Mechatronics
ETM 4931
Lecture 7

Dr. Farbod Khoshnoud

Outline

Selected topics on **Microelectromechanical (MEMS) Sensors and Actuators**:

- Biomedical sensors
- Mechanical sensors
- Thermo-fluid and electromagnetic sensors
- Biomedical actuators

MEMS technology provides the benefits of:

- **Small size**
- **Low weight**
- **High performance**
- **Easy mass production**
- **Low cost.**

Introduction to MEMS "Micro-Electro-Mechanical System“
https://www.youtube.com/watch?v=CNmk-SeM0ZI

Sensors and actuators

- ***Piezoelectric Sensors***

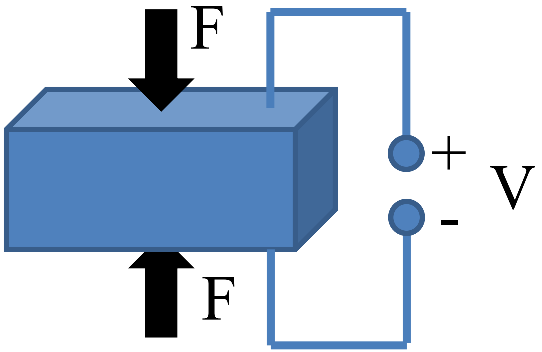
- ***Capacitive Sensors***

- ***Electromagnetic Sensors***

Energy Conversion Mechanisms

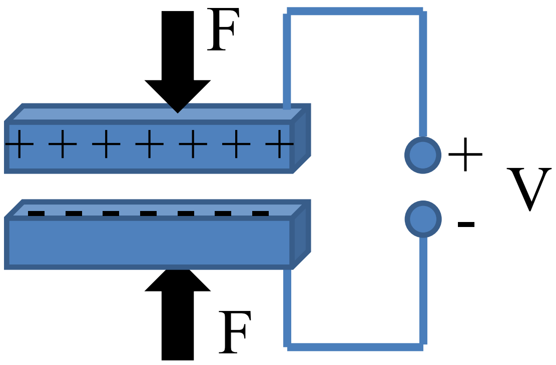
- **Piezoelectric:**

Mechanical strain in a piezoelectric material causes a charge separation across the material producing a voltage. Does not need voltage source.



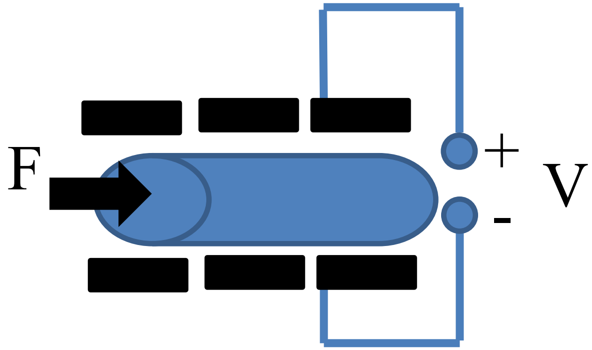
- **Electrostatic:**

As the conductors move the energy stored in the capacitor changes, thus providing the mechanism for mechanical to electrical energy conversion. Separate voltage source is needed. (MEMS: Easier to integrate)



- **Electromagnetic:**

In the first case, the relative motion between a coil and a magnetic field causes a current to flow in the coil. Does not need voltage source.



An introduction to MEMS

How MEMS Accelerometer Gyroscope Magnetometer Work & Arduino Tutorial
https://www.youtube.com/watch?v=eqZgxR6eRjo
MEMS Actuator
https://www.youtube.com/watch?v=NN1R3Sqimk8
The World Of Microscopic Machines
https://www.youtube.com/watch?v=iPGpoUN29zk
The Etching Process
https://www.youtube.com/watch?v=zkdQddMZSyM
LIGA Micromachining Process Overview
https://www.youtube.com/watch?v=CbN7h3o51Zo
The World's Smallest Robots: Rise of the Nanomachines
https://www.youtube.com/watch?v=loaqIqKCmog

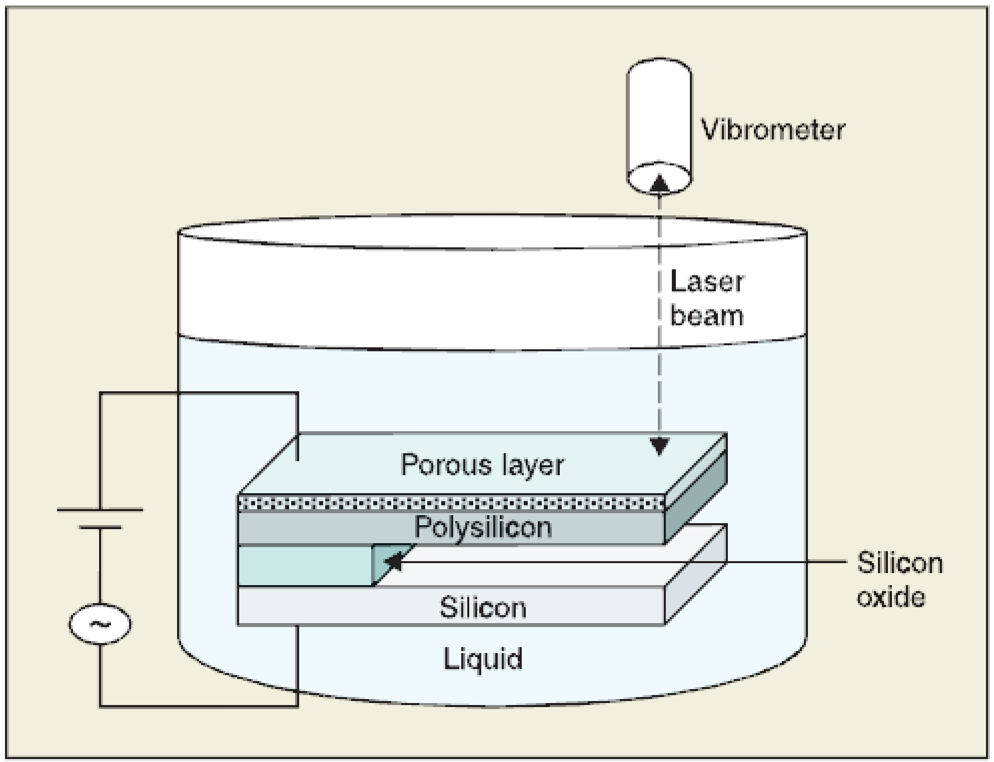
Recent Advances in MEMS Sensor Technology— Biomedical Applications

Farbod Khoshnoud and Clarence W. de Silva

Farbod Khoshnoud and Clarence W. de Silva, **Recent advances in MEMS sensor technology - Biomedical Applications**, *IEEE Instrumentation and Measurement*, Volume 15, Issue 1, pp. 8 – 14, 2012. **(The most accessed article, 2013)**

