

CHAPTER TWO

THEORETICAL BACKGROUND

2.1. Introduction to MEMS:

MEMS mean different things to different people. The acronym MEMS stands for micro-electromechanical systems and was coined in the United States in the late 1980s. Around the same time the Europeans were using the phrase Microsystems technology (MST). It could be argued that the former term refers to a physical entity, while the latter is a methodology. The word “system” is common to both, implying that there is some form of interconnection and combination of components. As an example, Microsystems might comprise the following:

- A sensor that inputs information into the system.
- An electronic circuit that conditions the sensor signal.
- An actuator that responds to the electrical signals generated within the circuit[1].

MEMS is a micrometer-sized device with three-dimensional (3-D) properties, namely sensors, pumps, and valves all capable of sensing and manipulating physical parameters. Some MEMS may not have any moving parts and can be made from plastic, glass, and dielectric materials. The operating principle of MEMS is based on high-frequency devices involving resonant structures and microelectronics. High-frequency elements involve resonating beam cantilevers, diaphragms, and other resonant structures. Production of MEMS devices involves micromachining and various specific processes such as deposition, etching, lithographic, and chemical. MEMS components can be manufactured using very large-scale integration (VLSI) processing techniques. MEMS fabrication involves a modified integrated circuit (IC) technology involving a stress-controlled polysilicon process[2].

In general, micro-electromechanical systems have features in the micrometer- and, increasingly, nanometer-size range. Often, they are miniaturized systems that combine sensors and actuators with high-performance embedded processors on a single integrated chip. The word electromechanical implies the transfer of technology from mechanical to electrical and vice versa. Those devices embedded in functional systems are sometimes referred to as Microsystems [3].

This field is increasingly leading to devices and material systems whose size is on the order of a nanometer, that is, the size of molecules. Microsystems and nanotechnology enable the building of very complex systems with high performance at a fraction of the cost and size of ordinary systems. As such, these systems are the enabling technology for today's explosive growth in computer, biomedical, communication, magnetic storage, transportation, and many other technologies and industries. Microsystems and nanotechnology challenges range from the deeply intellectual to the explicitly commercial. This field is by its very nature a link between academic research and commercial applications in the aforementioned and other disciplines. Indeed, these disciplines span a very broad range of industries that are at the forefront of current technological growth [3].

The MEMS structures and devices result from the sequence of design, simulation, fabrication, packaging, and testing. There are varieties of devices that can be classified as MEMS. There are passive devices, that is, nonmoving structures. There are devices that involve sensors and devices that involve actuators, which have micromechanical components. These are conceptually reciprocal in that sensors respond to the world and provide information and actuators use information to influence something in the world. Another class includes systems that integrate both sensors and actuators to provide some useful function. This classification, like most, is imperfect. For example, some devices that are dominantly sensors have actuators built into them for self-testing. Airbag triggers are an example. However, the framework provides a simple but quite comprehensive framework for considering MEMS devices[3].

Smart micro electromechanical systems (MEMS) refer to collections of micro-sensors and actuators which can sense their environments and have the ability to react to changes in such environments with the use of a micro- circuit control.

They include, in addition to conventional

microelectronics packaging, integrating antenna structures for command signals into micro-electromechanical structures for desired sensing and actuating functions [4].

These systems may also need micro-power supply, micro-relay and micro-signal processing units. Micro- components make the systems faster, more reliable, cheaper and capable of incorporating more complex functions[4].

2.2. Materials and Fabrication Techniques for MEMS:

2.2.1. Introduction:

MEMS devices and structures are fabricated using conventional integrated circuit process techniques, such as lithography, deposition, and etching, together with a broad range of specially developed micromachining techniques. Those techniques borrowed from the integrated circuit processing industry are essentially two dimensional, and control over parameters in the third dimension is only achieved by stacking a series of two-dimensional layers on the work piece, which is usually a silicon wafer. There are practical and economic limits, however, to the number of layers that can be managed in such a serial process, and therefore, the expansion of devices into the third dimension is restricted. Micromachining techniques enable structures to be extended further into the third dimension; however, it has to be understood that these structures are simply either extruded two-dimensional shapes or are governed by the crystalline properties of the material. True three-dimensional processing would allow any arbitrary curved surface to be formed, and this is clearly not possible with the current equipment and techniques. An important aspect of MEMS is to understand the limitations of the micromachining techniques currently available. Although the range of these

techniques is continually being expanded, there are some core techniques that have been part of the MEMS toolkit for many years [1].

