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Anatomy of MEMS Capacitive Accelerometer

Shubham Kandekar[1], Tushar Chaudhari[2], Abhay Chopde[3], Yashwant Kapgate[4]
[1, 2, 3, 4]Department of Electronics Engineering, Vishwakarma Institute of Technology, Pune

Abstract: MEMS accelerometers are one of the important and also most applicable micro-electromechanical systems (MEMS). Accelerometers have multiple applications in industry and science. Highly sensitive accelerometers are components of inertial navigation systems for aircraft and missiles. The primary focus of this paper is entirely based on the sensing mechanism of the capacitive type accelerometer. Furthermore, the paper also describes the principle criteria for selecting an accelerometer based on the application. This paper gives special importance to the working principle of capacitive type accelerometer and its applications. The paper closes with quite extensively described fabrication of MEMS.

Keyword: MEMS, Sensitivity, Accelerometer, Fabrication,

I. INTRODUCTION

An accelerometer is an electromechanical device that measures acceleration forces may be static, like the constant force of gravity pulling at our feet, or they could be dynamic - caused by vibrating or moving the accelerometer. There are many accelerometers developed and reported in the literature. The vast majority is based on piezoelectric crystals, but they are too big and is difficult to handle. People tried to develop something tiny, that could evolve applicability and started searching in the field of microelectronics. They developed MEMS (micro electromechanical systems) accelerometers. In 1979 the first micromachined accelerometer was developed at Stanford University, but it took over 15 years before such devices became accepted mainstream products for large volume applications[1]. In the 1990s MEMS accelerometers revolutionized the automotive-airbag system industry. Since then they have enabled unique features and applications ranging from hard disk protection on laptops to game controllers. In recent times, the same sensor-core technology has become available in fully integrated, full-featured devices useful for industrial applications [2][3].

Micromachined accelerometers are a highly evolving technology with a huge commercial potential. They provide lower power, compact and robust sensing. Multiple sensors are often combined to provide multi-axis sensing and for getting more accurate data. They are the combination of semiconductor and microfabrication technologies using micromachine processing to integrate all the electronics, sensors, and mechanical elements onto a common silicon substrate. MEMS system are depends on the mechanical elements, sensing mechanism, and the ASIC or a microcontroller. This document presents an overview of MEMS accelerometer sensors and gyroscopes. We discuss the principles of their operation, their sensing mechanism, the growing variety of applications for them, and the profound impact they are already having on our daily lives [4].

II. MEMS AS INERTIAL SENSORS

MEMS sensors have many useful applications in measuring linear acceleration along one or several axis, or angular motion about one or several axis as an input to control a system (Figure 1).

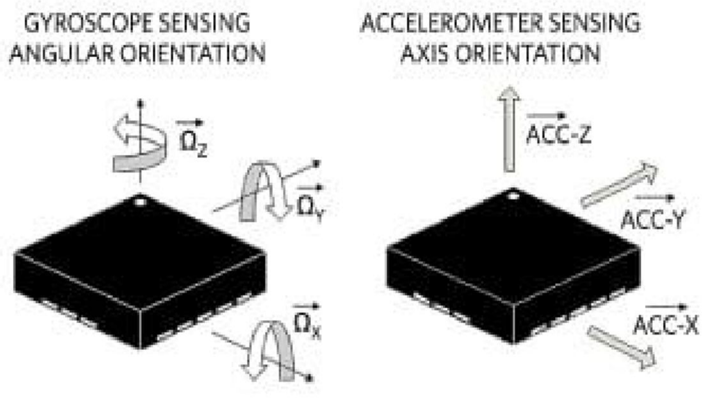


Figure 1. Angular versus linear motion.

All MEMS accelerometer sensors measure the displacement of a mass with a position measuring interface circuit. That measurement is then converted into a digital electrical signal through an analog-to-digital converter (ADC) for digital processing [4]. Gyroscopes are the devices which measure both the displacement of the resonating mass and its frame because of the Coriolis acceleration [5][23].

