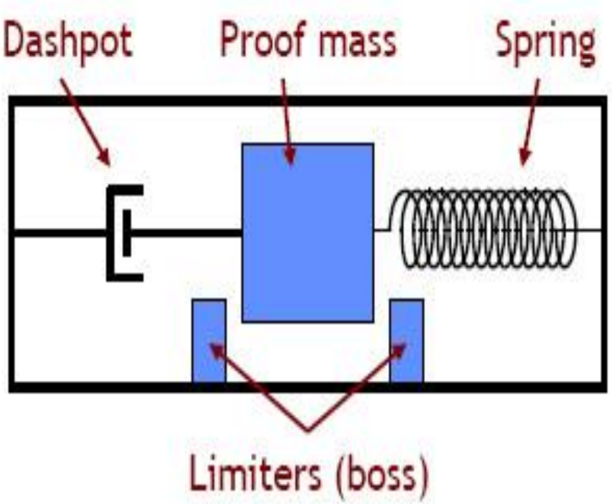
- Cross-axis sensitivity is the immunity of the sensor to accelerations along directions perpendicular to the main sensing axis
- Shock immunity is an important specification for the protection of the devices during handling or operation
  - The test is performed by dropping the device from a height of one meter over concrete
  - The shock impact can easily reach a dynamic peak of 10,000G



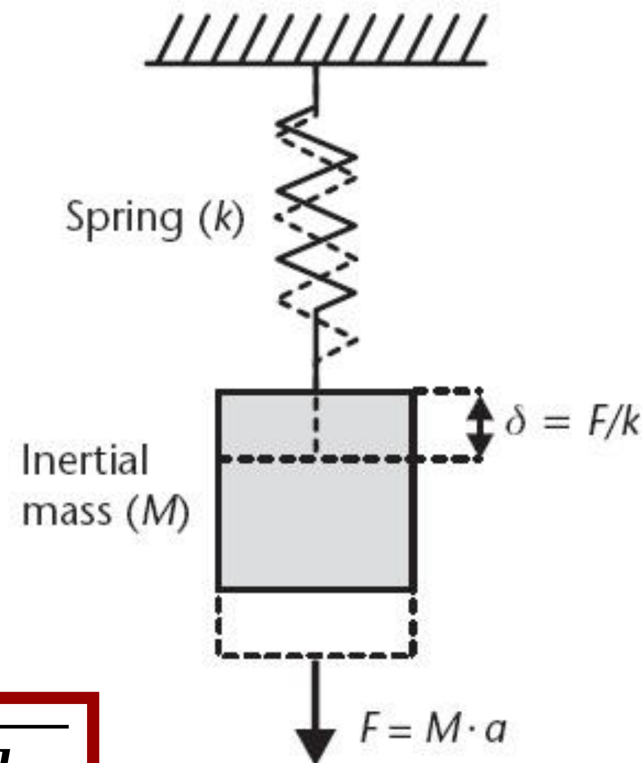


Accelerometers

- Basic structure



Movement of proof mass is proportional to acceleration.



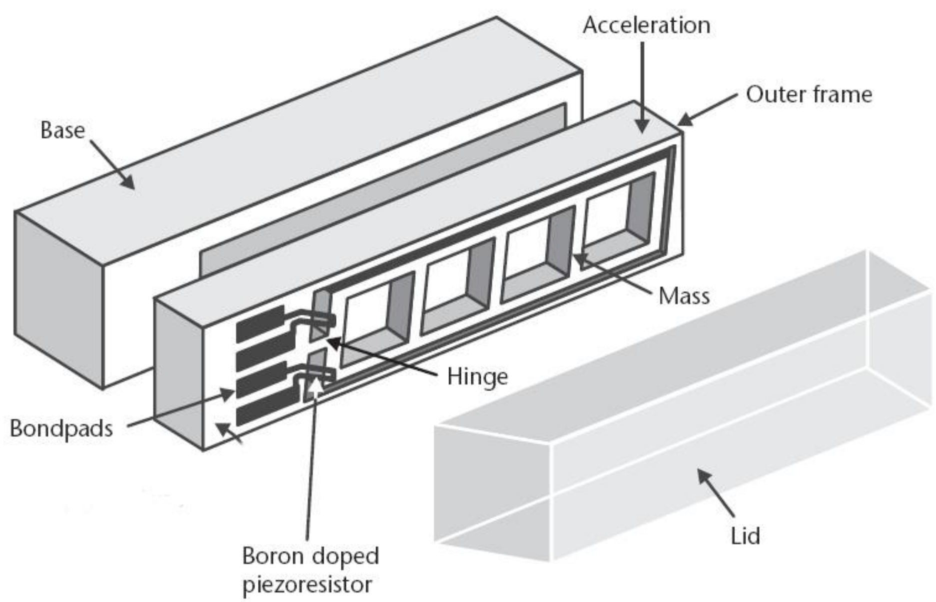
$$f_{resonance} = \frac{1}{2\pi}\sqrt{\frac{k}{M}}$$