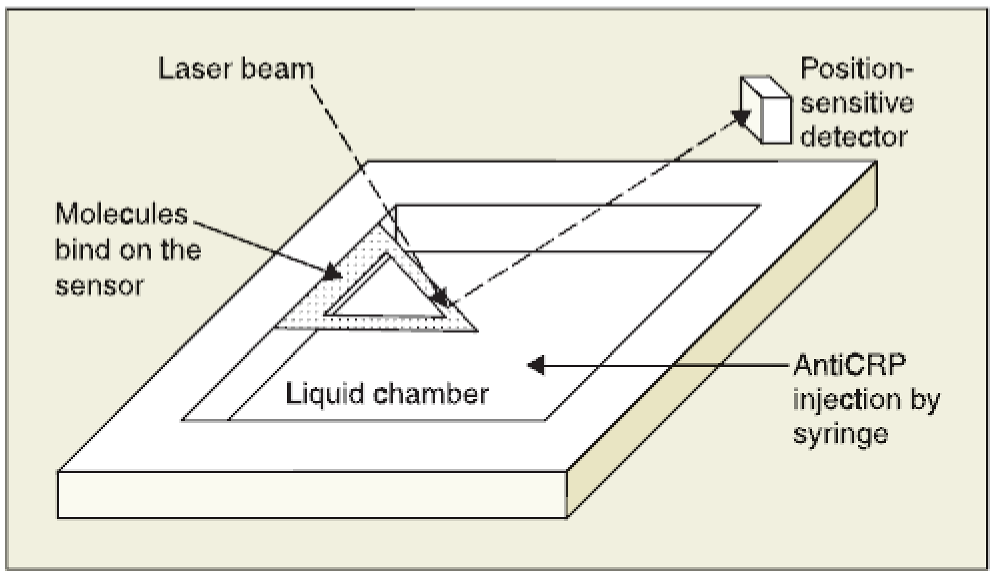
Triglyceride Biosensor

- Triglyceride measurement is in demand in the food and oil industries



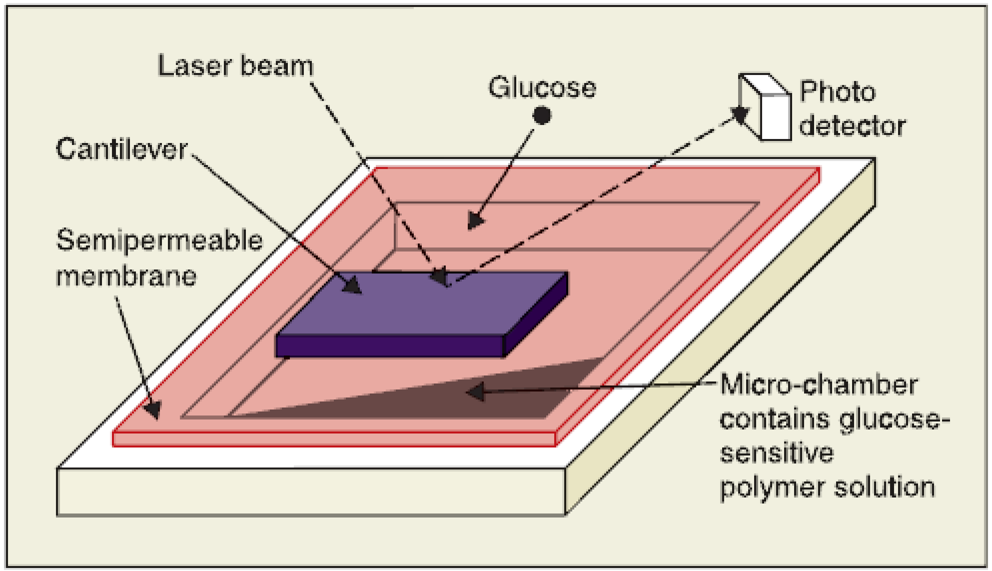
A triglyceride biosensor with a cantilever beam in liquid. The cantilever beam's dimensions: length = 100–200 μm, width = 10–20 μm, thickness = 2 μm. A 2 μm thickness of polysilicon is deposited by LPCVD on 1.6 μm thermal oxide.

Bio-MEMS Sensor for C-Reactive Protein Detection



Schematic diagram of a bio-MEMS sensor for C-reactive protein detection. Dimensions: length = 200 μm, width = 40 μm [5].

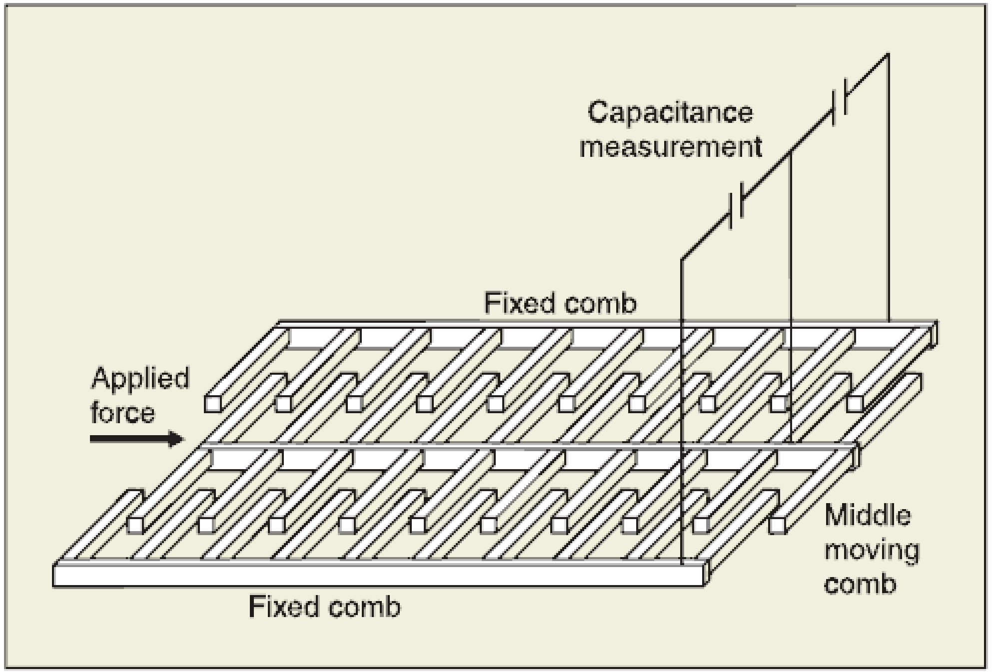
Continuous monitoring of glucose for diabetes management



A MEMS affinity sensor for detection of glucose. Its length and width are each approximately 750 μm.

MEMS Force Sensor in drug Delivery

- Characterization of the mechanical properties of mechanical strength
- The needle tract during injection, in the applied tissues. It is necessary to preserve their integrity during the process to avoid cell death.

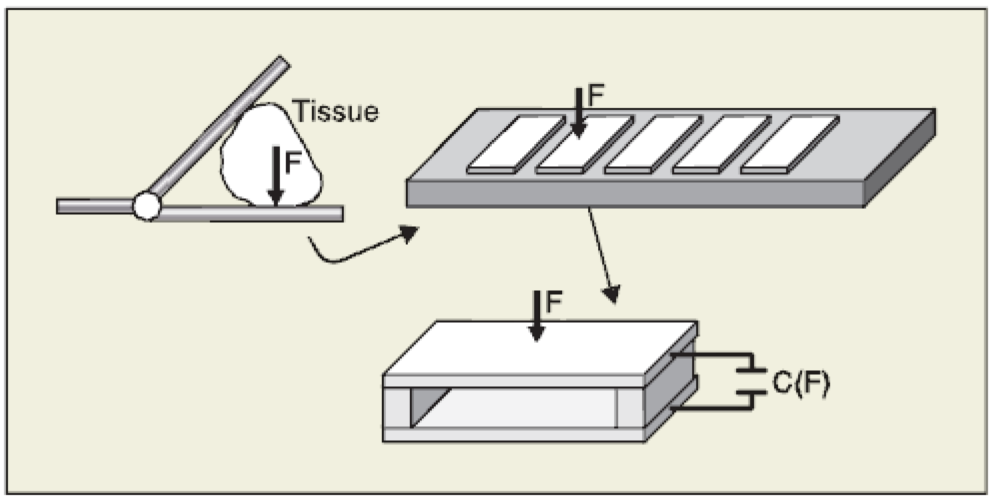


Schematic diagram of a MEMS force sensor in protein delivery. The cantilever thickness = 5 μm; the device size is approximately 5 mm x 5 mm.

Tissue Softness Characterization

Minimally invasive surgery (MIS) allows: smaller incisions, less pain during the recovery period, reduced blood loss and scarring, faster recovery time, fewer complications due to infection, better cosmetic results, and reduced overall costs.

The surgeon needs to distinguish between different types of tissue in the body when making an incision into the tissue and **identify the type of tissue** (e.g., fatty, muscular, vascular, or nerve) that is being incised. Inaccurate classification of a tissue may lead to cutting of nerve tissues with consequences such as loss of motor control in patients.

