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RECENT ADVANCES IN MEMS SENSOR TECHNOLOGY – BIOMEDICAL, MECHANICAL, THERMO-FLUID & ELECTROMAGNETIC SENSORS

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ABSTRACT

MEMS has been identified as one of the most promising technologies for the 21st Century. Trend toward smaller size, higher performance, and greater functionality for electronic devices is made possible by the success of solid-state microelectronics technology. Current MEMS devices include accelerometers for airbag sensors, inkjet printer heads, computer disk drive read/write heads, projection display chips, blood pressure sensors, optical switches, microvalves, biosensors and many other products that are all manufactured and shipped in high commercial volumes. Its techniques and micro system-based devices have the potential to dramatically affect of all of our lives and the way we live. So we will try to utilize advantages of the MEMS sensor technology in most of the important applications such as Bio-sensing and bio-inspired sensors, which are making an impact on technological development, innovation and progress in biomedical applications, mechanical sensors, thermo-fluid and electro-magnetic domains.

KEYWORDS: Biomedical, Bio-Sensor, Electromagnetic, Mechanical, MEMS, Sensor, Thermo-Fluid

INTRODUCTION

MEMS has been identified as one of the most promising technologies for the 21st Century and has the potential to revolutionize both industrial and consumer products by combining silicon-based microelectronics with micromachining technology. Its techniques and micro system-based devices have the potential to dramatically affect of all of our lives and the way we live[11]. This presents a general introduction to the field of MEMS, with emphasis on its commercial applications and medical applications. Also deals with the emerging field of micro-electromechanical systems, or MEMS.The origins of what we now know as micro-electromechanical system (MEMS) technology can arguably be traced back to 1 April 1954, when a paper by Smith (1954), then at the Bell Telephone Laboratories, was published in Physical Review. This described for the first time certain stress-sensitive effects in silicon and germanium termed piezoresistance[4].

During the mid-1950s, researchers were starting to investigate whether the same technologies that had yielded the transistor, which subsequently revolutionized the fledgling electronics industry, could be applied to sensors. Might not the bulky electromechanical sensors of the day be replaced by small, rugged devices in the same way that the transistor had replaced the thermionic valve? Smith's paper was followed a year later by what is probably the first publication to consider this possibility (Paul and Pearson, 1955) and during the early 1960s, a series of papers from the Honeywell Research Centre and the Bell Labs described the first silicon diaphragm pressure sensors and strain gauges (Pfann and Thurston, 1961; Tufte et al., 1962)[4]. Interest in silicon sensor technology grew dramatically and by the late 1960s a number of pioneering American companies had commercialized the first silicon pressure sensors. These were crude by today's standards but in the early 1970s developments in micromachining, as it was then called and improvements to silicon processing led to pressure sensors with non-planar diaphragm geometries which yielded superior performance. These were arguably the first true MEMS sensors[4].

The history of MEMS is useful to illustrate its diversity, challenges and applications. The following list summarizes some of the key MEMS milestones[11].

1950's

1958 Silicon strain gauges commercially available

1959 "There's Plenty of Room at the Bottom" – Richard Feynman gives a milestone presentation at California Institute of Technology. He issues a public challenge by offering $1000 to the first person to create an electrical motor smaller than 1/64th of an inch.

1960's

1961 First silicon pressure sensor demonstrated

1967 Invention of surface micromachining. Westinghouse creates the Resonant Gate Field Effect Transistor, (RGT). Description of use of sacrificial material to free micromechanical devices from the silicon substrate.

1970's

1970 First silicon accelerometer demonstrated

1979 First micro machined inkjet nozzle

1980's

Early 1980's first experiments in surface micro machined silicon.

Late 1980's micromachining leverages microelectronics industry and widespread experimentation and documentation increases public interest.

1982 Disposable blood pressure transducer

1982 "Silicon as a Mechanical Material". Instrumental paper to entice the scientific community – reference for material properties and etching data for silicon

1982 LIGA Process

1988 First MEMS conference

1990's Methods of micromachining aimed towards improving sensors.

1992 MCNC starts the Multi-User MEMS Process (MUMPS) sponsored by Defense Advanced Research Projects Agency (DARPA)

1992 First micro machined hinge

1993 First surface micro machined accelerometer sold (Analog Devices, ADXL50)

1994 Deep Reactive Ion Etching is patented

1995 BioMEMS rapidly develops

2000 MEMS optical-networking components become big business

Current MEMS devices include accelerometers for airbag sensors, inkjet printer heads, computer disk drive read/write heads, projection display chips, blood pressure sensors, optical switches, microvalves, biosensors and many other products that are all manufactured and shipped in high commercial volumes. If semiconductor microfabrication was seen to be the first micromanufacturing revolution, MEMS is the second revolution. This introduces the field of MEMS and is divided into four main sections. In the first section, the reader is introduced to MEMS, its definitions. The second section deals with the primary sensing techniques of MEMS including Piezoelectric Sensor, Capacitive Sensor, Electromagnetic Sensor, and Piezoresistance Sensor [12]. The third section completely deals with the Recent Advances In MEMS Sensors Technologies –

- Biomedical Applications
- Mechanical Applications
- Thermo Fluid Devices &
- Electromagnetic Devices.

Micro-electromechanical systems (MEMS) use micro miniature sensors and actuators. MEMS technology provides the large number of benefits.

OBJECTIVES OF TOPIC

Trend toward smaller size, higher performance, and greater functionality for electronic devices is made possible by the success of solid-state microelectronics technology. In the late 1980s, the silicon Very-Large-Scale-Integrated (VLSI) design and manufacturing was developed for use in field of Micro-Electro-Mechanical System (MEMS)[5]. These systems interface with both electronic and non-electronic signals and interact with non-electrical physical world as well as the electronic world by merging signal processing with sensing and/or actuation. So this is one of the best and advantageous factor for many applications in many different fields. Instead of dealing only electrical signals, MEMS also deals with moving-part mechanical elements, making miniature systems possible such as accelerometers, fluid-pressure and flow sensors, gyroscopes, and micro-optical devices. Today’s world is computer world so we can use this technique because MEMS are designed using computer-aided design (CAD) techniques based on VLSI and mechanical CAD tools and typically batch-fabricated using VLSI based fabrication process. MEMS devices are widely used due to their low cost and short turn-around time. Post-processing such as cavity etching, silicon bonding and flip chip soldering can be applied to produce the more complex mechanical structures for suitable applications. An early application of MEMS was in the field of micro sensor and micro actuator for measuring or driving position, pressure, velocity, acceleration, force, torque, flow, magnetic field, temperature, gas composition, humidity, pH, fluid ionic concentration, and biological gas or liquid-Molecular concentration. Some applications have been successfully commercialized in market such as thermal inkjet printer, automotive accelerometer, and high-resolution display projector[5].