Accelerometers

- Types for study
  - Piezoresistive Bulk Micromachined Accelerometer
  - Capacitive Bulk Micromachined Accelerometer
  - Capacitive Surface Micromachined Accelerometer

Piezoresistive Bulk Micromachined Accelerometer

- It consists of three substrates:
  - a lower base
  - a middle core containing a hinge-like spring, the inertial mass, and the sense elements
  - a top protective lid



Piezoresistive Bulk Micromachined Accelerometer

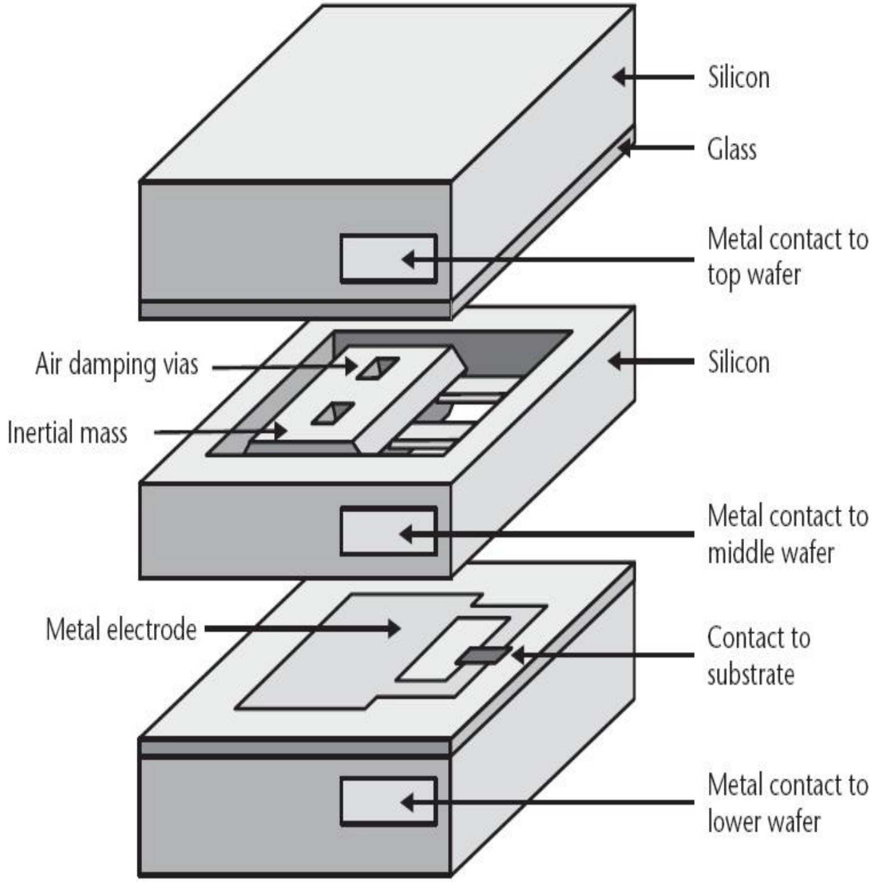
- The inertial mass sits inside a frame suspended by the spring
- Two thin piezoresistive elements in a Wheatstone bridge configuration span the narrow 3.5-μm gap between the outer frame of the middle core and the inertial mass
- The piezoresistors are only 0.6 μm-thick and 4.2 μm-long and are very sensitive to displacements of the inertial mass
- The output in response to an acceleration equal to 1G in magnitude is 25mV for a Wheatstone bridge excitation of 10V
- The thick and narrow hinge structure allows displacement within the plane of the device, but it is very stiff in directions normal to the wafer, resulting in high immunity to off-axis accelerations