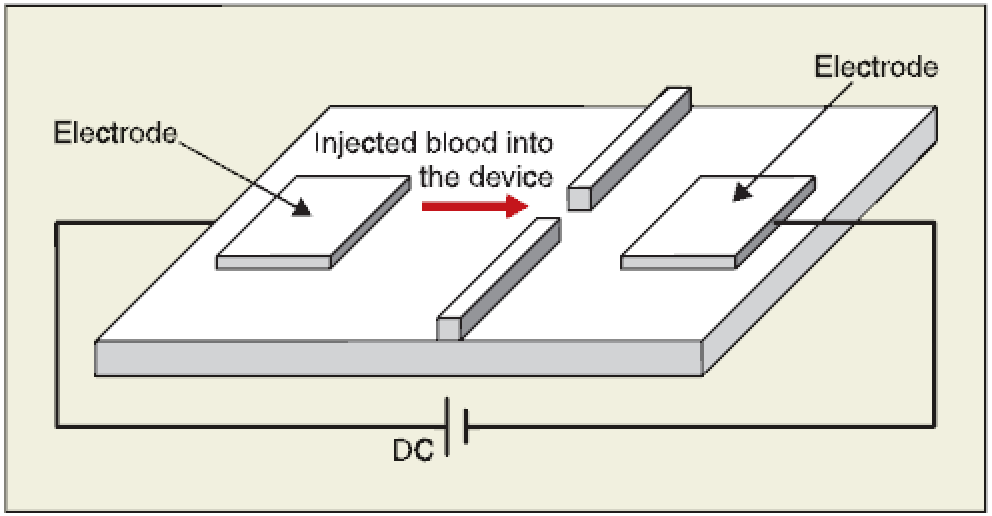


A MIS smart grasper and MEMS tactile sensors for quantifying tissue softness. Approximate size of a sensing unit: 7mm x 2 mm.

A Blood Cell Counter

Current blood cell counters are bulky and are not suitable for use at point-of-care. MEMS technology can overcome this limitation.

- When a blood sample is injected into the device, the change in the electrical resistance due to the passing blood cell is measured and is proportional to the volume of the cells.
- The number of blood cells is determined by counting from the total number of electrical pulses.
- Red and white blood cells are distinguished by the difference in the pulse heights they cause.



Schematic diagram of the blood counter sensor. Sensor size: 10 mm x 5 mm x 0.8 mm. Gap through which the injected blood flows = 80 μm.

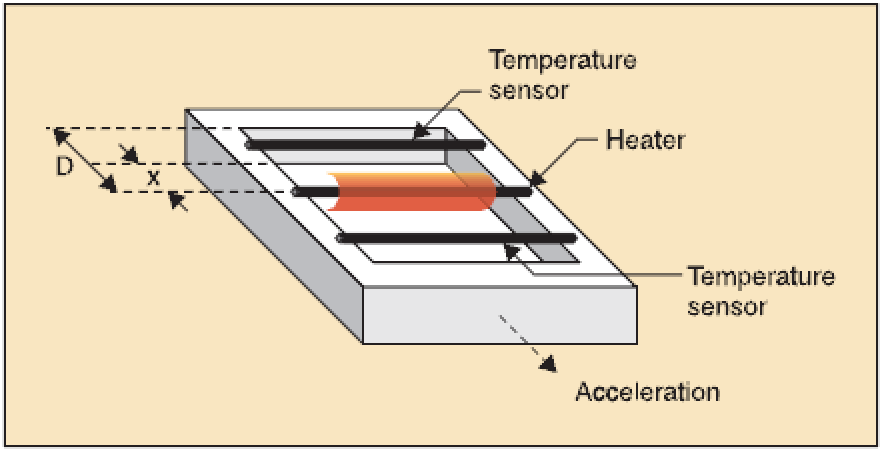
Recent Advances in MEMS Sensor Technology—Mechanical Applications

Farbod Khoshnoud and Clarence W. de Silva

Farbod Khoshnoud and Clarence W. de Silva, **Recent advances in MEMS sensor technology - Mechanical Applications**, *IEEE Instrumentation and Measurement*, Volume 15, Issue 2, pp. 14 – 24, 2012.

Acceleration Sensor

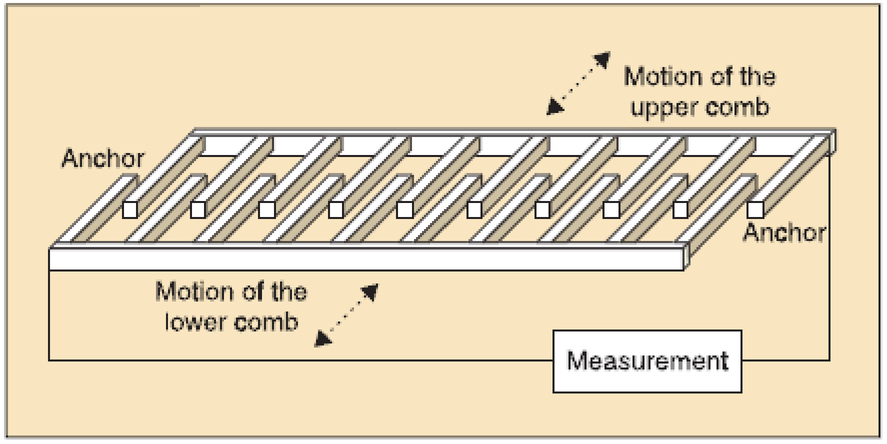
- A thermal convective micro-accelerometer uses a thermal bubble instead of a proof mass.
- It is based on the **movement of a small hot air bubble** created around the heater in a chamber.
- When the sensor is subjected to acceleration, the thermal bubble will move in the direction of applied acceleration, causing the temperature of one thermistor to increase and the opposite one to decrease.



Convective acceleration sensor.

Stain Sensors

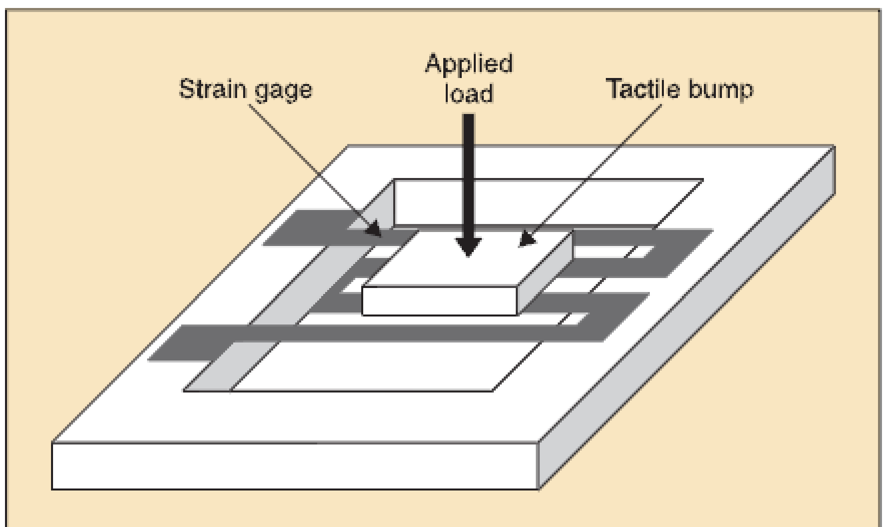
Multi-dimensional force measurement in micro-robotic manipulations can be attained by strain gauges which offer precise force measurement in the submicro-newton scale.



Comb drive or finger capacitive design of strain sensor.

Tactile Sensor for a Robotic Finger

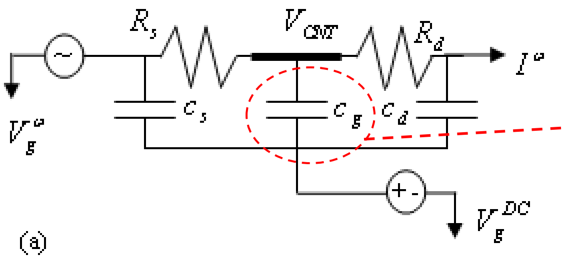
- Lifting and grasping tasks by robots can be controlled by sensor signals.
- Requirements for effective sensing include obtaining a rich data set by spatial distribution of contact forces on the robotic finger at high sensitivity.
- MEMS can meet these requirements due to their small size which allows distribution of a large number of sensors on the finger and provides high resolution and high sensitivity.
- Integrating the sensors on a robotic finger is enabled by a layer of elastomeric skin-like material on the finger surface.



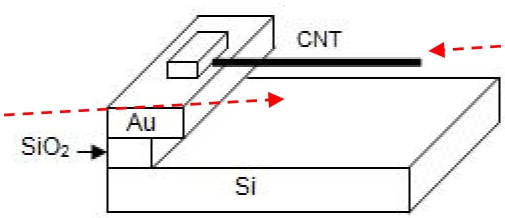
Schematic diagram of tactile sensor.

