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A Study on Micro-Electro-Mechanical Systems (Mems) Sensors & Their Applications

Anil Kumar Sharma, Anuj Kumar Ojha

Abstract:- ***Continued demands for better control of the operating conditions of structures and processes have led to the need for better means of measuring temperature (T), pressure (P), and relative humidity (RH). One way to satisfy this need is to use MEMS technology to develop a sensor that will contain, in a single package, capabilities to simultaneously measure T, P, and RH of its environment. Because of the advantages of MEMS technology, which include small size, low power, very high precision, and low cost, it was selected for use in this paper. Although MEMS sensors that individually measure T, P, and RH exist, there are no sensors that combine all three measurements in a single package. In this paper we present overview of microelectromechanical system (MEMS) sensors and its application, is the technology of very small mechanical devices driven by electricity. The critical physical dimensions of MEMS devices can vary from well below one micron on the lower end of the dimensional spectrum, all the way to several millimeters, it merges at the nano-scale into nanoelectromechanical systems (NEMS) and nanotechnology. MEMS are also referred to as micromachines (in Japan), or micro systems technology – MST (in Europe).***

Index Terms:- ***IMOD, MEMS, MST, NEMS , RH ,SAM.***

I. INTRODUCTION

The term MEMS is an acronym of micro-electromechanical systems. A MEMS is constructed to achieve a certain engineering functions by electromechanical or electrochemical means. The core element in MEMS generally consists of two principal components: a sensing or actuating element and a signal transudation unit. Microsensors are built to sense the existence and the intensity of certain physical, chemical, or biological quantities, such as temperature, pressure, force, humidity, light, nuclear radiation, magnetic flux, and chemical composition. Microsensors have the advantage of being sensitive and accurate with minimal amount of required sample substance. A sensor is a device that converts one form of energy into another and provides the user with a usable energy output in response to a specific measurable input. Pressure, temperature, and humidity sensors are presented together with their particular applications. The processes for the fabrication of micro-electromechanical devices are follows:

- Bulk micromachining
- Surface micromachining
- LIGA (Lithographie, Galvanoformung, Abformung) micromachining.

II. HISTORICAL DEVELOPMENT OF MEMS

Over the past several decades MEMS researchers and developers have demonstrated an extremely large number of microsensors for almost every possible sensing modality including temperature, pressure, inertial forces, chemical species, magnetic fields, radiation, etc. Remarkably, many of these micromachined sensors have demonstrated performances exceeding those of their macroscale counterparts. That is, the micromachined version of, for example, a pressure transducer, usually outperforms a pressure sensor made using the most precise macroscale level machining techniques. Not only is the performance of MEMS devices exceptional, but their method of production leverages the same batch fabrication techniques used in the integrated circuit industry – which can translate into low per-device production costs, as well as many other benefits. Consequently, it is possible to not only achieve stellar device performance, but to do so at a relatively low cost level. Not surprisingly, silicon based discrete microsensors were quickly commercially exploited and the markets for these devices continue to grow at a rapid rate.

III. SCOPE OF MEMS SENSORS

More recently, the MEMS research and development community has demonstrated a number of microactuators including: microvalves for control of gas and liquid flows; optical switches and mirrors to redirect or modulate light beams; independently controlled micromirror arrays for displays, microresonators for a number of different applications, micropumps to develop positive fluid pressures, microflaps to modulate airstreams on airfoils, as well as many others. Surprisingly, even though these microactuators are extremely small, they frequently can cause effects at the macroscale level; that is, these tiny actuators can perform mechanical feats far larger than their size would imply. For example, as shown in figure1 researchers have placed small microactuators on the leading edge of airfoils of an aircraft and have been able to steer the aircraft using only these microminiaturized devices.

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Dr. Anil Kumar Sharma, Professor, Department of Electronics & Communication Engineering, Institute of Engineering & Technology, Alwar, Rajasthan, India (E-mail: aks_826@yahoo.co.in).

Anuj Kumar Ojha, M. Tech. Scholar, Department of Electronics & Communication Engineering, Institute of Engineering & Technology, Alwar, Rajasthan, India., (E-mail: ojha.anuj11@gmail.com).