MEMS has several distinct advantages as a manufacturing technology. In the first place, the interdisciplinary nature of MEMS technology and its micromachining techniques, as well as its diversity of applications has resulted in an unprecedented range of devices and synergies across previously unrelated fields (for example biology and microelectronics). Secondly, MEMS with its batch fabrication techniques enables components and devices to be manufactured with increased performance and reliability, combined with the obvious advantages of reduced physical size, volume, weight and cost. Thirdly, MEMS provides the basis for the manufacture of products that cannot be made by other methods. These factors make MEMS as pervasive technology as integrated circuit microchips. Also, contrary to IC manufacturing, there is no such thing as a standard building component like the transistor. This leads to a more diverse technology base with more development and engineering work and therefore to a more expensive and more difficult to maintain technology[12]. However, three points makes it very different: MEMS products tend to be application specific, giving rise to a wide range of very different products. Secondly, the number of MEMS products will be always less than that for semiconductor IC's.Micro-electromechanical systems (MEMS) use microminiature sensors and actuators. MEMS technology provides the benefits of : small size, low weight, high performance, easy mass-production and low cost. So we can utilize all these benefits in all our applications very efficiently. The present article, we provide a general introduction to MEMS sensing and the primary sensing techniques. Next, MEMS-based bio-medical sensors are explained[1]. The second part will be dedicated to mechanical sensors[2]. The third part will treat MEMS sensing in the thermo-fluid and electro-magnetic domains[3]. So we will try to utilize advantages of the MEMS sensor technology in most of the applications such as Bio-sensing and bio-inspired sensors, which are making an impact on technological development, innovation and progress in biomedical applications, mechanical sensors, thermo-fluid and electro-magnetic domains.

MICRO-ELECTROMECHANICAL SYSTEMS (MEMS)

What is Mems?

Micro-electromechanical systems (MEMS) is a process technology used to create tiny integrated devices or systems that combine mechanical and electrical components. They are fabricated using integrated circuit (IC) batch processing techniques and can range in size from a few micrometers to millimetres. These devices (or systems) have the ability to sense, control and actuate on the micro scale, and generate effects on the macro scale[11]. MEMS, an acronym that originated in the United States, is also referred to as Microsystems Technology (MST) in Europe and Micromachines in Japan. Regardless of terminology, the uniting factor of a MEMS device is in the way it is made. While the device electronics are fabricated using 'computer chip' IC technology, the micromechanical components are fabricated by sophisticated manipulations of silicon and other substrates using micromachining processes. Processes such as bulk and surface micromachining, as well as high-aspect-ratio micromachining (HARM) selectively remove parts of the silicon or add additional structural layers to form the mechanical and electromechanical components. While integrated circuits are designed to exploit the electrical properties of silicon, MEMS takes advantage of either silicon's mechanical properties or both its electrical and mechanical properties.

In the most general form, MEMS consist of mechanical microstructures, microsensors, microactuators and microelectronics, all integrated onto the same silicon chip. This is shown schematically in Figure 1. Microsensors detect changes in the system's environment by measuring mechanical, thermal, magnetic, chemical or electromagnetic information or phenomena. Microelectronics process this information and signal the microactuators to react and create some form of changes to the environment[11]. MEMS devices are very small; their components are usually microscopic. Levers, gears, pistons, as well as motors and even steam engines have all been fabricated by MEMS (Figure 1).

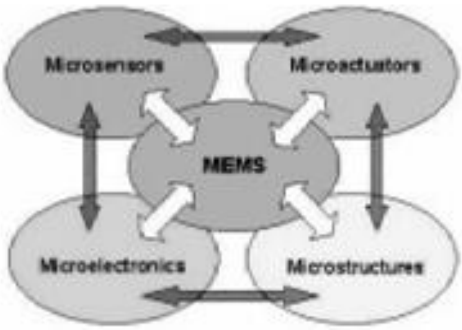

Figure 1: Schematic Illustration of MEMS Components

However, MEMS is not just about the miniaturization of mechanical components or making things out of silicon (in fact, the term MEMS is actually misleading as many micromachined devices are not mechanical in any sense). MEMS is a manufacturing technology; a paradigm for designing and creating complex mechanical devices and systems as well as their integrated electronics using batch fabrication techniques. From a very early vision in the early 1950's, MEMS has gradually made its way out of research laboratories and into everyday products. In the mid-1990's, MEMS components began appearing in numerous commercial products and applications including accelerometers used to control airbag deployment in vehicles, pressure sensors for medical applications, and inkjet printer heads.

Today, MEMS devices are also found in projection displays and for micropositioners in data storage systems. However, the greatest potential for MEMS devices lies in new applications within telecommunications (optical and wireless)[5], biomedical and process control areas. MEMS has several distinct advantages as a manufacturing technology. In the first place, the interdisciplinary nature of MEMS technology and its micromachining techniques, as well as its diversity of applications has resulted in an unprecedented range of devices and synergies across previously unrelated fields (for example biology and microelectronics).

Secondly, MEMS with its batch fabrication techniques enables components and devices to be manufactured with increased performance and reliability, combined with the obvious advantages of reduced physical size, volume, weight and cost. Thirdly, MEMS provides the basis for the manufacture of products that cannot be made by other methods. These factors make MEMS potentially a far more pervasive technology than integrated circuit microchips[11]. However, there are many challenges and technological obstacles associated with miniaturization that need to be addressed and overcome before MEMS can realize its overwhelming potential.

Definitions and Classifications

This section defines some of the key terminology and classifications associated with MEMS. It is intended to help the reader and newcomers to the field of micromachining become familiar with some of the more common terms[11]. Sensors and transducers are necessary to measure excitations (inputs), responses (outputs) and parameter values for a variety of purposes including monitoring, fault prediction, detection and diagnosis, experimental modeling, and control. In practical applications, one should be able to identify and select suitable sensors, model and analyze individual components or the overall systems, and choose parameter values that meet the performance requirements for the intended functions with respect to some specifications. Identification, analysis, selection, matching and interfacing of sensors, and tuning of the integrated system (adjusting parameters to obtain the required response from the system) are essential tasks in the instrumentation and design of a system.