III. BASIC ACCELEROMETER OPERATION

According to Newton’s Second law of the acceleration (m/s2) of a body is directly proportional to, and in the same direction as, the net force (Newton) acting on the body, and inversely proportional to its mass (kilogram)[6][7].

$$\text{Acceleration (m/s2)} \quad = \quad \frac{\boldsymbol{Force(N)}}{\boldsymbol{Mass(Kg)}} \textbf{(Eq. 1)}$$

The important point to note that acceleration creates a force that is sensed by the force-detection mechanism of the accelerometer. So the accelerometer actually measures force, not acceleration; it basically measures acceleration indirectly through a force applied to one of the accelerometer's axes.

Using microfabrication technology an accelerometer is also an electromechanical device, including holes, cavities, springs, and channels, that is machined [5]. By using multilayer wafer process, measuring acceleration forces by detecting the displacement of the mass relative to fixed electrodes accelerometers are fabricated.

IV. THE ACCELEROMETER'S SENSING MECHANISM

An often used sensing approach used in accelerometers is capacitance sensing in which acceleration is related to change in the capacitance of a moving mass (Figure 2). This sensing technique is known for its high accuracy, stability, low power dissipation, and simple structure to build. It is not prone to noise and variation with temperature [6]. Bandwidth for a capacitive accelerometer is only a few hundred Hertz because of their physical geometry (spring) and the air trapped inside the IC that acts as a damper [8][19].

$$C \quad = \frac{\varepsilon 0 \ X \ \varepsilon r \ X \ A}{D}$$

ε0 = Permitted free space
εr = Relative material permitted between plates
A = Area of overlap between electrodes
D= Separation between the electrodes

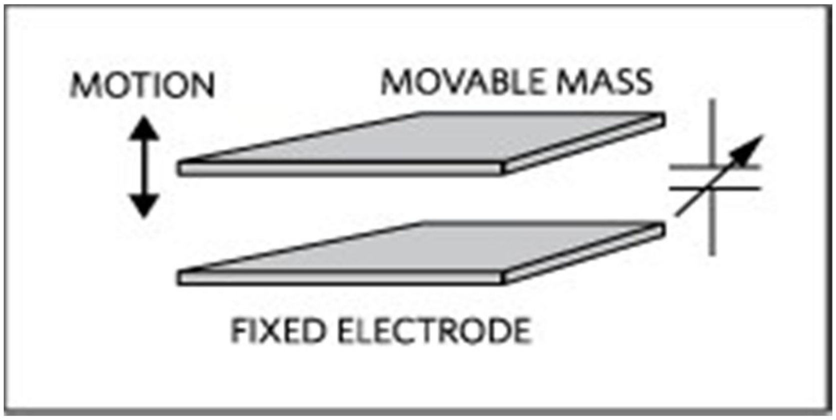


Figure 2. Moving mass and capacitance.

The capacitance can either be arranged as single-sided or a differential pair. Let’s look at accelerometers arranged as a differential pair (Figure 3). It is composed of a single movable mass (one planar surface), that is placed along with a mechanical spring between two, fixed, reference silicon substrates or electrodes (another planar surface) [7]. It is obvious that the movement of the mass (Motion x) is relative to the fixed electrodes (d1 and d2), and causes a change in capacitances (C1 and C2). By calculating the difference between C2 and C1 we can derive the displacement of our mass and its direction.

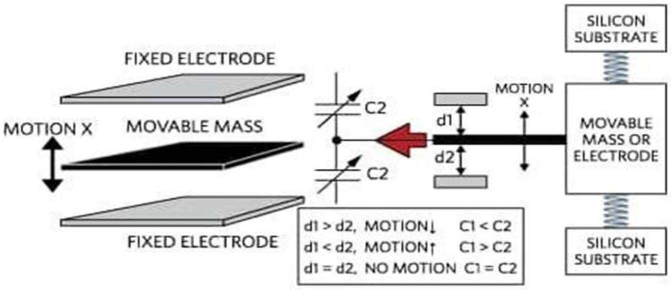


Figure 3. Acceleration associated with a single moving mass.