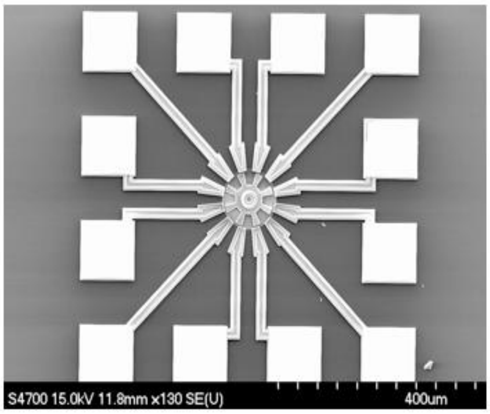

Fig.1 A surface micromachined lectro-statically-actuated micromotor

The real potential of MEMS starts to become fulfilled when these miniaturized sensors, actuators, and structures can all be merged onto a common silicon substrate along with integrated circuits (i.e., microelectronics). While the electronics are fabricated using integrated circuit (IC) process sequences (e.g., CMOS, Bipolar, or BICMOS processes), the micromechanical components are fabricated using compatible "micromachining" processes that selectively etch away parts of the silicon wafer or add new structural layers to form the mechanical and electromechanical devices. It is even more interesting if MEMS can be merged not only with microelectronics, but with other technologies such as photonics, nanotechnology, etc. This is sometimes called “heterogeneous integration.” Clearly, these technologies are filled with numerous commercial market opportunities. While more complex levels of integration are the future trend of MEMS technology, the present state-of-the-art is more modest and usually involves a single discrete microsensor, a single discrete microactuator, a single microsensor integrated with electronics, a multiplicity of essentially identical microsensors integrated with electronics, a single microactuator integrated with electronics, or a multiplicity of essentially identical microactuators integrated with electronics. Nevertheless, as MEMS fabrication methods advance, the promise is an enormous design freedom wherein any type of microsensor and any type of microactuator can be merged with microelectronics as well as photonics, nanotechnology, etc., onto a single substrate as shown in Fig.2. This vision of MEMS whereby microsensors, microactuators and microelectronics and other technologies, can be integrated onto a single microchip is expected to be one of the most important technological breakthroughs of the future. This will enable the development of smart products by augmenting the computational ability of microelectronics with the perception and control capabilities of microsensors and microactuators. Microelectronic integrated circuits can be thought of as the "brains" of a system and MEMS augments this decision-making capability with "eyes" and "arms", to allow microsystems to sense and control the environment. Sensors gather information from the environment through measuring mechanical, thermal, biological, chemical, optical, and magnetic phenomena.

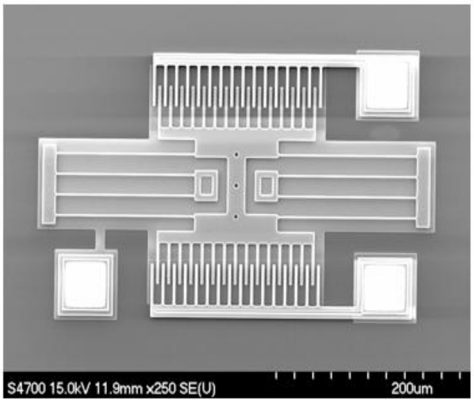

Fig.2 A surface micromachined resonator

The electronics then process the information derived from the sensors and through some decision making capability direct the actuators to respond by moving, positioning, regulating, pumping, and filtering, thereby controlling the environment for some desired outcome or purpose. Furthermore, because MEMS devices are manufactured using batch fabrication techniques, similar to ICs, unprecedented levels of functionality, reliability, and sophistication can be placed on a small silicon chip at a relatively low cost. MEMS technology is extremely diverse and fertile, both in its expected application areas, as well as in how the devices are designed and manufactured. Already, MEMS is revolutionizing many product categories by enabling complete systems-on-a-chip to be realized.

IV. TYPES OF MEMS SENSORS

A. Pressure sensors

Mechanical methods of measuring pressure have been known for centuries. The first pressure gauges used flexible elements as sensors. As pressure changed, the flexible element moved, and this motion was used to rotate a pointer in front of a dial. In these mechanical pressure sensors, a Bourdon tube, a diaphragm, or a bellows element detected the process pressure and caused a corresponding movement.