Self-powered micro/nano-electromechanical sensors

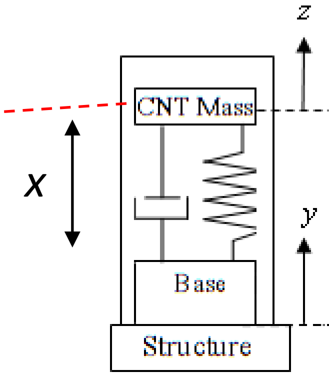
The base ***motion detection*** by NEMS vibration sensors:



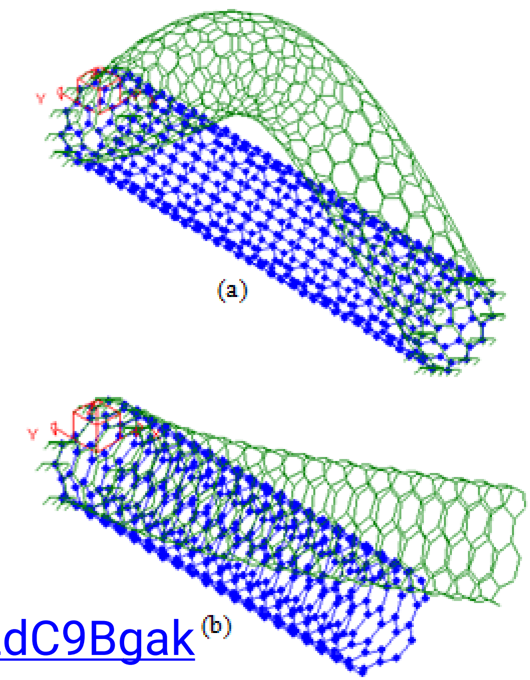
Equivalent Electrical Circuit



Physical representation of the capacitance sensor



Equivalent Mechanical System



Equation of the motion of the system:

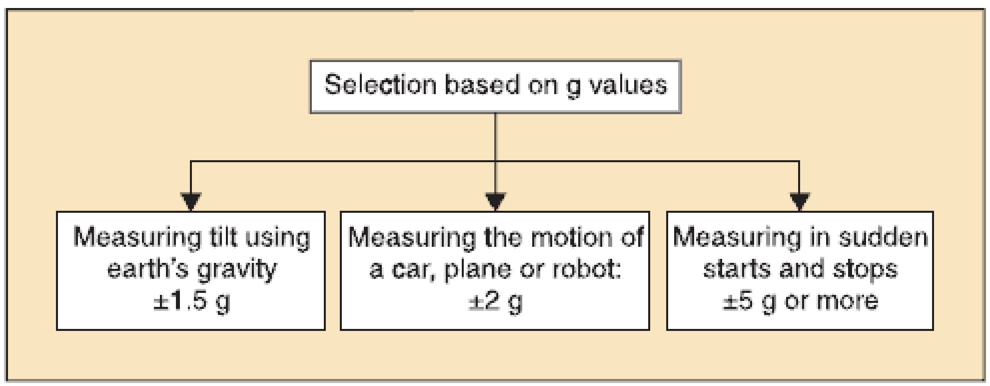
$$Y = \frac{2I\sqrt{\left[1-\left(\frac{\omega}{\omega_n}\right)^2\right]^2 + \left[2\zeta\frac{\omega}{\omega_n}\right]^2}}{\frac{dG^{DC}}{dV_g}\frac{1}{C_g}C'_g V_g^{DC}\tilde{V}_g\left(\frac{\omega}{\omega_n}\right)^2}$$

Farbod Khoshnoud, De Silva, C.W., Owhadi, H., **Analysis and design of a nano-electromechanical vibration sensor**, Proc. of the ASME IMECE, Vancouver, B.C, **2010**.

Carbon nanotubes: https://www.youtube.com/watch?v=H-a2dC9Bgak

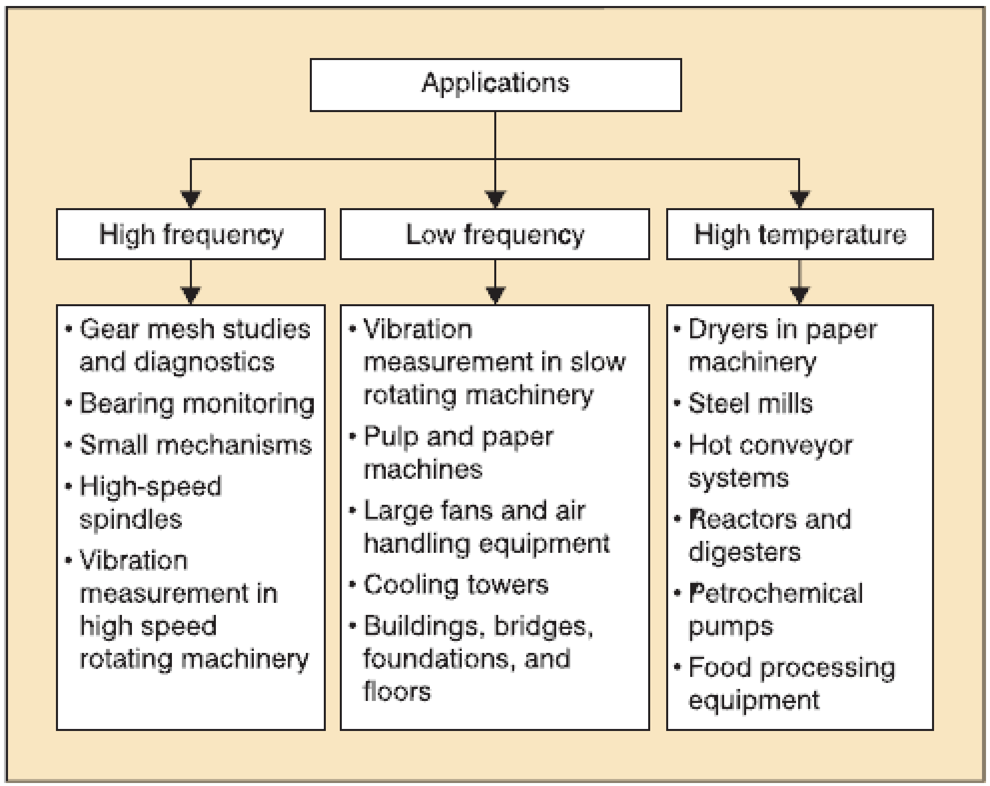
Accelerometer Selection

- Category of g value:



Accelerometer Selection

- General applications:



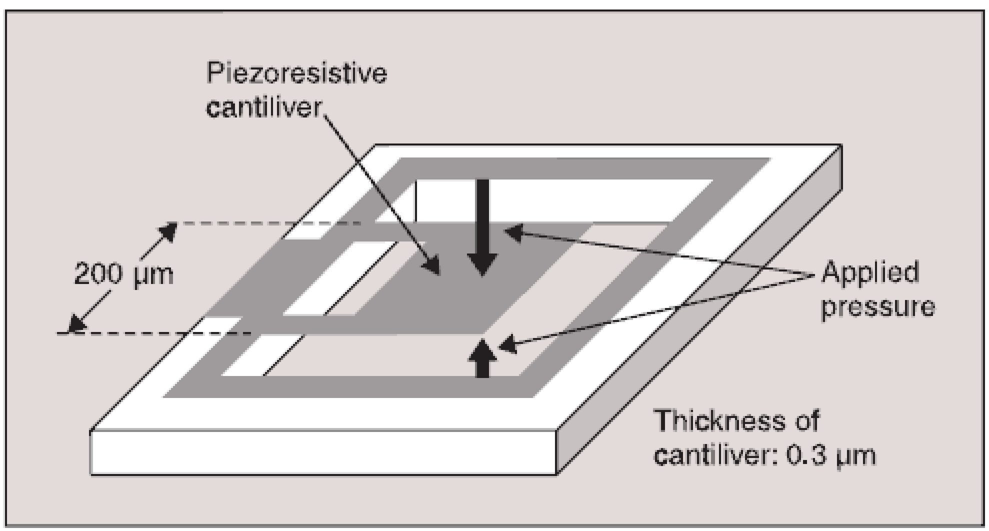
Recent Advances in MEMS Sensor Technology—Thermo-fluid and Electro-magnetic Devices

Farbod Khoshnoud and Clarence W. de Silva

Farbod Khoshnoud and Clarence W. de Silva, **Recent advances in MEMS sensor technology - Thermo-Fluid and Electrical**, *IEEE Instrumentation and Measurement*, Volume 15, Issue 3, pp. 16-20, 2012.