The displacement of the non-fixed mass (in micrometre) is kindle by acceleration, and it creates very minute change in capacitance for proper detection (Equation 1). This authorized for using multiple movable and set electrodes, all connected in a parallel layout[24]. This design enables a greater change in capacitance, which can both be detected more accurately, which ultimately makes capacitance sensing a more feasible technique [8].

Force causes a displacement of the mass which, in return, causes a change in capacitance. Now, placing multiple electrodes in parallel allows a larger capacitance, which will be more easily detected (Figure 4). V1 and V2 are electrical connections to each side of the capacitors and form a voltage-divider with the center point as the voltage of our mass [11][12].

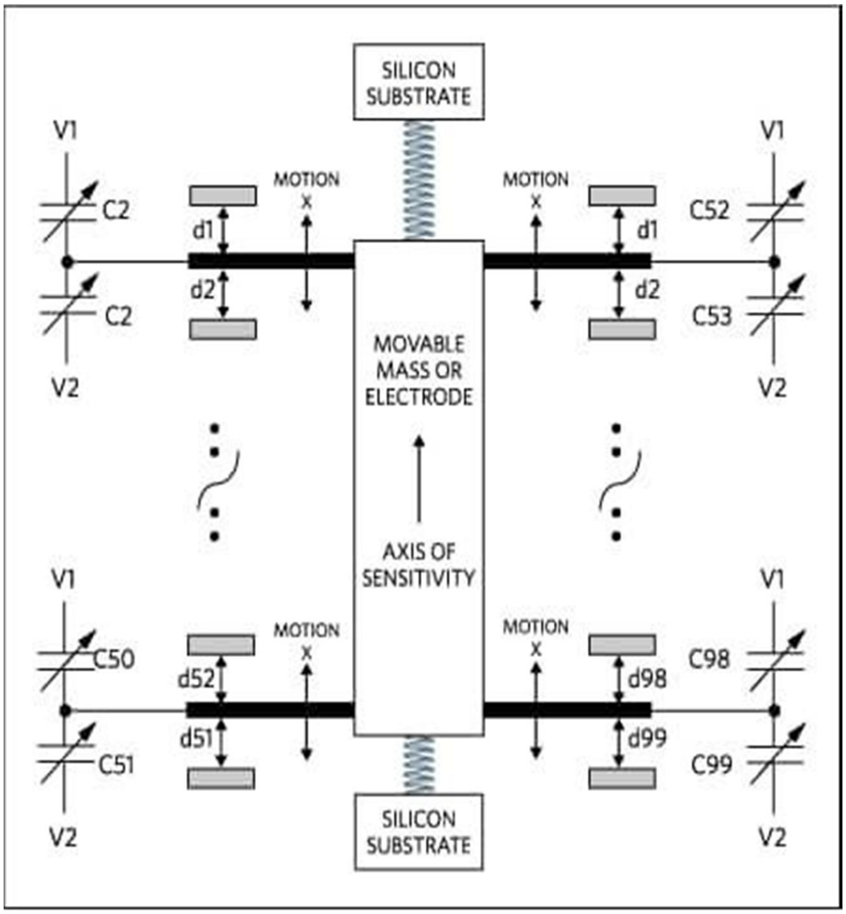


Figure 4. Acceleration associated with multiple moving masses.

The analog mass voltage will go through charge amplification, signal conditioning, demodulation, and lowpass filtering before it gets converted into a digital domain using a sigma-delta ADC. The ADC provide serial digital bit stream is passed to a FIFO (First in first out) buffer that converts the serial signal into a parallel data stream. That parallel data stream can then be transformed using a serial protocol like I2C or SPI which uses data line and clock before it is sent to the host for further processing (Figure 5).