Bourdon tube: A bourdon tube is C-shaped and has an oval cross-section with one end of the tube connected to the process pressure. The other end is sealed and connected to the pointer or transmitter mechanism. To increase their sensitivity, Bourdon tube elements can be extended into spirals or helical coils. This increases their effective angular length and, therefore, increases the movement at their tip, which in turn increases the resolution of the transducer. Designs in the family of flexible pressure sensor elements also include the bellows and the diaphragms, Fig.3. Diaphragms are popular because they require less space and because the motion (or force) they produce is sufficient for operating electronic transducers. They also are available in a wide range of materials for corrosive service applications. After the 1920s, automatic control systems evolved in industry, and by the 1950s pressure transmitters and centralized control rooms were commonplace.

Therefore, the free end of a Bourdon tube (bellows or diaphragm) no longer had to be connected to a local pointer, but served to convert a process pressure into a transmitted (electrical or pneumatic) signal. At first, the mechanical linkage was connected to a pneumatic pressure transmitter, which usually generated a 3-15 psig output signal for transmission over distances of several hundred feet, or even farther with booster repeaters. Later, as solid-state electronics matured and transmission distances increased, pressure transmitters became electronic. The early designs generated dc voltage outputs: 10-50 mV, 0-100 mV, 1-5 V (Omega, 2003), but later were standardized as 4-20 mA dc current output signals.

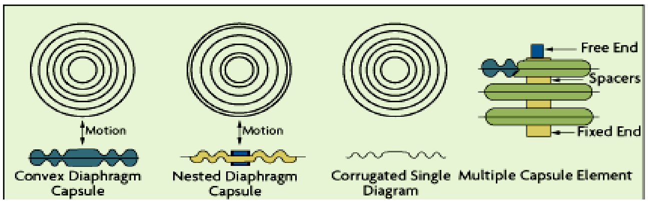

Fig. 3 Pressure sensor diaphragm

Because of the inherent limitations of mechanical motion-balance devices, first the force-balance and later the solid state pressure transducer were introduced.

Strain gauge pressure sensors: The first unbonded-wire strain gauges were introduced in the late 1930s. In this device, the wire filament is attached to a structure under strain, and the resistance in the strained wire is measured. This design was inherently unstable and could not maintain calibration. There also were problems with degradation of the bond between the wire filament and the diaphragm, and with hysteresis caused by thermoelastic strain in the wire. The search for improved pressure and strain sensors first resulted in the introduction of bonded thin-film and finally diffused semiconductor strain gauges. These were first developed for the automotive industry, but shortly thereafter moved into the general field of pressure measurement and transmission in all industrial and scientific applications. Semiconductor pressure sensors are sensitive, inexpensive, accurate, and repeatable. When a strain gauge, which is shown in Fig.4, is used to measure the deflection of an elastic diaphragm or Bourdon tube, it becomes a component in a pressure transducer. Strain gauge-type pressure transducers are widely used. Strain-gauge transducers are used for narrow-span pressure and for differential pressure measurements. Essentially, the strain gauge is used to measure the displacement of an elastic diaphragm due to a difference in pressure across the diaphragm. These devices can detect gauge pressure if the low pressure port is left open to the atmosphere, or differential pressure if connected to two process pressures. If the low pressure side is a sealed vacuum reference, the transmitter will act as an absolute pressure transmitter.

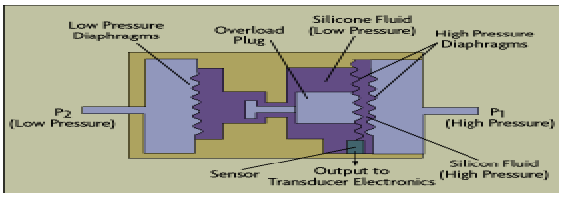

Fig. 4 Strain-gauge based pressure cell

Potentiometric pressure sensors: The potentiometric pressure sensor provides a simple method for obtaining an electronic output from a mechanical pressure gauge. The device consists of a precision potentiometer, whose wiper arm is mechanically linked to a Bourdon or bellows element. The movement of the wiper arm across the potentiometer converts the mechanically detected sensor deflection into a resistance measurement, using a Wheatstone bridge circuit Fig.5. The mechanical nature of the linkages connecting the wiper arm to the Bourdon tube, bellows, or diaphragm element introduces unavoidable errors into this type of measurement. Temperature effects cause additional errors because of the differences in thermal expansion coefficients of the metallic components of the system. Errors will also develop due to mechanical wear of the components and of the contacts. Potentiometric transducers can be made small and installed in very tight quarters, such as inside the housing of a 4.5-in. dial pressure gauge. They also provide an output that can be used without additional amplification. This permits them to be used in low power applications. They are also inexpensive. Potentiometric transducers can detect pressures between 5 and 10,000 psig (35 kPa to 70 MPa).