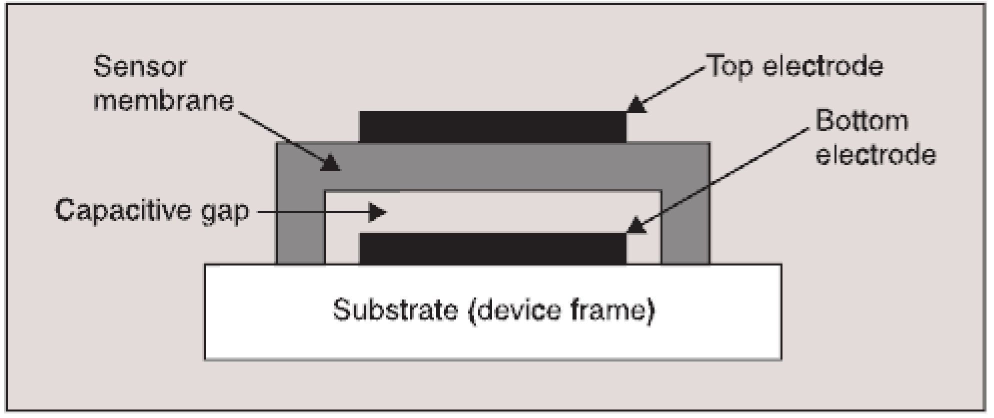
Pressure Measurement

- Design and analysis of insect-like flying robots require a knowledge of the pressure applied to their wings during flight. For this, a pressure sensor at least ten times lighter than the wings should be used.
- For instance, the wing length and weight of a hawk moth are about 50 mm and 100 mg, respectively. A sensor that weighs about 10 mg is needed to provide good performance in flight.
- A MEMS-based pressure sensor that measures differential pressure can be employed to evaluate aerodynamic forces of the flapping wings.
- Deflections of the cantilever due to aerodynamic forces change the resistance of the piezoresistor which is calibrated to measure pressure fluctuations.



Intramuscular pressure measurement

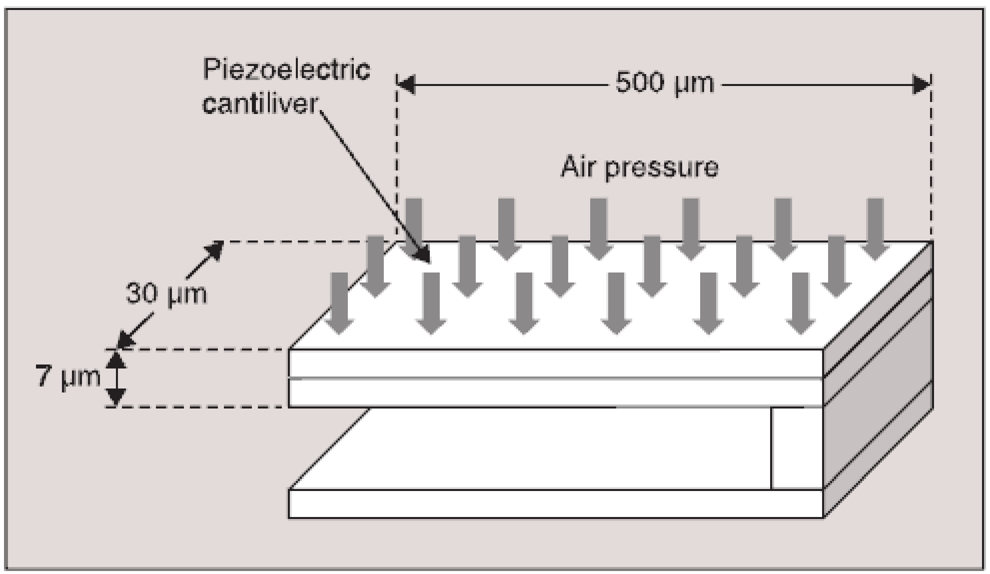
- Treatment of neuromuscular diseases requires assessment of the patients' muscles.
- By attaching a capacitive MEMS sensor to the muscle tissue, the IMP can be measured using the change in capacitance.
- Anchors are designed in the sensor to grip the surrounding muscle tissue during muscle contractions.



Capacitive transducer for intramuscular pressure measurement.

Flow Sensors

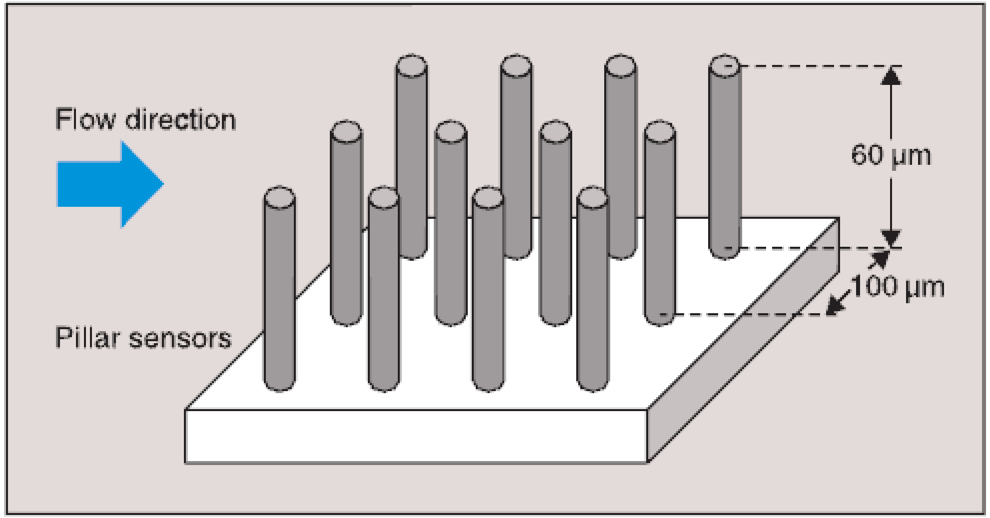
- A MEMS respiratory flow sensor can greatly reduce the cost of instrumentation.
- The flow velocity of exhaled breath applies pressure on the sensor surface and deforms a piezoelectric cantilever.
- The deformation of the sensor is detected through the generated charge, which is proportional to the applied pressure.



Respiratory flow sensor.

Shear Stress

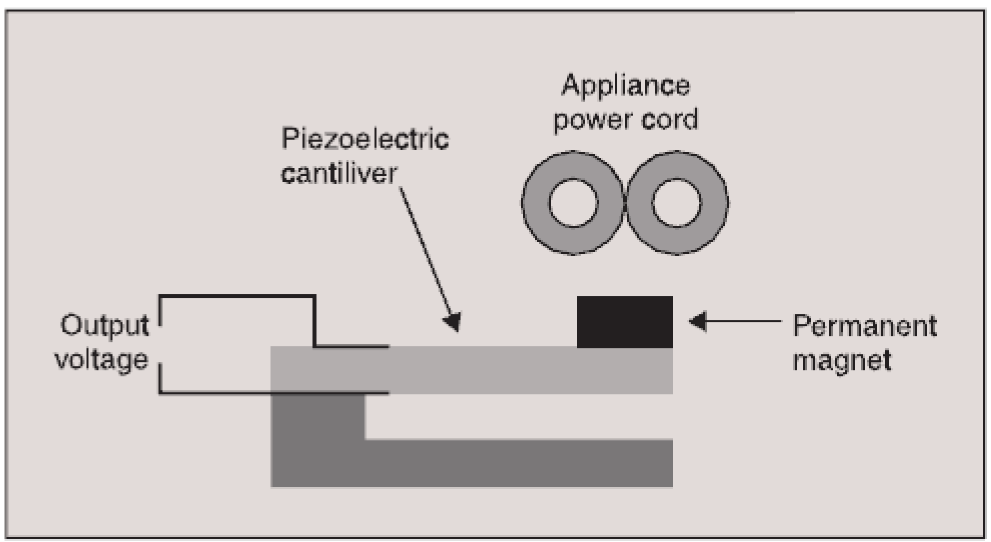
- A surface experiences a shear stress when it is exposed to fluid motion. This phenomenon is used to obtain measurements of lift and drag forces on surfaces in studies of aerospace, automotive, biomedical, etc. systems.
- Shear stress at the fluid–wall interface requires the measurement of very small parameters with high resolution force sensors. Macro-sensors exhibit limited resolution due to fluctuating shear stress.
- MEMS devices are capable of high resolution measurement particularly in turbulence research.
- The shear force is measured using capacitive, piezoresistive and optical principles.



Micro-pillar shear stress sensor.