Piezoresistive Bulk Micromachined Accelerometer

- The outer frame acts as a stop mechanism that protects the device in the event of excessive acceleration shocks
- It takes 6,000G for the inertial mass to touch the frame
- The device can survive shocks in excess of 10,000G
- Open apertures reduce the weight of the inertial mass and combine with the stiff hinge to provide a rather high resonant frequency of 28 kHz

Capacitive Bulk Micromachined Accelerometer

- It consists of a stack of three bonded silicon wafers, with the hinge spring and inertial mass incorporated in the middle wafer
- The inertial mass forms a moveable inner electrode of a variable differential capacitor circuit
- The two outer wafers are identical and are simply the fixed electrodes of the two capacitors



Capacitive Bulk Micromachined Accelerometer

- Holes through the inertial mass reduce the damping effect from air trapped in the enclosed cavity, increasing the operating bandwidth of the sensor
- Measuring range is from ±0.5G to ±12G
- Electronic circuits sense changes in capacitance, then convert them into an output voltage between 0 and 5V
- The rated bandwidth is up to 400 Hz for the ±12G accelerometer
- The cross-axis sensitivity is less than 5% of output
- The shock immunity is 20,000G

Capacitive Surface Micromachined Accelerometer

- Surface micromachining emerged in the late 1980s as low-cost alternative for accelerometers in automotive applications
- Both Bosch company (Germany), and Analog Devices (USA), offer surface micromachined accelerometers,
- The Bosch sensor is incorporated in the Mercedes Benz family of luxury automobiles
- The Analog Devices parts are used on Ford, General Motors, and other vehicles, as well as inside joysticks for computer games

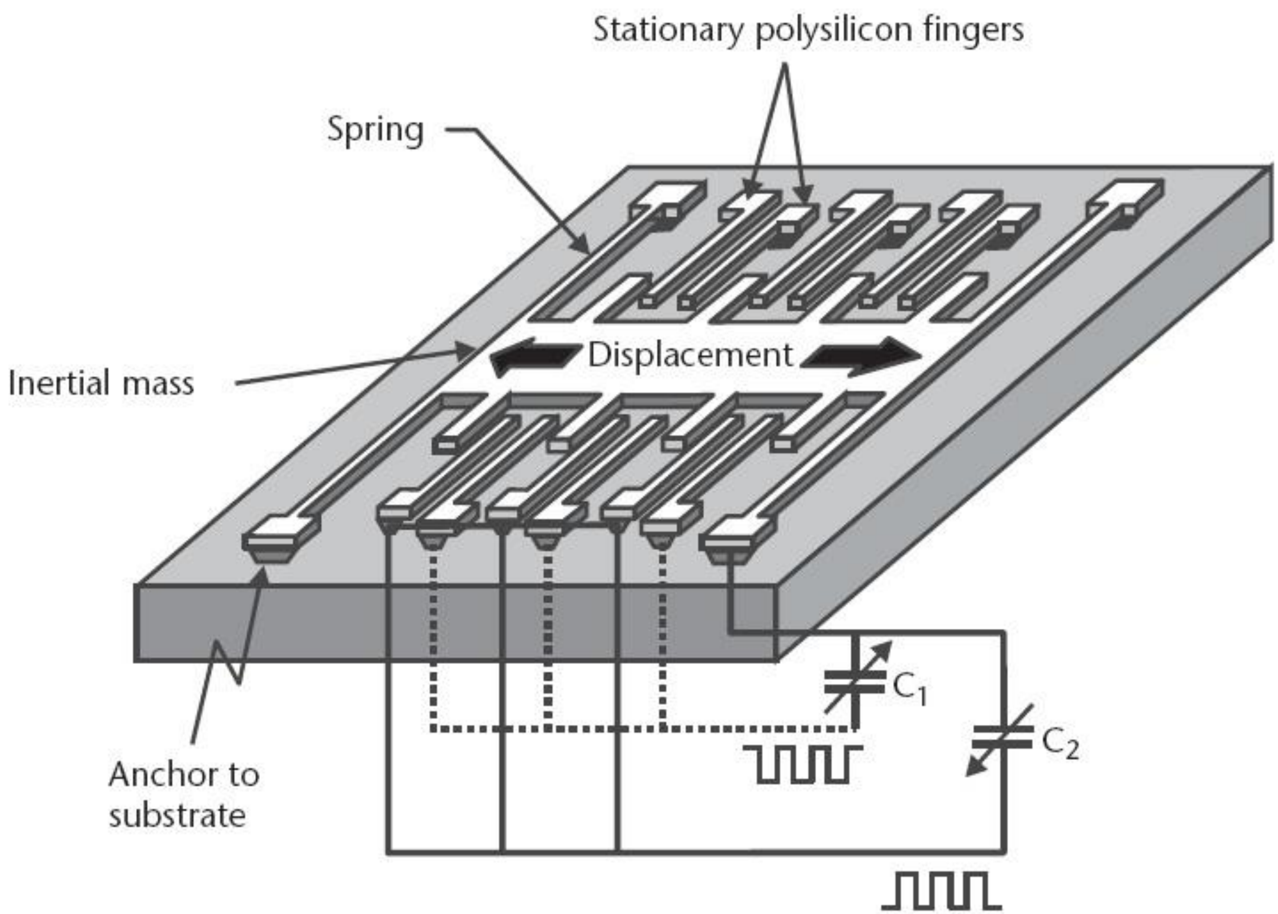
Capacitive Surface Micromachined Accelerometer