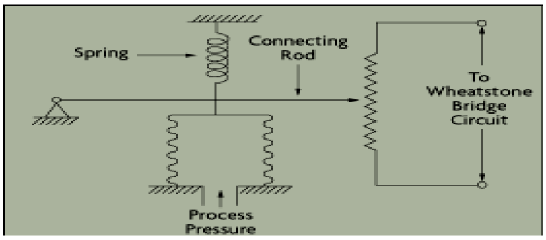

Fig 5. Potentiometric pressure transducer

Resonant-wire pressure sensors: The resonant-wire pressure transducer was introduced in the late 1970. In this design, Fig. 6 a wire is gripped by a static member at one end, and by the sensing diaphragm at the other. An oscillator circuit causes the wire to oscillate at its resonant frequency. A change in process pressure changes the wire tension, which in turn changes the resonant frequency of the wire. A digital counter circuit detects the shift. Because this change in frequency can be detected quite precisely, this type of transducer can be used for low differential pressure applications as well as to detect absolute and gauge pressures.

The most significant advantage of the resonant wire pressure transducer is that it generates an inherently digital signal, which can be sent directly to a stable crystal clock in a microprocessor. Limitations include sensitivity to temperature variation, a nonlinear output signal, and some sensitivity to shock and vibration. These limitations typically are minimized by using a microprocessor to compensate for nonlinearities as well as ambient and process temperature variations.

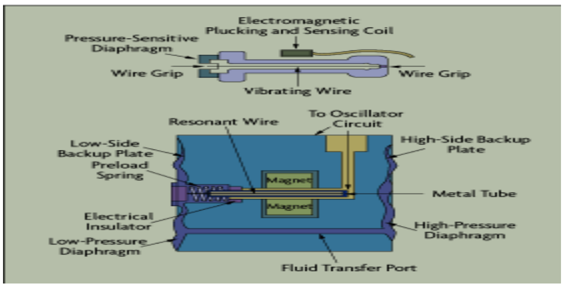

Fig.6 Resonant-wire pressure transducer

Capacitive pressure sensors: Capacitive pressure sensors use a thin diaphragm, usually metal or metal-coated quartz, as one plate of a capacitor. The diaphragm is exposed to the process pressure on one side and to a reference pressure on the other. Changes in pressure cause it to deflect and change the capacitance. The change may or may not be linear with pressure and is typically a few percent of the total capacitance. The capacitance can be monitored by using it to control the frequency of an oscillator or to vary the coupling of an AC signal. The schematic of a capacitive pressure sensor is shown in Fig.7 (Omega, 2003).

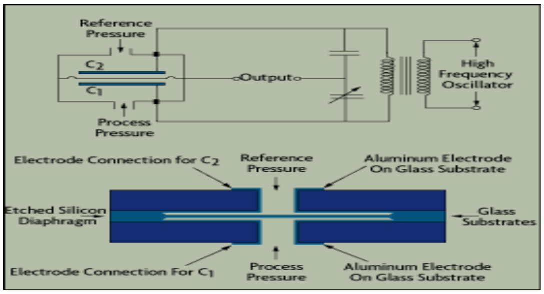

Fig.7 Capacitive pressure sensor.

Piezoresistive pressure sensors: The piezoresistive pressure sensor elements consist of a silicon chip with an etched diaphragm and, a glass base anodically bonded to the silicon at the wafer level. The front side of the chip contains four ion-implanted resistors in a Wheatstone bridge configuration. The resistors are located on the silicon membrane and metal paths provide electrical connections. When a pressure is applied, the membrane deflects, the piezoresistors change unbalancing the bridge. Then a voltage develops proportional to the applied pressure. Silicon piezoresitive sensors have been widely used for industrial and biomedical electronics. The piezoresitive sensors have excellent electrical and mechanical stability that can be fabricated in a very small size.