Transducer

A transducer is a device that transforms one form of signal or energy into another form. The term transducer can therefore be used to include both sensors and actuators and is the most generic and widely used term in MEMS. A transducer converts the detected measurand into a convenient form for subsequent use (monitoring, diagnosis, recording, actuation, control, etc.). The transducer signal may be filtered, amplified, and suitably modified prior to this. For example, a piezoelectric accelerometer senses acceleration and converts it into an electric charge; an electromagnetic tachometer senses velocity and converts it into a voltage; and a shaft encoder senses a rotation and converts it into a sequence of voltage pulses.

Sensor

A sensor is a device that measures information from a surrounding environment and provides an electrical output signal in response to the parameter it measured. A sensor detects (feels) the quantity that is being measured (the measurand).

Actuator

An actuator is a device that converts an electrical signal into an action. It can create a force to manipulate itself, other mechanical devices, or the surrounding environment to perform some useful function[11].

PRIMARY SENSING TECHNIQUES

Sensing techniques are typically based on piezoelectric, capacitive, electromagnetic and piezoresistance principles. These sensing technologies are briefly discussed now.

Piezoelectric Sensors

Some substances, such as barium titanate, single-crystal quartz, and lead zirconate-titanate (PZT) can generate an electrical charge and an associated potential difference when they are subjected to mechanical stress or strain. This piezoelectric effect is used in piezoelectric transducers[1].

Piezoelectric Effect

When pressure (stress) is applied to a material it creates a strain or deformation in the material. In a piezoelectric material this strain creates an electrical potential difference, a voltage. The effect is reversible. When an electric potential is applied across two sides of a piezoelectric material, it strains. Both effects were discovered by Jacques and Pierre Curie in 1880-1.

The piezoelectric effect is found in materials with a specific electrical crystalline structure. These are known as piezoelectric materials[11].An equivalent circuit of a piezoelectric microsensor is given in Figure 2. The dielectric displacement in the direction normal to a pair of parallel plates of a piezoelectric capacitor of facing area A and carrying a charge Q is given by $D = Q / A$

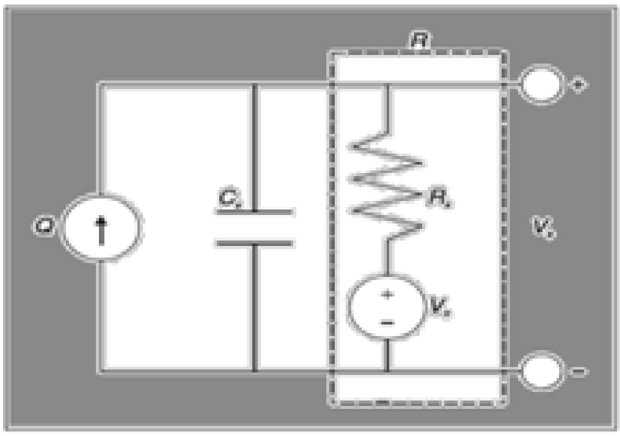

Figure 2: Equivalent Circuit for a Piezoelectric Micro Sensor

Capacitive Sensors

A capacitor is formed by two plates which can store an electric charge. The charge generates a potential difference which may be maintained using an external voltage[12]. A capacitive pressure sensor measures a pressure by detecting an electrostatic capacitance change; at least one electrode of the capacitor is on a moving structure. Capacitive sensors have the advantage over the piezoresistive type in that they consume less power, but have a non-linear output signal and are more sensitive to electromagnetic interference.

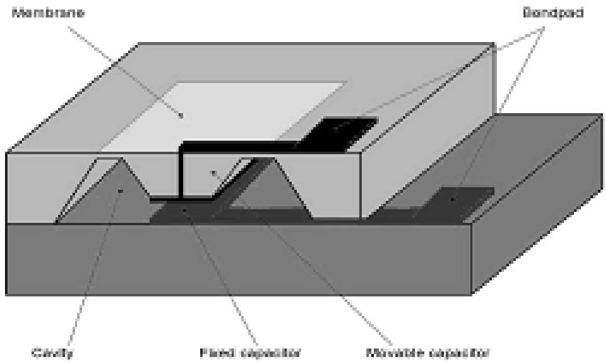

Figure 3: Schematic Capacitive Pressure Sensor

Capacitive sensors are compatible with most mechanical structures, and they have high sensitivity and low temperature drift. An equivalent circuit for a capacitive sensor is shown in Figure 3. The capacitance of a parallel plate capacitive transducer is given by: $D = \varepsilon 0 \varepsilon r\ A /d$ where εr and $\varepsilon 0$ denote the relative and vacuum permittivity, respectively.

Electromagnetic Sensors

Sensors that employ the principle of electromagnetic induction are termed variable-inductance or electromagnetic sensors. Those variable-inductance transducers that use a non-magnetized ferromagnetic medium to alter the reluctance (magnetic resistance) of the flux path are known as variable-reluctance transducers. Magnetic force on a magnet placed in an external magnetic field is given by:$F = B2S /2\mu 0$ where F denotes the magnetic force, $\mu 0$ is the permeability of free space, and B and S are the magnetic field intensity and area of the ferromagnetic material perpendicular to the magnetic field[1].

Piezoresistive Sensors

In a piezo-resistive device, conductivity of the doped semiconductor is influenced by mechanical deformation. This principle allows detection of movement in an inertial sensor or deformation in a pressure sensor. The advantages are: a good sensitivity and a good linearity at constant temperature. The major disadvantage is its strong temperature dependence[1]. Typically four piezoresistors are connected into a Wheatstone bridge configuration to increase accuracy. Piezoresistive sensors use the change of the electrical resistance in material when it has been mechanically deformed. The resistance of a piezoresistor is given by: $R = \rho\ l/tw$ where ρ, l and t denote the resistivity, the length, and the thickness and the piezoresistor, and w is the width of the contact. depends on the doping concentration of the piezoresistor. In particular, strain gauges sometimes make use of piezoresistive sensors[12].