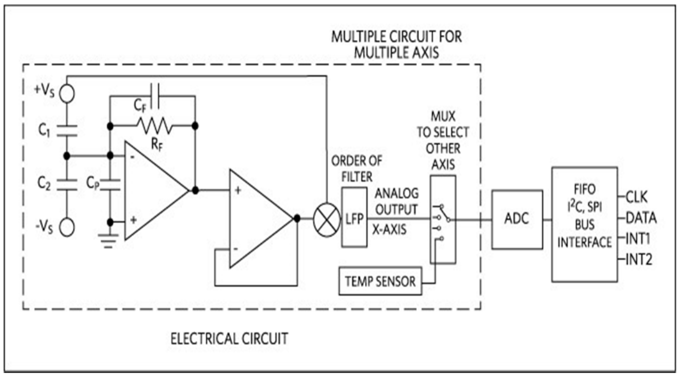


Figure 5. Electrical circuit of an accelerometer.

A sigma-delta ADC is well suited for accelerometer applications because of its low signal bandwidth and high resolution [13][14][15]. With an output value defined by its number of bits, a sigma-delta ADC can be translated into “g” units for an accelerometer application very easily. The “g” is a unit of acceleration equal to the earth’s gravity at sea level:

For example, if the X-axis reading of our 10-bit ADC is equal to 600 out of the available 1023 (210 - 1 = 1023), and with 3.3V as the reference, we can find the voltage for the X-axis specified in “g” with the following equation:

X voltage = (600×3.3)/1023=1.94V (Eq. 3) Each accelerometer has a zero-g voltage level that is the voltage that corresponds to 0g. First of all find the voltage shifts from 0-g voltage (specified in the data sheet and assumed to be 1.65V) as:

$$1.94V - 1.65V = 0.29V \qquad (Eq.\ 4)$$

Now, to do the final conversion we divide 0.29V by the accelerometer’s sensitivity (specified in the data sheet and assumed to be 0.475V/g):

$$0.29V/0.475V/g = 0.6g \qquad (Eq.\ 5)$$

V. A MULTI AXIS ACCELEROMETER

Let’s take another look at Figure 3 and add an actual manufactured accelerometer as shown in Figure 6. Now we can clearly relate each component of an accelerometer to its mechanical model [14][17].

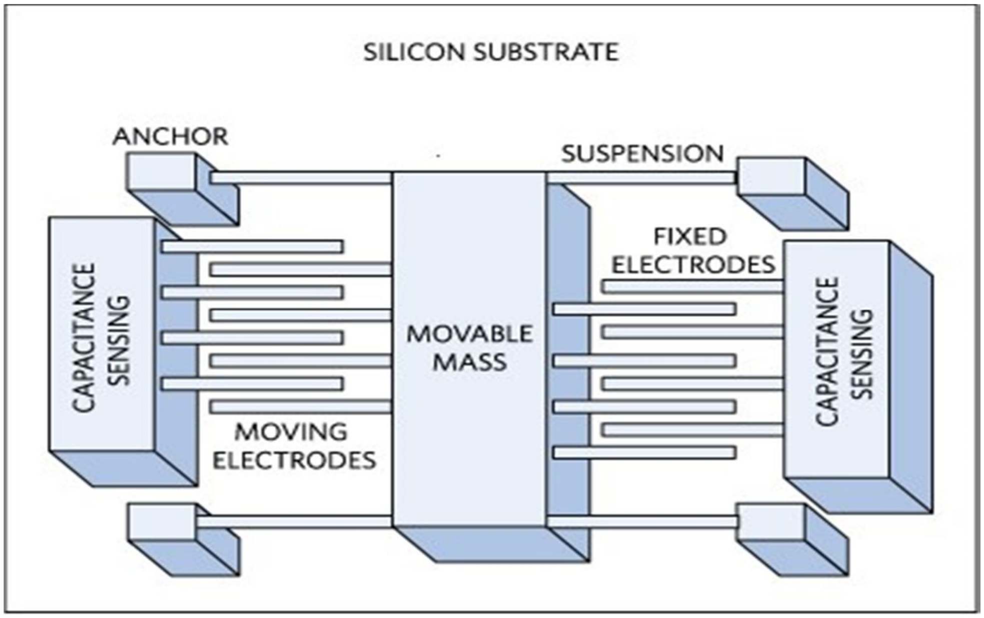


Figure 6. A mechanical model of an actual accelerometer.