2.2.2. Materials:

2.2.2.1 Substrates:

A- Silicon:

Just as silicon has dominated the integrated circuit industry, so too is it predominant in MEMS. There are a number of reasons for this: firstly is pure, cheap, and well- characterized material readily available; secondly a large number and variety of mature, easily accessible processing techniques; thirdly the potential for integration with control and signal processing circuitry. In addition to these reasons, the mechanical and physical properties of silicon give it a powerful advantage for its use in mechanical sensors, and therefore, this research deals mainly with device fabricated from two layer of silicon, that make actuation with each other [1].

B- Quartz and Glasses:

Quartz is mined naturally but is more commonly produced synthetically in large, long faceted crystals. Unlike silicon, however, this has not been extensively used as an advantage but has been identified more as a disadvantage due to the development of unwanted facets and poor edge definition after etching [1].

Glass can be etched in hydrofluoric acid solutions and is often electrostatic-ally bonded to silicon to make more complicated structures [1].

2.2.2.2 Additive Materials:

Materials used in MEMS mechanical sensors are: ceramics (e.g., alumina, which can be sputtered or deposited by a sol-gel process); polymers, such as polyimides and thick X-ray resists and photoresists; a host of other metals and metallic compounds (e.g., Au, Ni, ZnO) deposited either by PVD, electroplating, or CVD; and alloys (e.g., SnPb) deposited by cosputtering or electroplating [1].

2.2.3. Fabrication Techniques:

The fabrication techniques used in MEMS consist of the conventional techniques developed for integrated circuit processing and a variety of techniques developed specifically for MEMS. The three essential elements in conventional silicon processing are deposition, lithography, and etching. The common deposition processes, which include growth processes, are oxidation, chemical vapor deposition, epitaxy, physical vapor deposition, diffusion, and ion implantation. The types of lithography used are either optical or electron beam, and etching is done using either a wet or dry chemical etch process. Many of these conventional techniques have been modified for MEMS purposes, for example, the use of thick photoresists, grayscale lithography, or deep reactivation etching. Other processes and techniques not used in conventional integrated circuit fabrication have been developed specifically for MEMS, and these include surface micromachining, wafer bonding, thick-film screen printing, electroplating, porous silicon, LIGA (the German acronym for Lithographie, Galvansformung, Abformung), and focused ion beam etching and deposition[1].

2.3. MEMS Devices and Applications:

There are varieties of applications of MEMS. This section gives a brief overview of MEMS applications with reference to commercial devices. There are many fields in which MEMS devices have been introduced. Table (2.1) shows examples of MEMS applications [3].

Table (2.1) summarizes some of the applications of MEMS and shows the air bag accelerometer developed by Analog Devices in which the structure of the sensors is based on a variable-capacitor device [3].

Table(2.1):MEMS Devices and Applications.[3]

Pressure Sensors	Inertia Sensors	Optical Devices	Data Storage	RF-MEMS	Acoustic MEMS	Micro Fluidic	Chemical Sensors
Aeronautical	Air bag accelerometer	Optical beam steering	Hard disk component	Miniature antenna	Microphone	Micro-pumps	Polymer gas sensors
Blood pressure	Motion control sensors	Micro-lasers	Miniature read / write	RF-switch	Acoustic vibratos	Micro-valves, Micro-channels	Tin oxide gas sensors
Auto tire	Automobile suspension	Optical switch	Magnetic devices	Filters and resonators		Lab on chip	Preconcentrators
Touch pressure	Vibration sensor	Micro-mirrors	Optical storage	Inductors and capacitors		Ink bubble jet nozzle	Smart gas sensors