- Surface-micromachined accelerometers incorporate a suspended comb-like structure whose primary axis of sensitivity lies in the plane of the die
- This is often referred to as an x-axis (or y-axis) type of device, as opposed to z-axis sensors where the sense axis is orthogonal to the plane of the die
- Surface micromachined accelerometers suffer from sensitivity to accelerations out of the plane of the die (z-axis)
  - Shocks along this direction can cause catastrophic failures

Capacitive Surface Micromachined Accelerometer

- It consists of three sets of 2-μm-thick polysilicon finger-like electrodes
- Two sets are anchored to the substrate and are stationary
  - They form the upper and lower electrode plates of a differential capacitance
- The third set has the appearance of a two-sided comb whose fingers are interlaced with the fingers of the first two sets
- It is suspended approximately 1 μm over the surface by means of two long, folded polysilicon beams acting as suspension springs
  - It also forms the common middle and displaceable electrode for the two capacitors

Capacitive Surface Micromachined Accelerometer



Capacitive Surface Micromachined Accelerometer

- The inertial mass consists of the comb fingers
- Under no externally applied acceleration,
  - The two capacitances are identical
  - The output signal, proportional to the difference in capacitance, is null
- An applied acceleration displaces the suspended structure, resulting in an imbalance in the capacitive half bridge
- The differential structure is such that one capacitance increases, and the other decreases
- The overall capacitance is small, typically on the order of 100 fF (1 fF = 10^{-15} F)
- Programmable ADXL 105 measuring range ±1G or±5G
- ADXL 190 measuring range ±100G
- 1G is converted to 0.1 fF capacitance change
  - This must be measured on-chip to avoid parasitic capacitances of off-chip wires

AMN- 606
MEMS/NEMS Technology and Devices
Course Project

Dr. Hassan Mostafa
hmostafa@uwaterloo.ca
Cairo University

Fall 2018

Project

- The project is individual
- Each student should select any MEMS device from the literature that has not been covered in the lectures and prepare the following for it:
  - COMSOL Model Simulations files
  - Power Point Presentation of his work to be presented in maximum of 10 minutes (Every extra minute = -10% of the grade)
  - Report following the IEEE two column paper format of maximum 4 pages explaining everything. One fifth page is allowed as a cover page for the report. Every page more than 5 pages = -10% of the grade.
- Deadline: Last Lecture.
  - Tentative Dec. 20, 2018.