B. Humidity sensors

The need for environmental protection has led to expansion in sensor development. Humidity sensors have attracted a lot of attention in industrial and medical fields. The measurement and control of humidity is important in many areas including industry (paper, electronic), domestic environment (air conditioning), medicine (respiratory equipment), etc. Different methods are used for measurements humidity, e.g., changes in mechanical, optical, and electrical properties of the gas water vapor mixtures. Three types of humidity sensors are:

- Capacitive humidity sensor,
- Resistive humidity sensor,
- Thermal conductivity humidity sensor.

C. Capacitive humidity sensors

Capacitive relative humidity sensors are widely used in industrial, commercial, and weather telemetry applications. They consist of a substrate on which a thin film of polymer or metal oxide is deposited between two conductive electrodes. The sensing surface is coated with a porous metal electrode to protect it from contamination and exposure to condensation. The substrate is typically glass, ceramic, or silicon. The incremental change in the dielectric constant of a capacitive humidity sensor is nearly directly proportional to the relative humidity (RH) of the surrounding environment. The change in capacitance is typically 0.2–0.5 pF for a 1% RH change, while the bulk capacitance is between 100 and 500 pF at 50% RH and 25°C. Capacitive sensors are characterized by low temperature coefficient, ability to function at high temperatures (up to 200°C), full recovery from condensation, and reasonable resistance to chemical vapors. The response time ranges from 30 to 60 s for a 63% RH step change. State-of-the-art techniques for producing capacitive sensors take advantage of many of the principles used in semiconductor manufacturing to yield sensors with minimal long-term drift and hysteresis. Thin film capacitive sensors may include monolithic signal conditioning circuitry integrated onto the substrate.

The most widely used signal conditioner incorporates a Complementary Metal-Oxide Semiconductor (CMOS) timer to pulse the sensor and to produce a near-linear voltage output. The typical uncertainty of capacitive sensors is ±2% RH from 5% to 95% RH with two-point calibration. Capacitive sensors are limited by the distance the sensing element can be located from the signal conditioning circuitry, due to the capacitive effect of the connecting cable with respect to the relatively small capacitance changes of the sensor. Direct field repeatability can be a problem unless the sensor is laser trimmed to reduce variance to ±2% or a computer-based recalibration method is provided.

Resistive humidity sensors: Resistive humidity sensors measure the change in electrical impedance of a hygroscopic medium such as a conductive polymer, salt, or treated substrate. The impedance change is typically an inverse exponential relationship to humidity. Resistive sensors usually consist of noble metal electrodes either deposited on a substrate by photoresist techniques or wire-wound electrodes on a plastic or glass cylinder. The substrate is coated with a salt or conductive polymer. Alternatively, the substrate may be treated with activating chemicals such as acid. The sensor absorbs the water vapor and ionic functional groups are dissociated, resulting in an increase in electrical conductivity. The response time for most resistive sensors ranges from 10 to 30 seconds for a 63% (RH). The impedance range of typical resistive elements varies from 1 k to 100 M . Most resistive sensors use symmetrical AC excitation voltage with no DC bias to prevent polarization of the sensor. The resulting current flow is converted and rectified to a DC voltage signal for additional scaling, amplification, liberalization, or A/D reconversion. A distinct advantage of resistive RH sensors is their repeatability, usually within ±2% RH, which allows the electronic signal conditioning circuitry to be calibrated by a resistor at a fixed RH point. This eliminates the need for humidity calibration standards, so resistive humidity sensors are generally field replaceable. The accuracy of individual resistive humidity sensors may be confirmed by testing in an RH calibration chamber or by a computer-based data acquisition (DA) system referenced to standardized humidity controlled environment. Nominal operating temperature of resistive sensors ranges from –40°C to 100°C. In residential and commercial environments, the life expectancy of these sensors is greater than five years, but exposure to chemical vapors and other contaminants such as oil mist may lead to premature failure. Another drawback of some resistive sensors is their tendency to shift values when exposed to condensation if a water-soluble coating is used. Resistive humidity sensors have significant temperature dependencies when installed in an environment with large (>10°F) temperature fluctuations. Simultaneous temperature compensation is incorporated for accuracy. The small size, low cost interchangeability, and long-term stability make these resistive sensors suitable for use in control and display products for industrial, commercial, and residential applications. One of the first mass-produced humidity sensors was the Dunmore type, developed by NIST in the 1940s and still in use today. It consists of a dual winding of palladium wire on a plastic cylinder that is then coated with a mixture of polyvinyl alcohol (binder) and either lithium bromide (LiBr) or lithium chloride (Licl). Varying the concentration of LiBr or LiCl results in very high-resolution sensors that cover humidity spans of 20% to 40% RH. For a very low RH control function in the 1% to 2% RH range, accuracies of 0.1% can be achieved. Dunmore sensors are widely used in precision air conditioning controls to maintain the environment of computer rooms and as monitors for pressurized transmission lines, antennas, and wave-guides used in telecommunications. The latest development in resistive humidity sensors uses a ceramic coating to overcome limitations in environments where condensation occurs. The sensors consist of a ceramic substrate with noble metal electrodes deposited by a photoresist process. The substrate surface is coated with a conductive polymer/ceramic binder mixture, and the sensor is installed in a protective plastic housing with a dust filter. The binding material is a ceramic powder suspended in liquid form. After the surface is coated and air-dried, the sensors are heat treated. The process results in a clear non-water-soluble thick film coating that fully recovers from exposure to condensation. The manufacturing process yields sensors with a repeatability of better than 3% RH over the 15% to 95% RH range. The precision of these sensors is confirmed to ±2% RH by a computer-based DA system coupled to a standard reference. The recovery time from full condensation to 30% is a few minutes. When used with a signal conditioner, the sensor voltage output is directly proportional to the ambient relative humidity.