2.4. Actuators and Actuation:

An actuator is a device that converts energy from one form, such as electrical, mechanical, thermal, magnetic, chemical, and radiation energy, into the mechanical form. (For example, resistive heating elements convert electrical energy into bending of a bimorph microstructure.) In some cases, a micro-actuator may convert energy into intermediate forms before resulting in the final mechanical output (such as inductively coupled heating elements, which convert electrical energy first into magnetic energy before finally resulting in thermal energy serving to deflect a microelement) [5].

Actuation refers to the act of effecting or transmitting mechanical motion, forces, and work by a device or system on its surroundings, in response to the application of a bias voltage or current. A wide variety of actuation mechanisms have been researched in the MEMS field. These include electrostatic, piezoelectric, electromagnetic, shape memory alloy [(SMA), that is, materials which, upon experiencing deformation at a lower temperature, can return to their original unreformed shape when heated], and thermo-electromechanical [6].

As the MEMS field is relatively new, this question has perhaps only been answered in the affirmative in what pertains to one of the above mechanisms, namely, electrostatic. Indeed, it has been found that at microscopic scale sizes it is easier to produce electric fields. For example, electric fields exceeding 3.106 V/m , the coronal discharge of air, can be easily generated by applying low voltages across the micron-sized gaps encountered in micro-machined ICs. Moreover, even nature seems to be teaching us that electrostatic fields are best suited for producing actuation in small devices; muscular motion is the response to electrostatic forces [6].

2.4.1. Electrical Micro-actuators:

Electrical micro-actuators are by far the most common and diverse type of micro-actuator. This is primarily because of the ease with which most electrical micro-actuators can be produced using conventional micro-fabrication processes and materials. Examples of electric micro-actuators include static, resonant, rotary, and stepper-motor configurations. Electrical micro-actuators can be driven by an electrical-to-mechanical conversion that makes use either of the direct electrostatic forces between charged objects or a piezoelectric material that can mediate the energy transformation. Electrostatic and piezoelectric transduction mechanisms, the physical relationships involved, the material properties that govern their operation [5].

2.4.2. Electrostatic Actuation:

Electrostriction is the phenomenon of mechanical deformation of a material due to an applied electric field. This is a fundamental phenomenon which is present to varying degrees in all materials and occurs due to the presence of polarizable atoms and molecules. An applied electric field can distort the charge distribution within the material, resulting in modifications to bond length, bond angle or electron distribution functions, which in turn affects by the macroscopic dimensions of the material[4].

Electrostatic transduction is the most common actuation and sensing method in MEMS because of its simplicity and high efficiency. Two of the classical successful MEMS devices have been relying on this method: the Analog Devices accelerometers for airbag deployments, which use capacitive detection to sense the motion, and the micro-mirror in the digital mirror display DMD for projection displays by Texas Instruments, which relies on electrostatic actuation. Other examples of micro devices employing this method include microphones, pressure sensors, temperature sensors, RF switches, band-pass filters, and resonators. MEMS devices utilizing electrostatic transduction are also called electrostatic MEMS [7].

Electrostatic transduction relies on simple capacitors of parallel plate electrodes. These can be easily fabricated using surface micromachining. Electrostatic transduction does not require any special material, such as piezoelectric materials, deposition of any patches, such as piezoresistors, or any external field sources, such as electromagnetic transduction. It only requires a voltage source, which is readily available on most IC and electronics circuits. Also, it is characterized by very low power consumption. Power dissipation requires passing a current in a circuit beside the voltage source. A parallel-plate capacitor is an open-circuit component that does not typically pass a current. In the case of an AC or variable voltage, a small amount of current is induced in the capacitor circuit, which is proportional to the rate of change of the voltage.