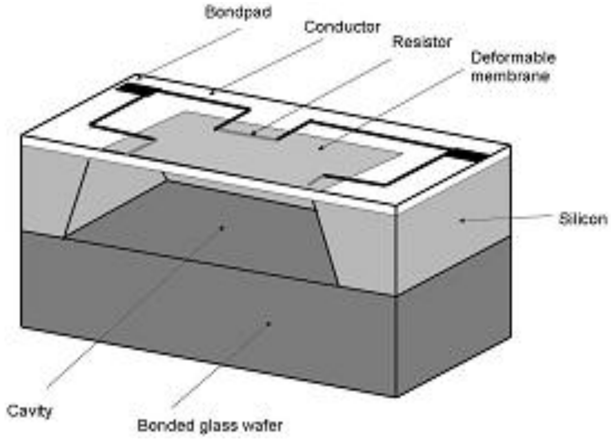

Figure 4: Schematic Piezoresistive Pressure Sensor

RECENT ADVANCES IN MEMS SENSOR TECHNOLOGY – BIOMEDICAL

MEMS-based biological sensors are applied in : 1) physiological 2) medical and 3) health applications.

Several examples of such Bio-MEMS sensors are presented below[1] :

Triglyceride Biosensor

Triglyceride measurement is in demand in the food and oil industries. Composite porous silicon/polysilicon micro-cantilevers are used in biosensing applications, such as triglyceride sensing. Micro-cantilevers are able to transduce a variety of chemical and physical phenomena into mechanical motion. Micro-cantilevers have been employed in detecting cells, proteins, heavy metals, and other chemical and biological species. Arrays of these cantilevers are capable of detecting multiple parameters simultaneously. In chemical and biochemical sensing, the micro-cantilever surface is coated with a suitable chemical substance through self-assembled alkanethiols, organosilane films, direct covalent attachment of molecular receptors, or dip coating. Micro-cantilever mass increases when the biomolecules adhere to the coated cantilever surface. Variation in the cantilever mass changes the natural frequencies of the cantilever which is detected by a Doppler vibrometer. Porous layers on the surface of the micro-cantilever provide a larger sensing area for the sensor. Porous silicon provides a large surface area with a small volume. A triglyceride biosensor is illustrated in Figure 3. Such a biosensor can have a cantilever beam with length = 100–200 µm, width = 10–20 µm, and thickness = 2 µm. A 2 µm thickness of polysilicon is deposited by LPCVD on 1.6 µm thermal oxide for this sensor[1].

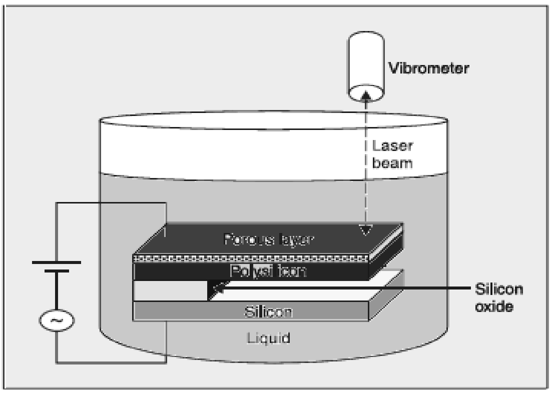

Figure 5: A Triglyceride Biosensor with a Cantilever Beam in Liquid

C-Reactive Protein Detection

Proteins have many biological functions in the human body. Proteins catalyze the biochemical reactions to transport and store nutrients, provide protection from viruses/bacteria, and transmit biological signals. C-reactive protein (CRP) concentration in human serum is below 1 mg/mL in a healthy body. CRP can increase to 100 and in some cases up to 500 times due to infection. Increasing the CRP in the bloodstream may cause cardiovascular disease and heart attacks, a major cause of death. Development of low cost CRP detection is crucial for human health monitoring. The CRP sensing techniques allow detection of biological molecules. Fluorescence based bio-sensing is the most common technique in biological molecule sensing. However, this technique requires a complicated labeling process of target molecules with dye and is expensive. A 200 µm long micro-cantilever in a wireless MEMS sensor is realized to detect disease related CRP. Cross-biolinker binding on the sensor is performed by injecting self-assembled molecules into the sensor to adhere to a gold-coated silicon nitride microcantilever. AntiCRP is then injected to the sensor and adheres to the cantilever surface. Biomolecular interactions between CRP and antiCRP change the intermolecular nanomechanical interactions within the biolinker layer and bend the cantilever. Deflection of the micro-cantilever is measured optically or using piezoresistive techniques[1].

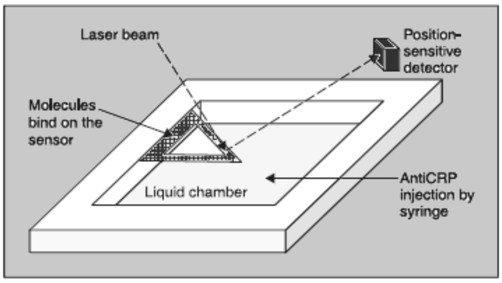

Figure 6: Schematic Diagram of Bio-MEMS Sensor for CRP Detection

Detection of Glucose

Glucose is measured in diabetic patients to monitor blood sugar levels. Commercially available enzymatic electrochemical detection implants for continuous glucose monitoring provide irreversible measurements. These sensors consume glucose throughout the measurement and therefore change the equilibrium of glucose concentration in the tissue. This results in inaccuracy in the sensed glucose level. MEMS sensors based on the binding of glucose do not affect sensed glucose measurement.

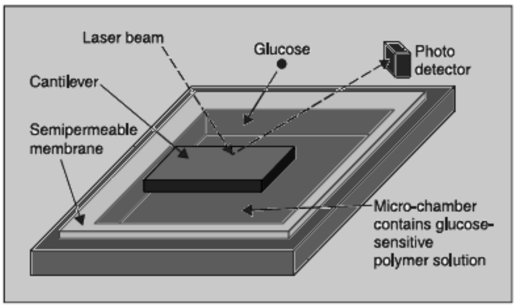

Figure 7: A MEMS Affinity Sensor for Detection of Glucose

Continuous monitoring of glucose for diabetes management can also be attained by a magnetically driven vibrating micro-cantilever that is similar to an affinity glucose sensor except that the oscillating membrane is replaced with a micro-cantilever. The principle of operation is affinity binding. The cantilever detects viscosity changes due to affinity binding between glucose and poly (acrylamide-ran-3- acrylamidophenylboronic acid) (PAA-ran-PAAPBA). The cantilever is placed in a micro-chamber filled with PAA-ran-PAAPBA solution. When glucose permeates through a membrane and binds to the phenylboronic acid moiety of the polymer, it changes the viscosity of the solution. Changes in the viscosity of the solution vary the damping of the vibration behavior of the cantilever in the solution. The vibration behavior of the cantilever is monitored by an optical lever setup. Figure 8 is a MEMS affinity sensor for detection of glucose. Using this device, readings of glucose concentrations in the range of 27 mg/dL to 324 mg/dL are possible. Such sensors have a response time of approximately 3 min