Thermal conductivity humidity sensors: Thermal conductivity humidity sensors measure the absolute humidity by quantifying the difference between the thermal conductivity of dry air and that of air containing water vapor. When air or gas is dry, it has a greater capacity to “sink” heat, as in a desert climate. A desert can be extremely hot in the day but at night the temperature rapidly drops due to the dry atmospheric conditions. By comparison, humid climates do not cool down so rapidly at night because heat is retained by water vapor in the atmosphere. Thermal conductivity humidity sensors (or absolute humidity sensors) consist of two matched negative temperature coefficient (NTC) thermistor elements in a bridge circuit; one is hermetically encapsulated in dry nitrogen and the other is exposed to the environment. When current is passed through the thermistors, resistive heating increases their temperature to >200°C. The heat dissipated from the sealed thermistor is greater than the exposed thermistor due to the difference in the thermal conductively of the water vapor as compared to dry nitrogen. Since the heat dissipated yields different operating temperatures, the difference in resistance of the thermistors is proportional to the absolute humidity. A simple resistor network provides a voltage output equal to the range of 0 to 14 mV at 60°C. Calibration is performed by placing the sensor in moisture-free air or nitrogen and adjusting the output to zero. Absolute humidity sensors are very durable, operate at temperatures up to 575°F (300°C) and are resistant to chemical vapors by virtue of the inert materials used for their construction, i.e., glass, semiconductor material for the thermistors, high-temperature plastics, or aluminum.

An interesting feature of thermal conductivity sensors is that they respond to any gas that has thermal properties different from those of dry nitrogen; this will affect the measurements. Absolute humidity sensors are commonly used in appliances such as clothes dryers and both microwave and steam-injection ovens. Industrial applications include kilns for drying wood; machinery for drying textiles, paper, and chemical solids; pharmaceutical production; cooking; and food dehydration. Since one of the by-product of combustion and fuel cell operation is water vapor, particular interest has been shown in using absolute humidity sensors to monitor the efficiency of those reactions. In general, absolute humidity sensors provide greater resolution at temperatures >200°F than do capacitive and resistive sensors, and may be used in applications where the other sensors would not survive. The typical accuracy of an absolute humidity sensor is ±3 g/m3; this corresponds to about ±5% RH at 40°C and ±0.5% RH at 100°C.

D. Temperature sensors

Measurement of temperature is critical in modern electronic devices, especially laptop computers and other portable devices with densely packed circuits, which dissipate considerable power in the form of heat. Knowledge of system temperature can also be used to effectively control battery charging as well as prevent damage to microprocessor.

V. APPLICATIONS

In one viewpoint MEMS applications are categorized in three types i.e. Sensor, Actuator and Structure. In another view point MEMS applications are categorized by the field of application as shown in Fig.8.