Electrostatic actuation depends on the attractive force between the two plates of a capacitor to generate a force or displacement. Electrostatic actuation offers high energy density, high mechanical flexibility, and well controlled force. Also, it is considered fast actuation method, compared for instance to electro-thermal actuation, since the time constant for charging a capacitor is small. In electrostatic or capacitive sensing, a physical quantity, such as pressure or acceleration, changes the capacitance values of the parallel-plate capacitor. Using an electronic circuitry, this change is related to the physical quantity being measured. The main

disadvantage of electrostatic actuation and detection is their nonlinearity, especially for out-of-plane capacitors. This limits the controlled travel range of actuators and can result in un-expected collapse, short circuit, stiction, and functional failure of sensors. Also, the large driving voltage for actuation applications, such as in RF switches, is another limitation.

The most common forms of electrostatic sensing and actuation are based on either simple parallel-plate capacitors or comb-drive configuration of multiple interdigitated or non-interdigitated fingers. Because these depend somehow on the electrostatic forces generated between parallel electrodes[7].

Conventional mechanical actuators are rarely driven by an electrostatic force because the force is usually too small to displace or lift mechanical parts unless the voltage used is extremely high. With the miniaturization of mechanical structures, the electrostatic force becomes relatively large. Therefore, electrostatic driving has found wide applications in micro mechanical actuators [8].

The electrostatic force in micro mechanical systems has the following features, which are very important for the analysis and design of the devices, or, in some cases, they are explored for novel applications:

- For microstructures, the electrostatic force is comparable with the elastic force of the mechanical structure and the damping force of the surrounding air. Therefore, all the forces must be considered simultaneously in many cases.
- The electrostatic force is nonlinear with the distance. The joint action of the electrostatic force and the elastic force could cause severe nonlinearity or instability problems.
- As the distances between mechanical parts and the dimensions of the mechanical structures are quite close, the fringe effects of the electrostatic force have to be considered in many cases [8].

2.4.2.1 Electrostatic Gaps:

Micromechanical devices are at such a small scale that the electro-mechanical effects are quasistatic; that is, the behavior at any instant in time is accurately found from static electric field solutions. Electrostatic elements within a Microsystems always assume a dual role as actuators and sensors, although usually only one role is intended. Electrostatic elements are referred to as actuators in most of this discussion. Actuators may be made from two or more electrodes; however, only two electrodes are intentionally used in most designs. The charge on an electrode in a system with n electrodes is related to the voltages on the electrodes by Eq. (2.1):[5].

$$q_k = \sum_{l=1}^{n-1} C_{kl} V_l \quad \text{Eq. (2.1)}$$

C_{kl} are coefficients of the capacitance matrix, and the voltage reference is taken as the n th electrode. Off-diagonal terms have negative values because a positive voltage on one electrode creates negative charge on another electrode. A time-varying charge on an actuator electrode gives rise to a displacement current. Eq. (2.2)[5].

$$i_k = \frac{dq_k}{dt} = \sum_{l=1}^{n-1} \left(C_{kl} \frac{dV_l}{dt} + V_l \frac{dC_{kl}}{dt} \right) \quad \text{Eq. (2.2)}$$

Electronic detection of this current is the basis for capacitive motion sensing. The first term in the summand is the electrical displacement current arising from time-varying voltage across electrodes, and is proportional to displacement for small motions. The second term is the mechanical displacement current arising from time-varying capacitance of movable micromechanical electrodes and is proportional to velocity for small motions. The predominant term depends on the nature of the applied voltages and electrodes. The electrical displacement current is zero for DC applied voltage and increases with the frequency of the voltage.

The mechanical displacement current is zero for static electrodes and increases with the frequency of the mechanical displacement.

Electrostatic force, F_e , acting in an arbitrary direction x , is found from conservation of energy Eq. (2.3):[5].

$$\frac{dU_e}{dt} = \sum_{k=1}^{n-1} \left(V_k \frac{dq_k}{dt} - F_e \frac{dx}{dt} \right) \text{Eq. (2.3)}$$

where the total change in stored energy, U_e , in the system is equal to the electrical power into each electrode pair less the rate of mechanical work done by the system. The stored energy is expressed in terms of electrode charge and displacement in the system; however, electrode charge is rarely used to control electrostatic force in practical micro-systems [5].