By simply placing an accelerometer differently 90 degrees as shown in Figure 7, we can create a 2-axis accelerometer needed for more sophisticated applications.

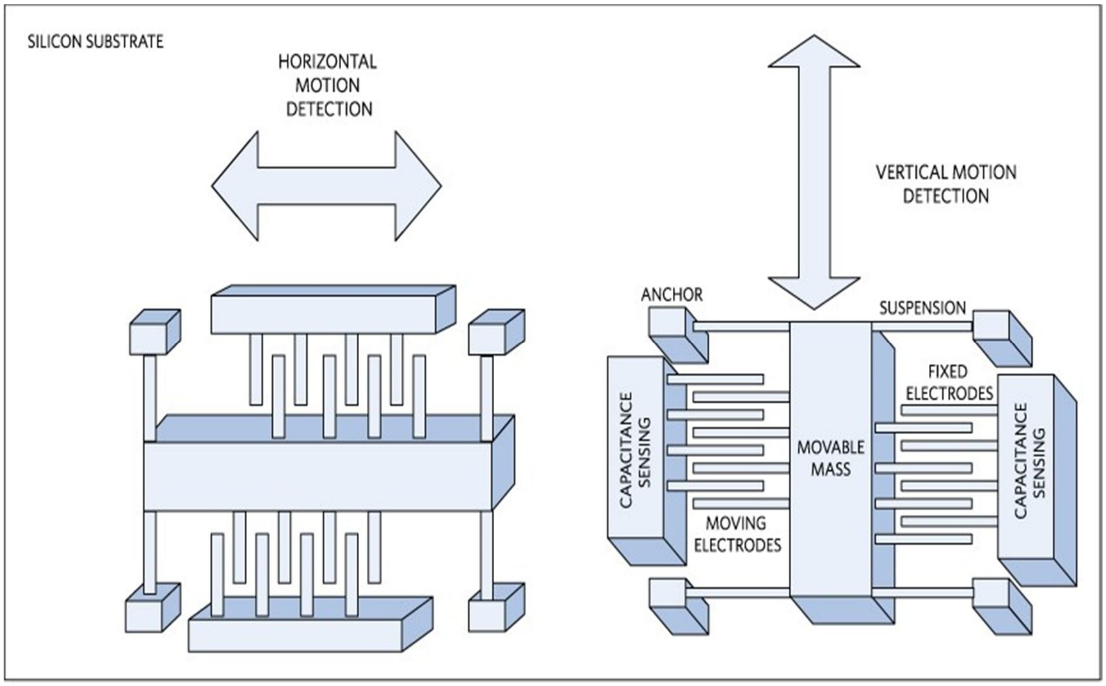


Figure 7. A 2-axis accelerometer.

There are two ways to construct a two-axis accelerometer: lay out the two different single-axis accelerometer sensors perpendicular to each other, or use a single mass with capacitive sensors arranged to measure movement along both axes.

A. *Selecting an Accelerometer*

For selecting an accelerometer for a specific application, it is important to consider some of the key characteristics such as:

1) *Bandwidth (Hz):* The bandwidth of a sensor indicates the range of vibration frequencies to which the accelerometer responds or how often a reliable reading can be taken. Humans are not able create body motion much beyond the range of 10Hz to12Hz [13]. For this reason, a bandwidth of 40Hz to 60Hz is adequate for sensing a tilt or human motion.
2) *Sensitivity (mV/g or LSB/g):* A measure of the minimum detectable signal or the change in output electrical signal per change in input mechanical change called as Sensitivity. This is valid in one frequency only.
3) *Voltage noise density (µg/SQRT Hz):* Voltage noise changes with the inverse square root of the bandwidth. Faster reading of accelerometer changes causes the worse accuracy. And as usual noise has a higher influence on the performance of the accelerometers when operating at lower g conditions with a smaller output signal[24].
4) *Zero-g voltage:* this term specifies the range of voltages that can be expected at the output under 0g of acceleration[17][4].
5) *Frequency response (Hz):* This is the frequency range specified with a tolerance band (±5%, etc) for which the sensor will detect motion and report a true output. At the allotted band tolerance lets the user calculate how much the device's sensitivity deviates from the reference sensitivity at any frequency within its specified frequency range.
6) *Dynamic range (g):* this is the range between the smallest detectable amplitude that the accelerometer can measure to the largest amplitude before distorting or clipping the output signal.