MEMS Force Sensor in Protein Delivery

Mechanical properties of soft hydrogel microcapsules as a protein delivery mechanism have been studied using a MEMS capacitive force sensor illustrated in Figure 8. The sensor can measure both the normal and tangential forces on the soft hydrogel microparticles and is capable of resolving forces up to 110 µN with a resolution of 33.2 nN along two independent axes with linear response and minimized cross-axis coupling.

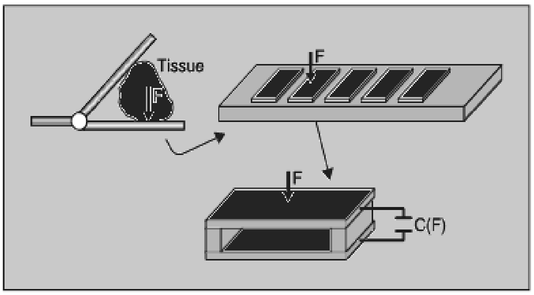

Figure 8: MEMS Tactile Sensors for Quantifying Tissue Softness

These results are used to characterize the mechanical properties of hydrogel microcapsules so that the controlled delivery of therapeutic agents (e.g., protein drugs) and the encapsulation of living cells is possible. Due to their hydrophilic nature that resembles living tissues, they exhibit high biocompatibility. Hydrogel microcapsules offer a suitable environment for stabilizing proteins as a result of their capability of holding a large quantity of water. Hydrogel microcapsule characteristics include high deformability and diameters in the range of 1 to 100 µm, which is comparable with most biological cells. The mechanical strength of hydrogel microcapsules determines if they can survive in the needle tract during injection, in the blood capillaries, and in the applied tissues. It is necessary to preserve their integrity during processing to avoid dose dumping, cell death, or immunoresponse. Characterization of the mechanical properties of hydrogel microcapsules using MEMS capacitive sensors allows developers to design efficient drug and cell delivery systems.

A Blood Cell Counter

Blood consists of plasma and blood cells. Blood cells are divided into red blood cells, white blood cells and platelets. Commercial blood cell counters are based on an aperture-impedance method and a light scattering method. Current blood cell counters are bulky and are not suitable for use at pointof- care. MEMS technology can overcome this limitation. A MEMS sensor for counting blood cells in humans has been realized. The sensor’s output is a voltage that is proportional to the blood count. When a diluted blood sample is injected into the aperture, 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 (Figure 9).

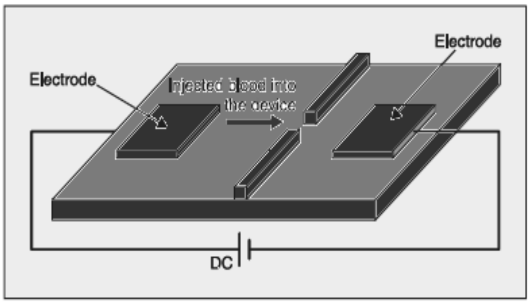

Figure 9: Schematic Diagram of the Blood Counter Sensor

Red and white blood cells are distinguished by the difference in the pulse heights they cause. There is a linear relationship between the red blood cells and the measured counts.

Acoustic Sensors

MEMS acoustic sensors assist human hearing using piezoresistive, condenser and piezoelectric methods.

Although new hearing devices such as digital hearing aids and cochlear implants are used today, the MEMS acoustic method is still applied in cell phones, micro-personal digital assistants, portable multimedia players, and voice recognition.

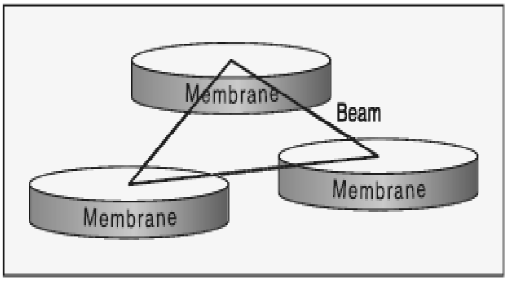

Figure 10: Schematic Diagram of the Fly-Ear Inspired 2-D Sound Source Localization Sensor

A MEMS micro-sensor for 2-D sound source localization has been developed that detects a sound's source in two dimensions described by the azimuth and elevation angles by using three mechanically coupled circular fiber-optic membrane systems (Figure 11). Size of silicon membrane: thickness = 0.5 µm, radius = 590 µm. The beam is made of alternating layers of silicon nitride and silicon oxide of size 1200 µm x 300 µm x 3 µm. This acoustic sensor is 1200 µm x 300 µm x 3 µm. It is inspired by the hearing organ of the fly Ormia ochracea. MEMS capacitive based microphones allow detection of small pressure gradients. A low-coherence capacitive fiber-optic interferometer measures the acoustic pressure from the small pressure gradients produced by the membrane oscillations and localizes the sound source. The fly-ear inspired sensor offers better amplification in both the directional cues and directional sensitivity detection when compared to other MEMS sound sensors.

RECENT ADVANCES IN MEMS SENSOR TECHNOLOGY – MECHANICAL

In this part, mechanical sensors for displacement, acceleration, impact, vibration, force and torque, and stress and strain are discussed. Various applications of these sensors include high-g measurement, study of golf swing dynamics, vibration control of space inflatable structures, force and torque measurement in micro-robots, bone stress monitoring, metrology, and characterization of nano-scale structures Sensing of mechanical variables such as motion (displacement, velocity, and acceleration), force (and other forms of loading such as moment and torque), deformation, stress, and strain are considered below. Applications that use sensors in this category are indicated[2].

Acceleration Sensor

Traditional accelerometers that use a proof mass as a detectable motion element of the sensors have the drawbacks of low shock resistance and a complex fabrication process. A thermal convective micro-accelerometer, developed by Dao et al., in 1996 and described in, uses a thermal bubble instead of a seismic mass. It is based on the movement of a small hot air bubble created around the heater in a chamber.