2.4.2.2 Parallel-Plate Capacitor:

Consider a parallel-plate capacitor, in which the plates are rigid and constrained from moving, as shown in Figure (2.1).

Parallel-plate capacitor as an actuator. (V) is the applied voltage, (d) is the plate separation, (t) its thickness, and (ϵ) is the permittivity of the volume between the plates.

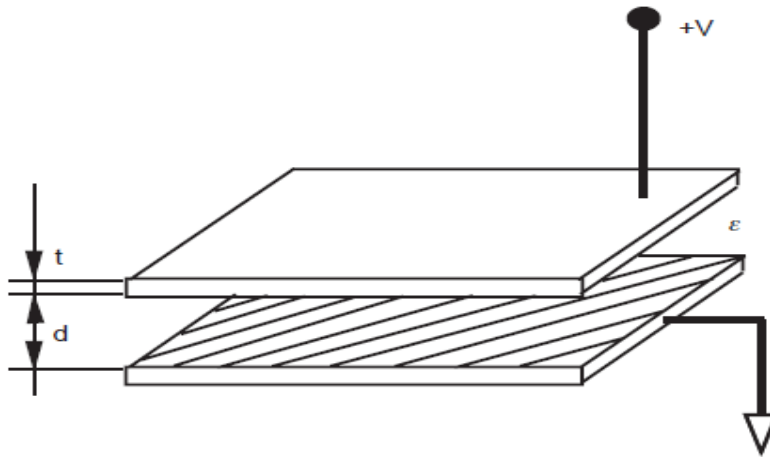


Figure (2.1): parallel-plate capacitor[6].

Assuming the area of the plates is much greater than the separation between them (i.e., ignoring the fringing fields), its capacitance is given by Eq.(2.4):[6].

$$C = \frac{\epsilon A}{d} \text{ Eq. (2.4)}$$

where (ϵ) denotes the dielectric permittivity of the medium between the plates, (d) represents the distance separating the plates, and (A) represents the area of the plates. Corresponding to a voltage (V) applied to the capacitor there exists an electrostatic potential energy, given by Eq. (2.5), stored in the volume between the plates [6].

$$U = \frac{1}{2} CV^2 \text{ Eq.(2.5)}$$

This potential energy represents the energy required to prevent the oppositely charged parallel plates from collapsing into each other as a result of the coulomb force of attraction Eq. (2.6):[6].

$$F = \frac{1}{4\pi\epsilon} \frac{q_T q_B}{d^2} \text{ Eq. (2.6)}$$

Where q_B and q_T are the equal but opposite charges in the bottom and top plates respectively. Alternatively, this force may also be expressed as the negative of the gradient in the potential energy between the parallel plates Eq. (2.7)[6].

$$F = -\nabla U \text{ Eq. (2.7)}$$

Substituting Eq. (2.4) into Eq. (2.5), we obtain Eq. (2.8):[6].

$$U = \frac{\epsilon AV^2}{2d} \text{ Eq. (2.8)}$$

Now substitution of Eq. (2.8) into Eq. (2.7) yields Eq. (2.9):[6].

$$F = \frac{\epsilon AV^2}{2d^2} \text{ Eq. (2.9)}$$

This equation quantifies the force that must be applied on the top plate in order to prevent it from collapsing on the bottom plate if the top plate were freed. It

expresses that this force increases linearly with area, quadratic-ally with voltage, and decreases quadratic-ally with the separation between plates.

If we lift the condition that the top plate be rigid, and assume that it is anchored at only one of its four sides, the top plate may be considered as a beam, namely, a cantilever beam, as shown in Figure (2.1). Then, in response to an applied voltage V , the top plate will deflect with zero deflection at the anchoring juncture, to a maximum deflection at the tip of the beam.