Current Sensor

- A piezoelectric MEMS cantilever with a permanent magnet mounted at the free end of the cantilever can measure alternating current (ac) when placed near a wire carrying the current to be measured.
- This sensor is used to measure ac current for residential and commercial applications.

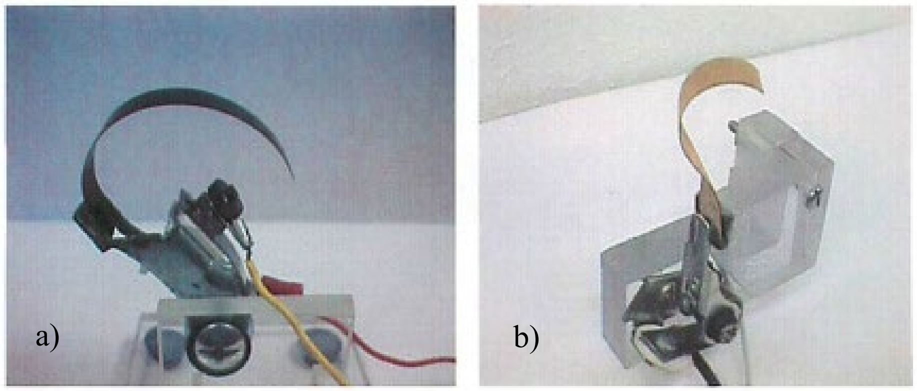


Schematic of the current sensor.

Bio-MEMS Actuators

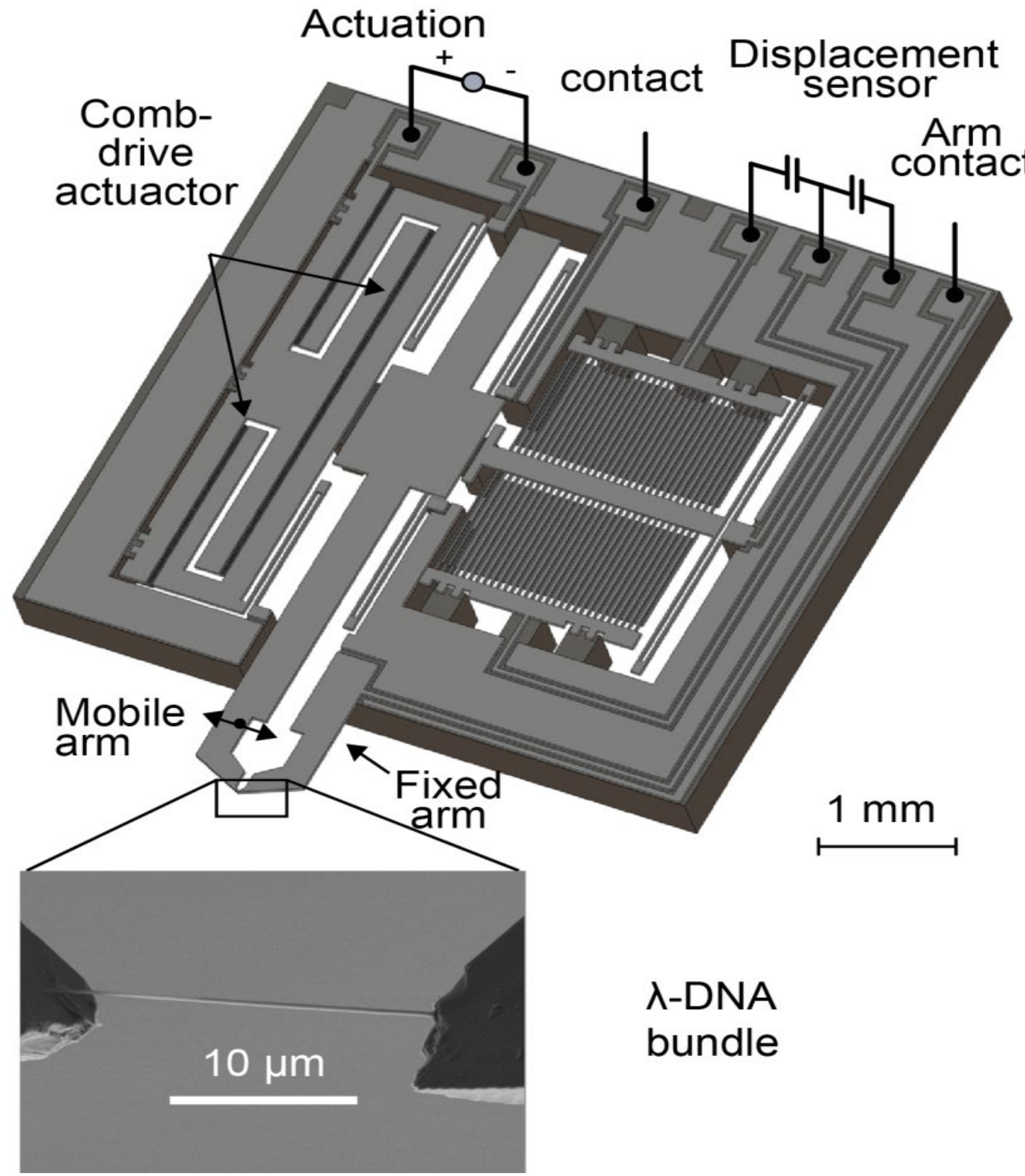
Reference:
Farbod Khoshnoud, Clarence W. De Silva, et al., **Mechatronics: Fundamentals and Applications, (**Chapters**: 1-Self-powered and Biologically Inspired Dynamic Systems, 2- Bio-MEMS Sensors and Actuators),** *Taylor & Francis / CRC Press*, 2015.

Artificial muscles
Ionic electroactive polymers

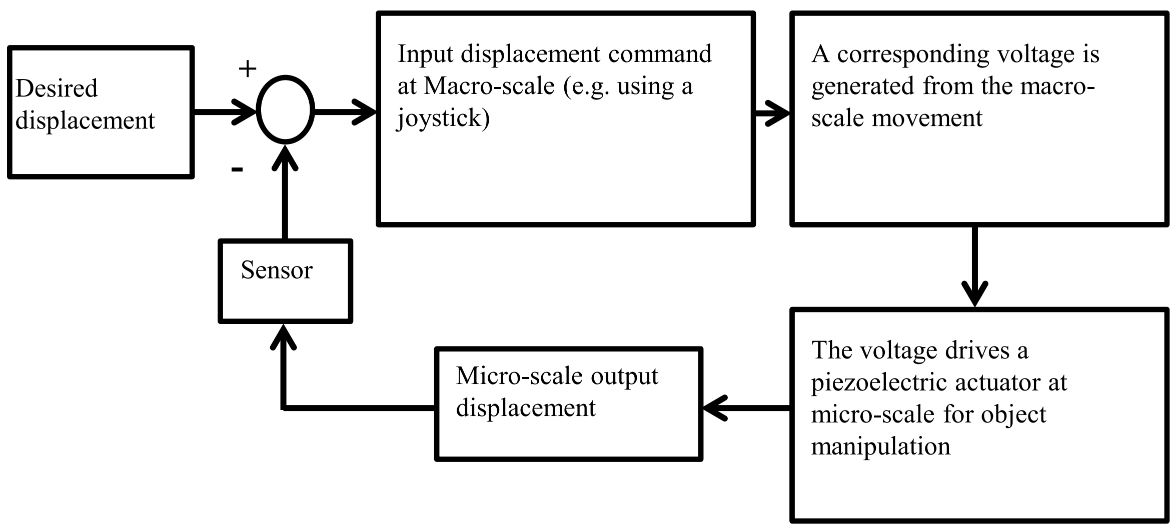


Ionic Polymeric-Metal Composites (IPMCs), a) Large bending deflection of a IPMC strip; b) Combined bending and torsional deflection. (From: Smart Materials and Artificial Muscles Laboratory, University of Maine. With Permission.)

Micro-nano-electromechanical systems (MNEMS) Tweezers device, and a stretched DNA bundle (From: LIMMS/CNRS-IIS, Center for International Research on MicroMechatronics CIRMM Institute of Industrial Science, University of Tokyo. With permission.)



