# content

MEMS

## 1. What is MEMS?

Micro-Electro-Mechanical Systems (MEMS) is the integration of mechanical elements, sensors, actuators, and electronics on a common silicon substrate through microfabrication technology. 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.[1]

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. 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. Because MEMS devices are manufactured using batch fabrication techniques similar to those used for integrated circuits, unprecedented levels of functionality, reliability, and sophistication can be placed on a small silicon chip at a relatively low cost.[2]

## 2. Scaling of mechanical systems

As the scale, or size, of a system changes by several orders or magnitude, the system tends to behave differently. Consider for example, a glass of water that is about 5cm on a side. Pour the glass of water onto a table, and notice how the water flows and runs off the edge of the table. If the size of the glass is decreased by two orders of magnitude, or a factor 100, the glass is now 0.05cm on a side. Pour this glass onto the table, and set that the surface tension pulls the water into a drop that stick to the table. Turn on the table on its side, and observe that it is difficult to make the drop flow to the edge of the table. In each case, the substance is the same, water, and it is the same table, but changing the scale size makes the water behave very differently. Different physical effects manifest themselves differently because of the system size.
As the size of a system changes, the physical parameters change, often in a dramatic way. To understand how these parameters change, consider the scale factor S. This scale factor is similar to the small notation on the corner of a mechanical drawing which might say the scale of the drawing is 1:10. The actual object to be made is 10 times the size of the drawing. In the micro domain, the scale might be 100:1, meaning the object is 100 times smaller than the drawing. When the scale size changes, all the dimensions of the object change by exactly the same amount S such that 1:S.
Volume is an example of a parameter that scales as $S^3$. The force due to surface tension scale as $S^1$, the force due to electrostatics scale as $S^2$, the force due to certain magnetic

forces scale as $S^3$, and gravitation forces scale as $S^4$.Now, if the size of the system decreases from a meter to a millimeter, this is a decrease in size of a thousand, S=1/1000. The surface tension force decreases by a factor of a thousand, $S^1=(1/1000)^1$; the electrostatic force decreases by a factor of a million, $S^2=(1/1000)^2=1/1000000$; the magnetic force decreases by a factor of a billion and the gravitational force decreases by a factor of a trillion. Indeed, changing the size of a mechanical system changes what forces are important.

How do the acceleration and transit times change for the different force scaling laws? Acceleration *a* is equal to force *F* divided by the mass m:

$$a = \frac{F}{m} = F \cdot m^{-1}$$

And we know the mass scales as $S^3$, and $m^{-1}$ scales as $S^{-3}$, giving:

$$a = \begin{bmatrix} S^1 \\ S^2 \\ S^3 \\ S^4 \end{bmatrix} \begin{bmatrix} S^3 \\ S^3 \\ S^3 \\ S^3 \end{bmatrix}^{-1} = \begin{bmatrix} S^1 \\ S^2 \\ S^3 \\ S^4 \end{bmatrix} \begin{bmatrix} S^{-3} \\ S^{-3} \\ S^{-3} \\ S^{-3} \end{bmatrix} = \begin{bmatrix} S^{-2} \\ S^{-1} \\ S^0 \\ S^1 \end{bmatrix}$$

As the system becomes smaller, the acceleration increases. In general, small systems tend to accelerate.

It is useful to understand how different forces scale. A more complete listing of forces and their scaling is given below,

$$F = \begin{bmatrix} S^1 \\ S^2 \\ S^3 \\ S^4 \end{bmatrix} = \begin{bmatrix} \text{Surface tension} \\ \text{Electrostatic, Pressure, Biological, Magnetic } (J = S^{-1}) \\ \text{Magnetic } (J = S^{-0.5}) \\ \text{Gravitational, Magnetic } (J = S^0) \end{bmatrix}$$

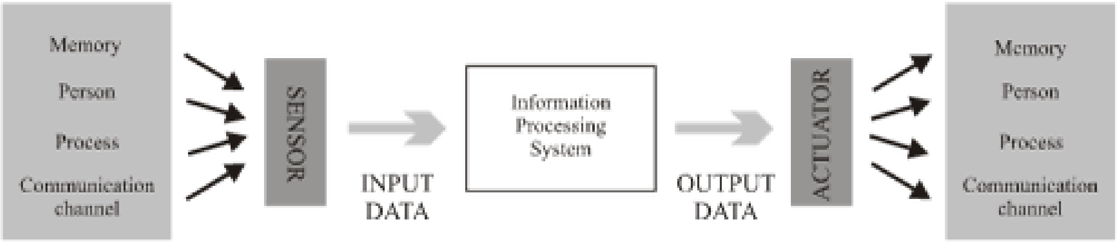
## 3. Flow Physics

Fluid flows in small devices differ from those in macroscopic machines. The operation of MEMS-based ducts, nozzles, valves, bearing, turbomachines, etc. cannot always be predicted from conventional flow models. Many questions have been raised when the result of experiments with microdivaces could not be explained via traditional flow modeling. In dealing with fluid flow-through microdivaces, one is faced with the question of which model to use, which boundary condition to apply and how to proceed to obtain solutions to the problem at hand.