As easily deduced from Figure(2.1), by controlling the state of deflection of the beam, switching may be effected. The fundamental physics characterizing electrostatic actuation is embodied in the relationship between the deflection and the applied voltage causing it.

Peterson obtained an approximate deflection-voltage relationship by modeling the cantilever beam as a parallel-plate capacitor whose top plate experiences a distributed force, as shown in Figure (2.3). As this force varies along the length of the beam, the inter-electrode gap (d) becomes a function of the length. Taking this gap variation into account in Eq. (2.9), the electrostatic force exerted on the beam at a point (x) due to the electrostatic potential is given by Eq. (2.10):[6]

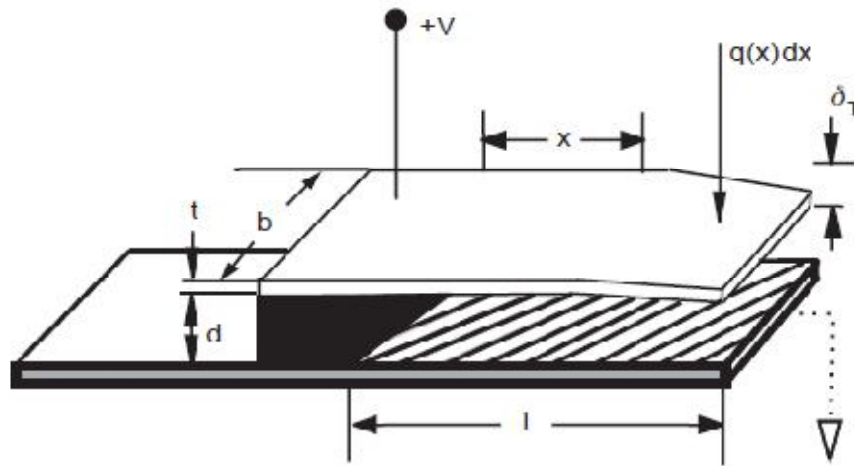


Figure (2.2): Cantilever Beam[6].

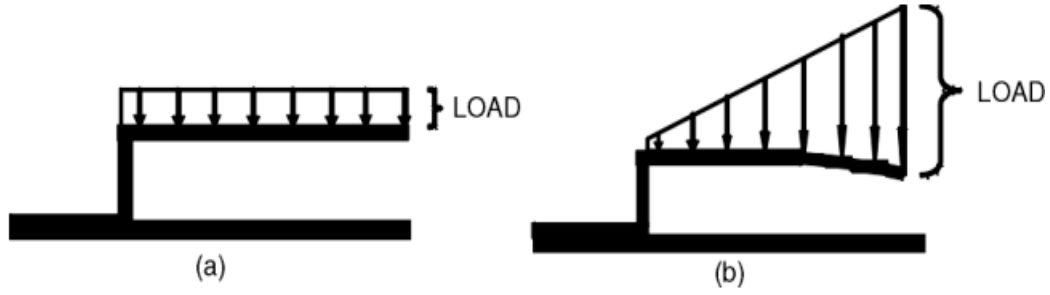


Figure (2.3): cantilever beam as a parallel-plate capacitor whose top plate experiences a distributed force[6].

$$F = \frac{\epsilon AV^2}{2(d-\delta(x))^2} \text{Eq. (2.10)}$$

As one would expect, the beam deflection $\delta(x)$ resulting from a given electrostatic force is a function of the structural and material properties of the beam, as given by its Young's modulus, (E), and its moment of inertia, (I). In particular, a concentrated load at a position(x) on a cantilever beam results in a deflection at the beam tip given by Eq. (2.11): [6].

$$\delta_T = \left[\frac{x^2}{6EI} \right] (3L - x) b q(x) dx \text{ Eq. (2.11)}$$

$$q(x) = \frac{\epsilon}{2} \left(\frac{V}{d-\delta(x)} \right)^2 \text{Eq. (2.12)}$$

where (b) is the beam width and The forces are distributed along the length of the beam , and the deflection at the tip is found by integrating Eq. (2.12) from $x = 0$ to $x = L$, Eq. (2.13):[6].