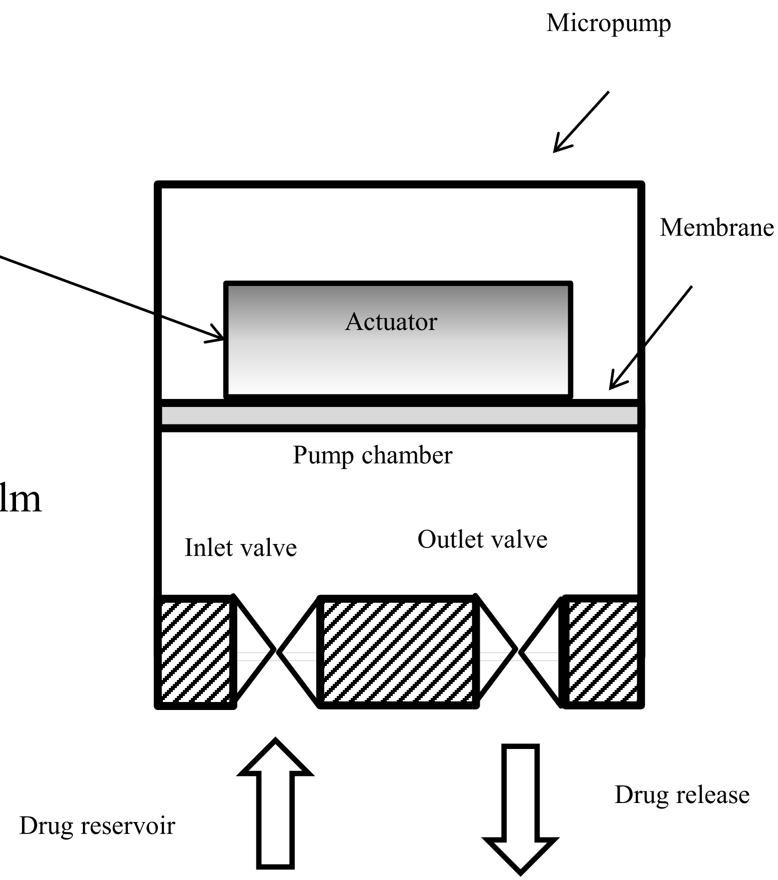
A multi-scale actuation mechanism for converting a macro-scale motion into a micro-scale displacement



Schematic representation of a Drug Delivery systems

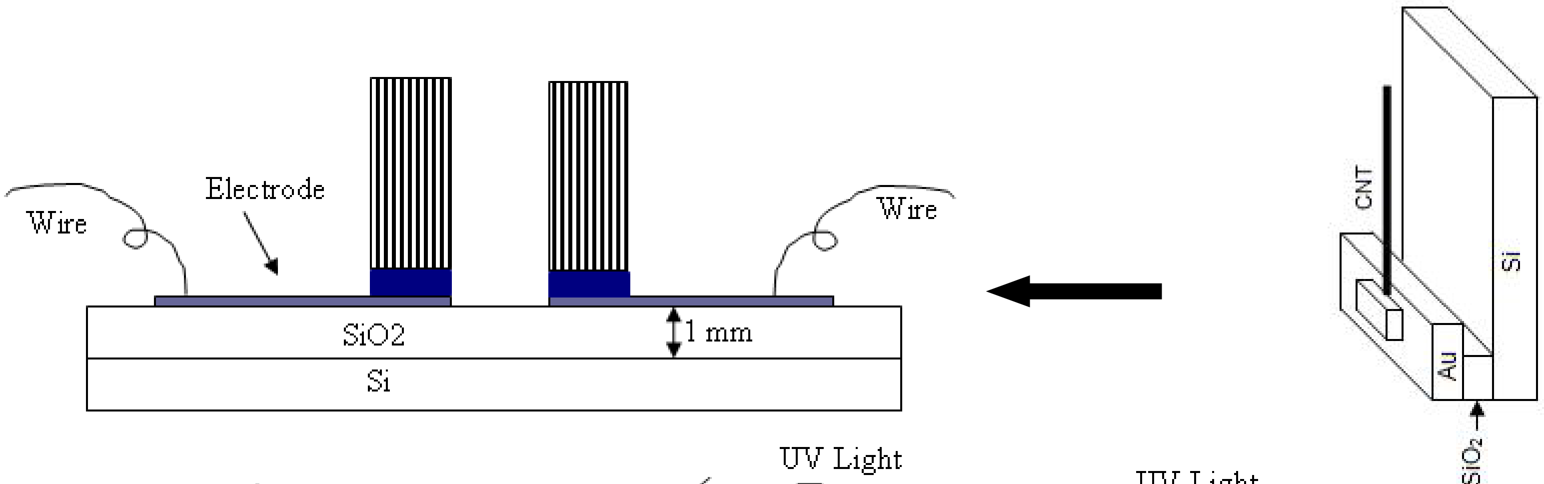
Micropump actuator types:

- Electrostatic
- Piezoelectric
- Thermopneumatic
- Bimetallic
- Shape memory alloy
- Ion conductive polymer film
- Electromagnetic
- Phase change type



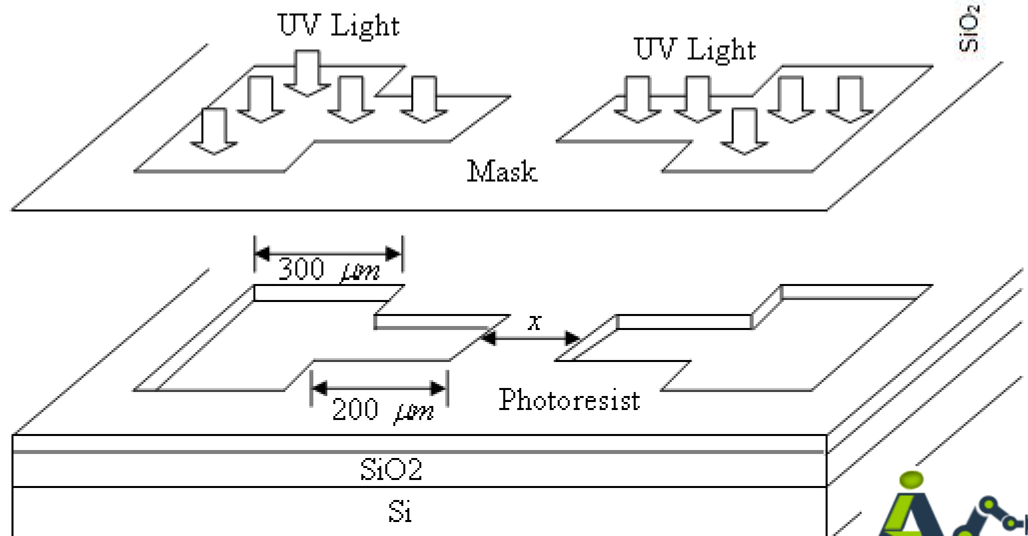
Fabrication of the Nano-Sensor

Fabricating of the nano-sensor device based on CNT forests.



Step 1: Apply Photoresist to the Sio2 Layer.

Step2: photolithography Expose the photoresist to UV light, with the mask pattern in the figure to remove the photoresist for this pattern.



Electron Beam Lithography: https://www.youtube.com/watch?v=PWV9pvdRBNY

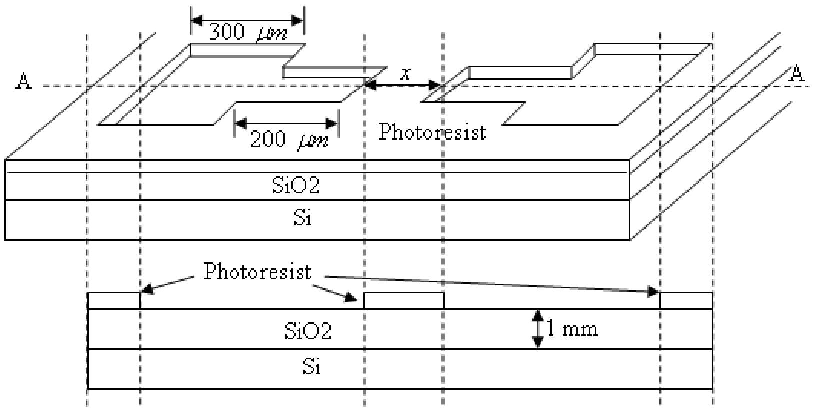
Photolithography: https://www.youtube.com/watch?v=9x3Lh1ZfggM