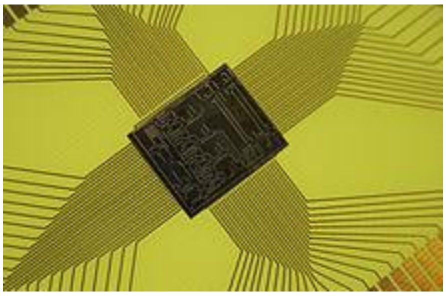

Fig. 8 Microelectromechanical systems chip

The commercial applications include:

- Inkjet printers, which use piezoelectrics or thermal bubble ejection to deposit ink on paper.
- Accelerometers in modern cars for a large number of purposes including airbag deployment in collisions.
- Accelerometers in consumer electronics devices such as game controllers (Nintendo Wii), personal media players / cell phones (Apple iPhone, various Nokia mobile phone models, various HTC PDA models) and a number of Digital Cameras (various Canon Digital IXUS models). Also used in PCs to park the hard disk head when free-fall is detected, to prevent damage and data loss.
- MEMS gyroscopes used in modern cars and other applications to detect yaw; e.g., to deploy a roll over bar or trigger dynamic stability control
- Silicon pressure sensors e.g., car tire pressure sensors, and disposable blood pressure sensors [9].
- Displays e.g., the DMD chip in a projector based on DLP technology, which has a surface with several hundred thousand micromirrors.
- Optical switching technology, which is used for switching technology and alignment for data communications.
- Bio-MEMS applications in medical and health related technologies from Lab-On-Chip to MicroTotalAnalysis (biosensor, chemosensor).
- Interferometric modulator display (IMOD) applications in consumer electronics (primarily displays for mobile devices), used to create interferometric modulation − reflective display technology as found in mirasol displays.
- Fluid acceleration such as for micro-cooling.
- Companies with strong MEMS programs come in many sizes. The larger firms specialize in manufacturing high volume inexpensive components or packaged solutions for end markets such as automobiles, biomedical, and electronics. The successful small firms provide value in innovative solutions and absorb the expense of custom fabrication with high sales margins. In addition, both large and small companies work in R&D to explore MEMS technology.

VI. CONCLUSION & FUTURE SCOPE

Each of the three basic microsystems technology processes we have seen, bulk micromachining, sacrificial surface micromachining, and micromolding/LIGA, employs a different set of capital and intellectual resources. MEMS manufacturing firms must choose which specific microsystems manufacturing techniques to invest in MEMS technology has the potential to change our daily lives as much as the computer has. However, the material needs of the MEMS field are at a preliminary stage. A thorough understanding of the properties of existing MEMS materials is just as important as the development of new MEMS materials. Future MEMS applications will be driven by processes enabling greater functionality through higher levels of electronic-mechanical integration and greater numbers of mechanical components working alone or together to enable a complex action. Future MEMS products will demand higher levels of electrical-mechanical integration and more intimate interaction with the physical world. The high up-front investment costs for large-volume commercialization of MEMS will likely limit the initial involvement to larger companies in the IC industry. Advancing from their success as sensors, MEMS products will be embedded in larger non-MEMS systems, such as printers, automobiles, and biomedical diagnostic equipment, and will enable new and improved systems.

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AUTHORS PROFILE

Dr. Anil Kumar Sharma, MIEEE received his M.E. in Electronics & Communication Engineering (ECE) from Birla Institute of Technology, Deemed University, Mesra, Ranchi, India, in 2007 with CGPA of 8.45 in a 10.00-point scale and Ph. D in ECE in 2011. He has an experience of 20 years on various RADARs and Communication Equipments. He is currently a Professor in the Department of ECE, Institute of Engineering & Technology, Alwar-301030, Rajasthan, India. He has published 13 papers in International Journals and 30 papers in Conferences. His research/teaching interest includes WSN, VLSI Design, RADARs and Soft Computing.

Anuj Kumar Ojha, has completed his B.Tech. in Electronics & Communication Engineering from Aligarh College of Engineering & Technology Aligarh (U.P.) affiliated to U.P.T.U., Lucknow in 2010 and Currently pursuing his dissertation work of M. Tech. in Digital Communication from I.E.T., Alwar, affiliated to RTU, Kota, Rajasthan, (India). His area of Interest is Digital Communication, Wireless Communication and MEMS Sensors.