$$\delta_T = \int_0^L \frac{3L-x}{6EI} x^2 q(x) d(x) \text{Eq. (2.13)}$$

Petersen assumed that the beam deflection at any point x along the beam could be approximated by a square-law dependence, namely Eq. (2.14): [6].

$$\delta(x) = \left(\frac{x}{L}\right)^2 \delta_T \quad \text{Eq. (2.14)}$$

2.5. The Cantilever Beam MEMS Resonator:

Silicon-based micro-machined electromechanical resonators with quality factors in the thousands and frequencies in the gigahertz range have become a reality. Micro-electromechanical resonators are small in size, consume no power, have quartz-like characteristics and can be integrated in silicon for a variety of signal processing applications such as on-chip frequency references, band pass filters and micro-sensors. Ultra-narrow bandwidth filtering can be achieved through strategic coupling of individual high-Q resonators [9].

To build a micro-machined structure with high resonant frequency, the mass must be further reduced. Beam resonators have been studied extensively at the University of Michigan, Ann Arbor, for this purpose, and Discera, Inc., of Ann Arbor, Michigan, is commercializing them for reference frequency oscillators to replace quartz crystals in cellular phones. The advantages include a much smaller size, the ability to build several different frequency references on a single chip, higher resonant frequencies, more linear frequency variation with temperature over a wide range, and the ability to integrate circuitry, either on the same chip or on a circuit chip bonded to the MEM chip, all at a lower cost than the traditional technology [10].

2.5.1. Cantilever Beam Design Requirements:

Cantilever beam design requires a comprehensive review of various dimensional parameters and potential shapes of the cantilever, which will lead to a design with high mechanical integrity and stable RF performance. It is important to mention that a cantilever beam is subjected to a combined actuation loading and interface adhesion force. Such actuation loading and interface adhesion force are

strictly dependent on the cantilever beam shape, crack length, air gap, support post height, and overlap section of the beam. The beam deflection profiles are strictly dependent on crack length s ($L - d$), applied force (F_a) or external force, contact zone length (d), interfacial energy of adhesion (joules per square meter), and region of interfacial adhesion forces ($0 \leq x \leq a$, where (a) represents the actuation pad length and the parameter (x) varies from 0 to crack length (s)) [2].

2.5.2 Electrostatic Coupling of MEMS Resonators:

Electrical coupling of MEM resonators can be accomplished without using distinct coupling elements. In the electrostatic coupling approach, an electrostatic force between the resonating bodies of two closely spaced micro-resonators causes coupling and results in a higher order resonant system, without the need for any physical coupling element [9].

2.5.3 Resonator Specifications:

Ideally, resonators are devices that vibrate at a specific frequency with negligible energy loss. In particular, it is desirable for a resonator to maintain its frequency of vibration despite changes in temperature, loading conditions, and age. The degree of stability exhibited by a resonator is given by its electrical parameters:

1. Center frequency; is the frequency of resonance of the first mode.
2. Quality factor (Q) is defined as in Eq. (2.16):[6].

$$Q = 2\pi \frac{\text{Energy stored during a cycle}}{\text{Energy lost during the cycle}} \quad \text{Eq. (2.16)}$$

It is proportional to the decay time, and inversely proportional to the bandwidth around resonance. The higher the Q , the higher the frequency stability and accuracy capability of the resonator.

3. Temperature stability [6].

2.6. ANSYS

Is a commercial FEA software with the capability to analyze a wide range of different problems. ANSYS runs under a variety of environments, including IRIX, Solaris, and Windows NT. Like any Finite-element software, ANSYS solves governing differential equations by breaking the problem into small elements. The governing equations of elasticity, fluid flow, heat transfer, and electro-magnetism can all be solved by the FEM in ANSYS.

ANSYS is available on all ME net Sun and SGI machines. It is available on the Linux machines by remote-login only. ANSYS provide simulation of the coupled systems which combined two or more fields.