Photolithography: https://www.youtube.com/watch?v=9x3Lh1ZfggM

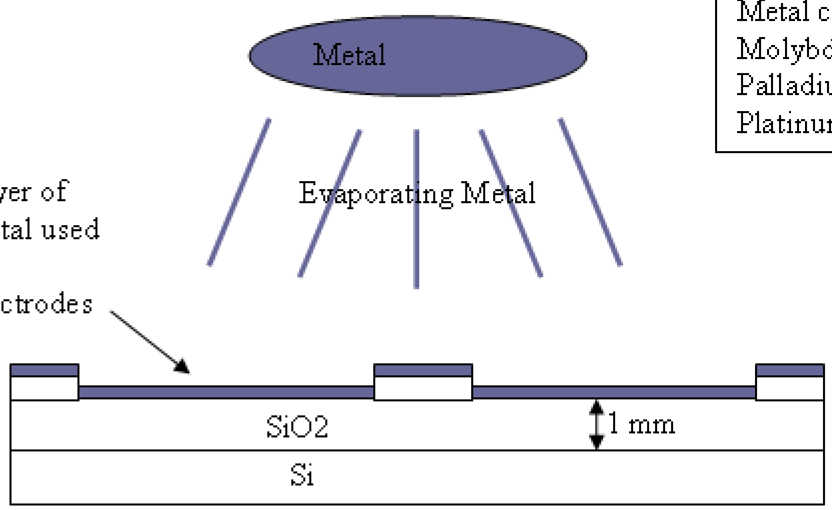
Nano-Sensor Fabrication

(Continued)

Step 3:
Evaporate metal on top of the SiO2 and photoresist by Evaporator.



Cross section at A-A.

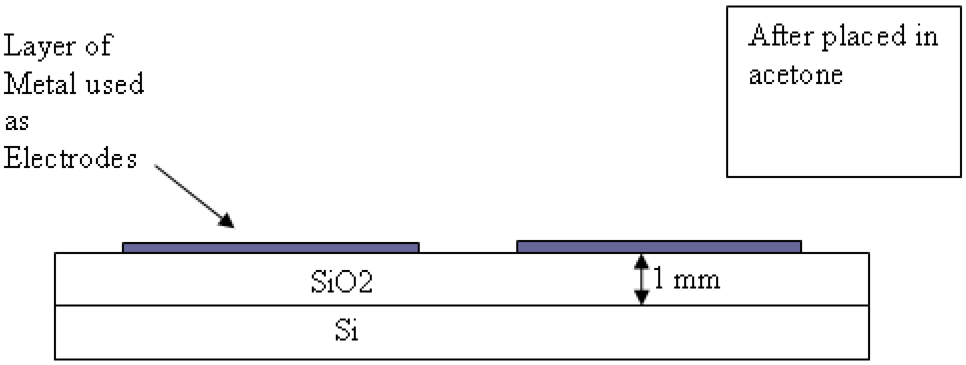


Metal can be:
Molybdenum,
Palladium, or
Platinum

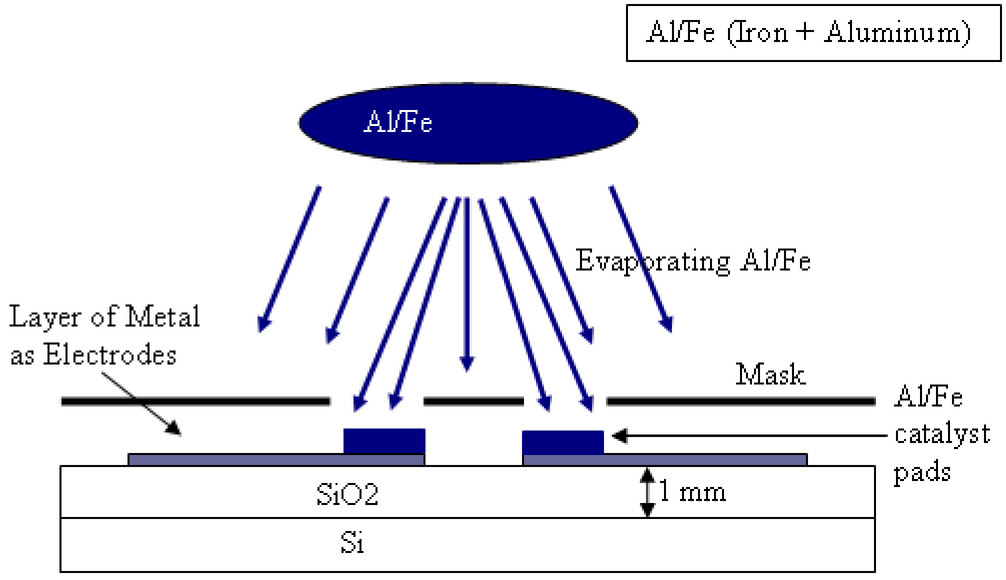
Nano-Sensor Fabrication

(Continued)

Step 4: Place it to Acetone to remove the photoresist and the metal layer on top of the photoresist.



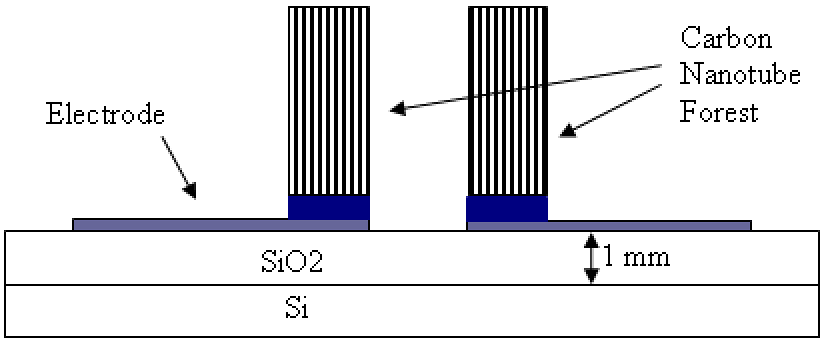
Step 5: Al/Fe (Iron + Aluminum) catalyst pads are patterned by evaporating Al/Fe on top of the Electrodes using photolithography.



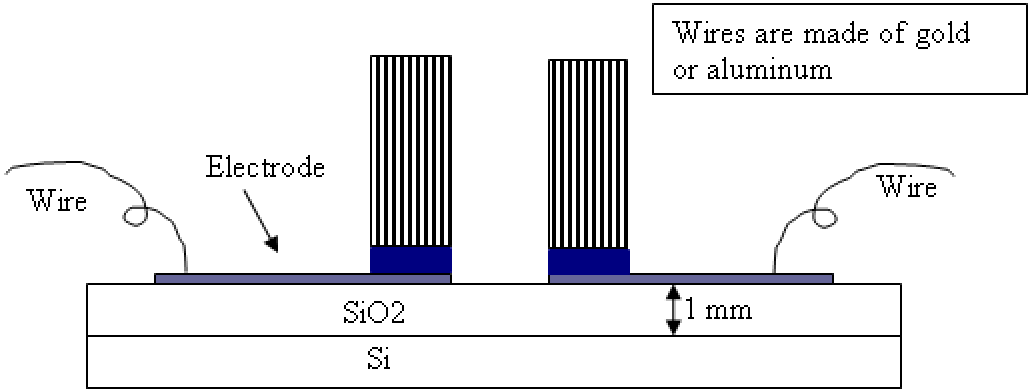
Nano-Sensor Fabrication

(Continued)

Step 6: Place the wafer into a Chemical Vapor Deposition furnace with constant flow of methane to grow the nanotube forest on top of the catalysts.



Step 7: Connecting Wires to electrodes by wire bonder for electrical contact.
Alternatively Probes can be used for electrical contacts.



References

- Farbod Khoshnoud, Clarence W. De Silva, et al., **Mechatronics: Fundamentals and Applications, (**Chapters**: 1-Self-powered and Biologically Inspired Dynamic Systems, 2- Bio-MEMS Sensors and Actuators),** *Taylor & Francis / CRC Press*, 2015.

- Farbod Khoshnoud and Clarence W. de Silva, Recent advances in MEMS sensor technology - Biomedical Applications, IEEE Instrumentation and Measurement, Volume 15, Issue 1, pp. 8 – 14, 2012.

- Farbod Khoshnoud and Clarence W. de Silva, Recent advances in MEMS sensor technology - Mechanical Applications, IEEE Instrumentation and Measurement, Volume 15, Issue 2, pp. 14 – 24, 2012.

- Farbod Khoshnoud and Clarence W. de Silva, Recent advances in MEMS sensor technology - Thermo-Fluid and Electrical, IEEE Instrumentation and Measurement, Volume 15, Issue 3, pp. 16-20, 2012.