Micro-fabrication is the group of technologies used to manufacture structures with useful micrometric features. As these task can unfortunately not rely on the traditional fabrication techniques such as milling, drilling, turning, forging and casting because of the scale [12] . So that the fabrication techniques had to come from another source. As MEMS devices have about the same feature size as integrated circuits (IC), MEMS fabrication technology quickly took inspiration from microelectronics. Techniques like photolithography, thin film deposition by chemical vapor deposition (CVD) or physical vapor deposition (PVD), thin film growth by oxidation and epitaxy, doping by ion implantation or diffusion, wet etching, dry etching, etc. have all been adopted by the MEMS technologists. Moreover, MEMS also grounded many unique fabrication techniques that we will describe in this seminar like bulk micromachining, surface micromachining, deep reactive ion etching (DRIE), etc [2].

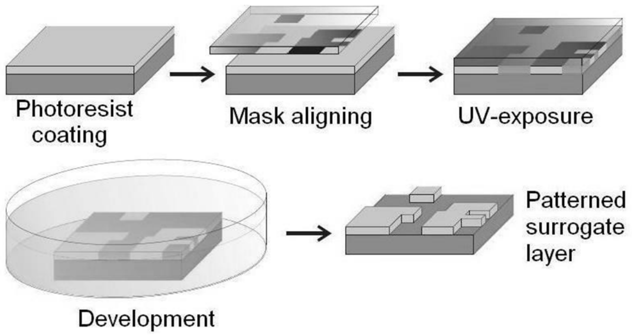


Figure 8.1; Photo-patterning.

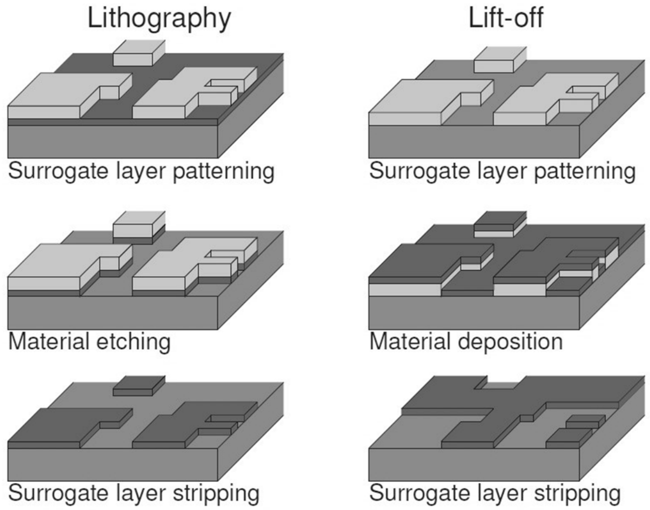
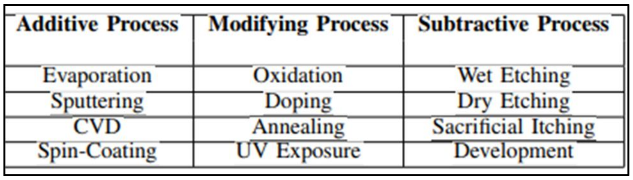


Figure 8.2: Pattern transfer by lithography and lift-off.