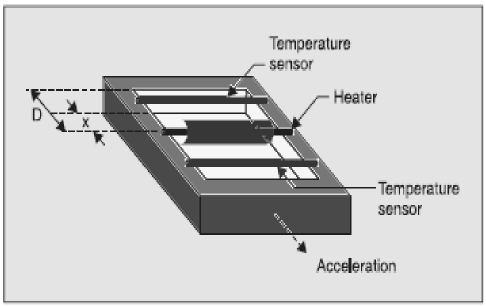

Figure 11: Convective Acceleration Sensor

The thermal heater is placed in between two thermistors, microminiature temperature sensors made of semiconductor material whose resistance changes with temperature. Applied acceleration to the sensor forces the thermal bubble to move. When the thermal bubble approaches one of the thermistors, it increases the thermistor's temperature and causes the opposing thermistor to exhibit a lower temperature. This temperature variation is reflected in the changes in the resistances of the thermistors and is converted to a voltage using Wheatstone bridges. The measured voltage is translated into an acceleration. Keeping the heater at a high temperature offers high sensitivity for the sensor. The sensor sensitivity also depends on the position of the thermistors. If the thermistors are placed at a position with a factor of $x/D = 0.2$, maximum sensitivity will be achieved. Here, D is the distance between the heater and the cavity wall, and x is the distance between the heater and the temperature sensor. Using carbon dioxide as the filling gas in the sensor leads to a more sensitive sensor than using air, nitrogen and hydrogen. Air and nitrogen provide the same sensitivity but less than carbon dioxide. The sensor's sensitivity is very low when hydrogen is used. The frequency response of the sensor and the behavior of its transient response depend on the density of the fluid in the sensor and the thermal diffusivity of the sensor. Conduction of the heat in the sensor will balance the energy between the heater and the enthalpy carried away by the buoyant layer. This decreases the response time. Moreover, lower gas density allows faster convection. Therefore, large thermal diffusivity and low gas density provide faster response. Hydrogen has low density and large thermal diffusivity, providing a high frequency response, although it has low sensitivity. A self-mixing laser displacement sensor coupled with a MEMS accelerometer enables reliable displacement measurements with a resolution of 300 nm.

Strain Sensors

Unwanted vibration may generate noise, reduce stability, or decrease positioning accuracy of sensors. Fiberoptic strain sensors sense the change in wavelength or phase of light which is a measure of strain. They generally provide high resolution (in microstrain and nanostrain per Hz range). However, they are bulky. Piezoresistive strain gauges are generally used for static to low frequency strain detection. Smaller sensors are influenced less by the structural dynamic behavior (due to their smaller mass) and detect local strains, not the average strains in the neighborhood of the sensor. Strain-based MEMS sensors such as pressure sensors, accelerometers, and atomic force microscopy sensors have been developed.

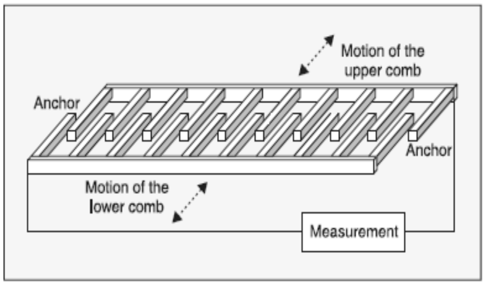

Figure 12: Comb Drive or Finger Capacitive Design of Strain Sensor

In piezoelectric sensors, response strength is proportional to piezoelectric material thickness of lead (Pb) zirconate titanate (PZT), zinc oxide (ZnO), or aluminum nitride (AlN) materials. Although piezoelectric materials have good signal-to noise ratios (SNR) over a large frequency range and are suitable for vibration monitoring, they lose sensitivity at the micro-scale. Unlike piezoelectrics, piezoresistive materials are less sensitive to smaller size. However, they have lower SNR relative to piezoelectrics. ZnO MEMS piezoelectric strain sensors for dynamic strain are sensitive to thermal noise and parasitic capacitance. However, if the sensing signal is properly handled, these piezoelectric sensors are superior to the laser-Doppler-vibrometer (LDV) in dynamic signal sensing. A high-performance dynamic strain MEMS sensor measures structural vibration without placing an extra burden on the host. The sensing element is composed of micro-ZnO piezoelectric. The sensor is capable of sensing a 40.0 nanostrain, time domain signal at frequencies above 2 kHz. Resonant sensors are favored in precision measurements due to their high sensitivity. The frequency output of the sensors can be measured with high accuracy. Silicon comb-driven double-ended tuning fork resonators are used for measuring acceleration, gyroscopic motion and strain. These can sense force for feedback control in robotic grippers and strain in structural monitoring. Silicon materials degrade at temperatures above 500°C, and their electronic properties fail beyond 150°C. Therefore, Si is not appropriate for applications in harsh environments such as high radiation exposure, operation in high temperature and corrosive media and ultrahigh g-shock. Silicon carbide (SiC) has a higher stiffness and fracture strength and is more resistant to wear, oxidation, high temperatures and corrosion relative to Si. A poly-SiC balanced-mass, double-ended tuning fork resonant strain sensor is used for structural monitoring of components in high temperature or otherwise harsh environments. Poly-SiC resonant strain sensors exhibit similar resolution to silicon sensors (0.11 microstrain resolution in a bandwidth of 10.20 kHz). These sensors have been used in environments with temperatures beyond 300°C and successfully subjected to 10,000 g-shock.

MEMS Tactile Sensor for a Robotic Finger

Lifting and grasping tasks by robots are controlled based on sensor signals. Piezoelectric and piezoresistive sensors allow robotic fingers to characterize different surface textures. 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.

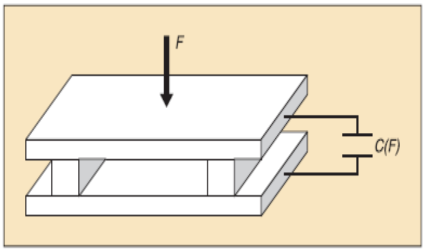

Figure 13: Schematic Diagram of Tactile Capacitive Sensor

Employing the capacitive sensing principle in the sensors (Figure 13) offers increased sensitivity, long term drift stability, lower temperature sensitivity and lower power consumption, which is advantageous compared to piezoresistive, strain gauge, and piezoelectric sensing approaches.