In general, MEMS fabrication tries to use combine process to benefit from the same economy of scale that is so successful in reducing the cost of ICs. As such, a typical fabrication process starts with a wafer (silicon, polymer, glass...) that may play an active role in the final device or may only be a substrate on which the MEMS is built[20].



Additive Process	Modifying Process	Subtractive Process
Evaporation	Oxidation	Wet Etching
Sputtering	Doping	Dry Etching
CVD	Annealing	Sacrificial Itching
Spin-Coating	UV Exposure	Development

Table 1: Process classification

The wafer is processed in a succession of processes as shown in (Table 1) that add, modify or remove materials along precise patterns. Additive process Modifying process Subtractive process Evaporation Oxidations Wet etching Sputtering Doping Dry etching CVD Annealing Sacrificial etching Spin-coating UV exposure Development .Table 1; Process classification[21]. We will explain some of them in this seminar. 9 The problem of patterning a material (or making layout) is generally split in two distinct steps: first, deposition and patterning of a surrogate layer that can be easily modified locally. In the most common process called photo-patterning, the surrogate layer used is a special polymer (called a photoresist) which is sensitive to UV-photon action (Figure 8.1). Figure 8.1; Photo-patterning. The photoresist is first coated on the substrate as a thin film. Then it is exposed to UV radiation through a mask. The mask has clear and opaque regions according to the desired pattern, the clear regions allowing the photoresist to be exposed to UV radiation and modifying it locally. After development the surrogate layer patterned over the whole surface of the wafer can be used for pattern transfer. Now we have to transfer the pattern to the material of interest. There are two main techniques that can be used to transfer the pattern: lithography and lift-off (Figure 8.2).Photolithography is the combination of photo patterning and lithography and is nowadays the most common techniques for micro-fabrication, lying at the roots of the IC revolution. This is how the basics of MEMS or at least patterned wafers, that will be used in further process, are made. Technologically very important and also quite expensive step in process is packaging. It can present even more than 50% of final product cost. Let's now look in detail at some materials and some processes or techniques that can be used during MEMS process. We already mentioned some above. Figure 8.2; Pattern transfer by lithography and lift-off [12][11]. In lithography the patterned layer allows exposing locally the underlying material and then the exposed material is then etched physically or chemically before the final removal of the protective layer. For lift-off, we deposit the material on top of the patterned layer. Complete removal of this layer (called a sacrificial layer) leaves the material only in the open regions of the pattern.

VI. MEMS ACCELEROMETERS – APPLICATIONS

A. Used in latest mobile phones and gaming joysticks as step counters, user interface control, and also for switching between different modes.
B. Used in mobile cameras for a tilt sensor so as to tag the orientation of photos taken.
C. To provide stability of images in camcorders and also to rotate the image to and fro when you turn the mobile.
D. As Nokia 5500 used a 3D accelerometer so as to provide easier tap and change feature by which you can change mp3's by tapping on the phone when it is lying inside the pocket.
E. Used to protect hard disk drives in laptops from getting damaged when the PC falls to the ground. The device senses the free fall and automatically switches off the hard disk.
F. Used in car crash airbag sensors, where it senses the sudden negative acceleration and determines the correct time to open the airbag.
G. Used in Practical applications like military monitoring, missile launching, projectiles, and so on.

VII. CONCLUSIONS

MEMS accelerometers exhibit many important characteristics that make them the sensor of choice for broadband single-sensor single source high-density 3D acquisition. The previous-generation MEMS sensors provided many successful examples of projects in which vertical resolution of the sections was increased because of broader frequency bandwidth. However, at low frequency and for deeper and weaker events, the improvement was not significant unless the survey was recorded with much higher trace density. Today, a new MEMS sensor generation has been developed that displays a significantly lower noise floor (at least –10 dB) and thus a higher dynamic range (+10 dB). Considering that MEMS sensor response is linear in the acceleration domain down to DC, there should be no attenuation and sufficient signal-to-noise ratio toward the low end of the spectrum. These are the ideal conditions to record low frequencies (down to 1 Hz) as emitted by heavy vibrators using low dwell sweeps.

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