Polymer-Based MEMS Tactile Sensor

Biological tactile sensors can provide information about an object's shape, force, hardness, motion, temperature, and so on. Tactile sensors are fabricated mainly from silicon, polymer or metal using the piezoresistive or capacitive principles (Figure 14).

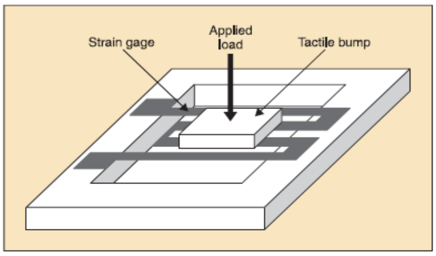

Figure 14: Schematic Diagram of Tactile Sensor

Other techniques under investigation include ultrasonic, pneumatic, and hybrid resistive principles. Because of the brittle characteristic of silicon materials, polymers are better suited for this use, and they offer greater robustness. Biological sensors provide excellent electrical and mechanical transduction characteristics. A polymerbased MEMS tactile sensor array on a polyimide substrate has been used to classify surface textures. These sensors are flexible and their sensing capabilities resemble those of biological skin. The texture classification is done by maximum likelihood decision making and using arrays of mechanical strain gauges. The sensor has demonstrated classification accuracy levels of about 70%. Techniques developed for satellite photography and RADAR imagery data processing, such as probability density function (pdf) estimation and neural networks (NNs), are utilized in tactile sensor data analysis. Among image-based texture classification approaches, the maximum likelihood (ML) estimation technique can correctly identify the texture 98% of the time, which is far better than the results from the autocorrelation method (76%), pdf estimation (83.97%), and NN identification (81.88%). The success of the ML identification is limited to Gaussian texture distributions.

RECENT ADVANCES IN MEMS SENSOR TECHNOLOGY – THERMO-FLUID

This includes MEMS sensing in the thermo-fluid domains. MEMS-based sensors are available for applications involving fluid flow, thermodynamics, and heat transfer. Several types of sensors are outlined below[3].

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 of an insect-type ornithopter.

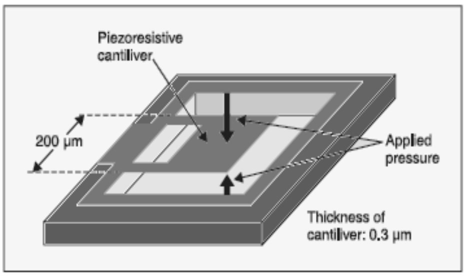

Figure 15: MEMS Differential Pressure Sensor for an Insect-Like Ornithopter

Sensing is carried out using a micro-cantilever with a piezoresistive layer on its surface whose resistance varies when subjected to mechanical stresses (Figure 16). Deflections of the cantilever due to aerodynamic forces change the resistance of the piezoresistor which is calibrated to measure pressure fluctuations. , the ratio of differential pressure to dynamic pressure, is the parameter evaluated for the experimental tests. It is given by:

$Cp = 2\Delta P / \rho V2$

where ΔP denotes the measured differential pressure using the piezoresistor in Figure 3, ρ is the air density, and V is the airflow velocity across the half wing length. With this sensor, pressure measurements in the frequency range of 0 – 1 kHz have been realized.

Ultraminiature MEMS Pressure Sensors

Treatment of neuromuscular diseases requires assessment of the patients' muscles. Common muscle strength assessment techniques include manual muscle testing, instrumented strength testing, and electromyography. Pressure is developed inside a muscle as the contracting muscle fibers apply pressure to the interstitial fluid volume.

There is a linear relationship between intramuscular pressure (IMP) and joint torque. By attaching a capacitive MEMS sensor to the muscle tissue, the IMP can be measured using the change in capacitance. The movement of the pressure sensor during measurement inside tissue has to be minimized. Anchors are designed in the sensor to grip the surrounding muscle tissue during muscle contractions.

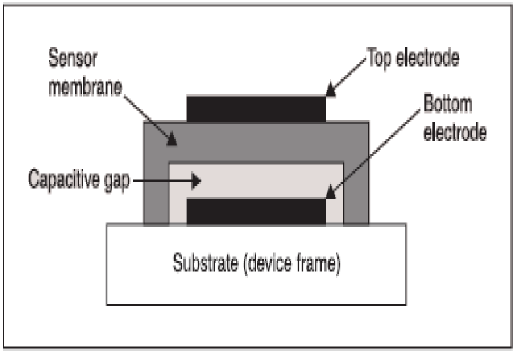

Figure 16: Capacitive Transducer for Intramuscular Pressure Measurement

The device, including its packaging, wiring, and tethering, fits inside a needle with an internal diameter of 250 µm.

MEMS Flow Sensors

Liquid handling robotic instruments for protein crystallization, drug delivery, and medical diagnostics require the transfer of liquid volumes at sub-microliter scale. Inkjet dispensers are designed based on piezoelectric and solenoid principles. Other liquid handling technologies use an electrical conductivity gradient, thermal actuation, and focused acoustics mechanisms.

Automated, high speed liquid dispensing systems for small liquid volumes should be able to handle liquids with different viscosities. A sensor information feedback system self-adjusts the open time of the solenoid valve to accurately dispense desired volumes of reagent using a high speed MEMS flow sensor.

A high-speed liquid flow sensor measures the pressure difference across a flow channel for static and dynamic liquid dispensing. A closed-loop control system evaluates the valve open time in each dispensing cycle for any fluctuation in liquid viscosity and pressure. An adaptive, high-precision liquid dispensing system integrated with an intelligent control system consists of a syringe pump, syringe valve, pressurized reagent bottle, pressure regulator, micro-solenoid valves, sensors, and a microcontroller.

Resistive, thermoelectric, pyroelectric, and piezoelectric sensing are employed in respiratory flow measurement. Common clinical applications include prevention of sudden infant death syndrome and determining the physiological status of a patient for sleep studies related to sports training. Respiratory flow sensing techniques include the measurement of transthoracic impedance, blood O2/CO2 concentration, and breathing airflow (a direct measurement method).

In resistive breathing airflow measurement, the relationship between flow rate and sensed voltage is linear. 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 (Figure 18).

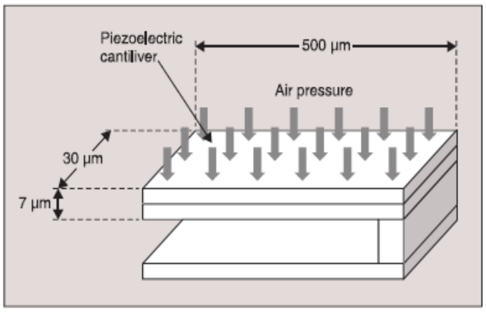

Figure 17: Respiratory Flow Sensor

The deformation of the sensor is detected through the generated charge, which is proportional to the applied pressure. As the resistance variation is small, a Wheatstone bridge consisting of the sensor and three integrated resistors is used to compensate for environmental effects and noise in the system. The bridge output voltage is then amplified for final measurement. Fluid flow can be measured by freestanding micro-cantilever piezoresistors. When air flows over the cantilevers, the resistance of the piezoresistors is changed. The change is measured using LCR meters and determines the air flow velocity. A hybrid MEMS vortex flow meter uses a cantilever-based displacement sensor to detect the frequency of vortex development using a piezoresistive bridge strain gauge system.

Shear Stress and Viscosity Sensors

A surface experiences a shear stress when it is exposed to fluid motion. This phenomenon is commonly used to obtain measurements of lift and drag forces on surfaces in studies of aerospace, automotive, marine and biomedical 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 and for industrial process control. The shear force is measured using capacitive, piezoresistive and optical principles. Piezoelectric and piezoresistive sensors are relatively slow to respond when dynamic measurements are being made (e.g., in the study of turbulence). An optical sensor is capable of measurement in the resolution range of 0.003 Pa to 10 Pa. Capacitive sensors require a large number of combs (capacitors) and measure shear stress of fluid flow with a resolution of 0.01 Pa and a bandwidth of 50 kHz. The sensor is composed of a beam element and capacitive comb drives supported by an inplane torsional spring. Displacement of the floating beam due to shear is detected by capacitive sensing of a resonant RLC circuit at the sub-femtofarad sensing scale. A micro-pillar shear stress measurement system (Figure 19) allows detection of wall shear stress at high spatial and temporal resolutions.

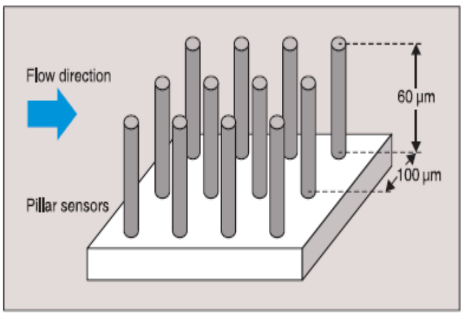

Figure 18: Micro-Pillar Shear Stress Sensor

The wall shear stress is proportional to the deflection of the pillars' tips. Pillar-tip deflection can be detected using a lens and a high-speed camera at a recording frequency of 10 kHz. Quartz shear resonators are commonly used as Newtonian viscosity sensors for liquids. Fluid loading changes the parameters of an electrical circuit coupled with a plate allowing the measurement of the mass density-shear viscosity product.

RECENT ADVANCES IN MEMS SENSOR TECHNOLOGY – ELECTROMAGNETIC

The domain of electro-magnetic and electronic sensors using MEMS technologies is considered below. Several practical applications are indicated[3].

AC 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 may be used to measure current (ac) in residential and commercial applications. The magnet is driven by the near wire ac current and generates a voltage in the cantilever through electro-magnetic induction. The generated voltage is proportional to the current. Force on the magnet in the plane normal to the wire can be obtained by where is the remanence of the permanent magnet, is the magnetic field, is the volume of the magnet, and denotes the vertical axis. Measuring the voltage generated by the vibration of piezoelectric MEMS cantilever does not require an input power source, and therefore, the sensor is passive (self-sustained).

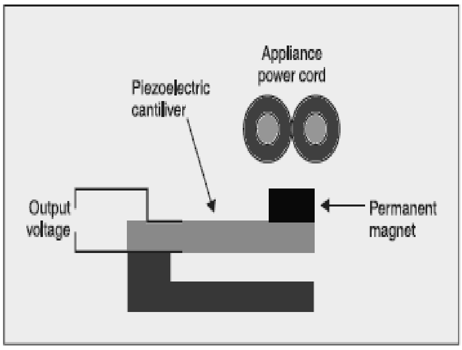

Figure 19: Schematic of the Current Sensor

RF Power Sensor

MEMS sensors measure the signal power by detecting the electrostatic force induced between an RF signal line and a suspended membrane using the capacitance principle.

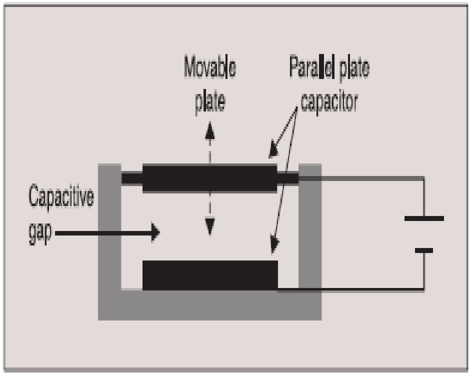

Figure 20: Schematic Diagram of a Capacitor with one Movable Plate

The required force for maintaining the movable capacitor plate (Figure 21) in a stationary position is proportional to the square of the root-mean-square (rms) signal voltage and, thus, to the signal power. Alternatively, measurement of the movable capacitor plate displacement gives the rms voltage amplitude of the ac signal.

CONCLUSIONS

This introduced the subject of MEMS sensing and recent advances in MEMS sensor technology in the domain of biomedical sensing. Bio-sensing and bio-inspired sensors are making an impact on biological development, innovation and progress in biomedical applications. MEMS sensing in the thermo-fluid and electro-magnetic domains is also the part of a discussion on advances in MEMS technology and presents their impact on technology innovation. MEMS sensing in the thermo-fluid and electro-magnetic domains is often advantageous to use mechanical sensors at the micro or nano scale rather than conventional macro-scale sensors. This addressed the recent advances in MEMS sensor technology and presented their impact in technological innovation and progress. MEMS has merged several fields of knowledge to create a micro-scale device by using today available IC fabrication technology.A variety of application scenarios and practical considerations related to these sensors are presented.

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