Let's discuss a little bit about Liquid flows in micro channels. Microchannels can be defined as channels whose dimensions are less than 1mm and grater than 1um. Currently, most microchannels fall into the range of 30 to 300 um. They offer advantage due to their high surface-to-volume ratio and their small volumes. The large surface-to-volume ratio leads to a high rate of heat and mass transfer, making microdevices excellent tools to compact heat exchange. An example of the application of microchannels is in the area

of microelectromechanical system devices for biological and chemical analyses. The primary advantages of microscale devices in these applications are the good match with the scale of biological structures and the potential for placing multiple functions for chemical analysis on a small area- the concept of a “chemistry laboratory on a chip.”
Microchanels are used to transport biological materials such as protein, DNA, cells and embryos or to transport chemical samples and analyses. Typical of such device is the i-STAT blood sample analysis cartridge. The sample is taken on board the chip through a port and moved through the microchannels by pressure to various sites where it is mixed with analyte and moved to a different site where the output is read.

## 4. Structure of MEMS



### 4.1 Sensors[3]

#### 4.1.1 Inertial sensors

Inertial sensors are designed to convert, a physical phenomenon into a measurable signal. This physical phenomenon is an inertial force. Often this force is transduced into a linearly scaled voltage output with a specified sensitivity. The methodologies utilized for macroscopic inertial sensors can and have been utilized for micromachined sensors in many applications. It is worth considering what factors have led to the introduction of micromachined inertial sensors. As will be demonstrated, differences in linear and angular sensor application requirements impact the choice of micromachining technology, transducer design, and system architecture. The system requirements often delineate micromachining technology options very clearly, although most sensing mechanisms and micromachining technologies have been applied to inertial sensors. These sensors can when is needed:
Convert Acceleration to Force
Convert Force to Displacement
Make Mechanical to Electrical Transduction

### 4.1.2 Pressure sensors

Pressure sensors represent one of the greatest successes of micromachining technology. In the past four decades, this field has produced both commercially available and research-oriented devices for a variety of automotive, biomedical, and industrial applications. Automotive applications include pressure sensors for the engine manifold, fuel lines, exhaust gases, tires, seats, and other uses. Biomedical applications that have been proposed or developed include implantable devices for measuring ocular, cranial, or bowel pressure, and devices in catheters that can aid procedures such as angioplasty. Many industrial applications exist that relate to monitoring manufacturing processes. In the semiconductor sector, for example, process steps such as plasma etching or deposition and chemical vapor deposition are very sensitive to operating pressures. The essential feature of most micromachined pressure sensors is an edge-supported diaphragm that deflects in response to a transverse pressure differential across it. This deformation is typically detected by measuring the stresses in the diaphragm, or by measuring the displacement of the diaphragm. An example of the former approach is the *piezoresistive pick-off*, in which resistors are formed at specific locations of the diaphragm to measure the stress. An example of the latter approach is the *capacitive pick-off*, in which an electrode is located on a substrate some distance below the diaphragm to capacitively measure its displacement. The choice of silicon as a structural material is amenable to both approaches because it has a relatively large piezoresistive coefficient and because it can serve as an electrode for a capacitor as well.

Pressure on a Diaphragm

The deflection of a diaphragm and the stresses associated with it can be calculated analytically in many cases. It is generally worthwhile to make some simplifying assumptions regarding the dimensions and boundary conditions. One approach is to assume that the edges are simply supported. This is a reasonable approximation if the thickness of the diaphragm, *h*, is much smaller than its radius, *a*. Mathematically, it permits the second derivative of the deflection to be zero at the edge of the diaphragm. However, the preferred assumption is that the edges of the diaphragm are rigidly affixed (built-in) to the support around its perimeter. Under this assumption the stress on the lower surface of a circular diaphragm can be expressed in polar coordinates by the equations:

$$\sigma_r = \frac{3 \cdot \Delta P}{8h^2}[a^2(1+v) - r^2(3+v)]$$

$$\sigma_t = \frac{3 \cdot \Delta P}{8h^2}[a^2(1+v) - r^2(1+3v)]$$

Piezoresistive Pressure Sensors

The majority of commercially available micromachined pressure sensors are bulk micromachined piezoresistive devices. These devices are etched from single crystal silicon wafers, which have relatively well controlled mechanical properties. The piezoresistors are fashioned by selectively doping portions of the diaphragm to form junction-isolated resistors. The maximum deflection of the diaphragm is limited to the thickness of the sacrificial layer, and can constrain the dynamic range. The resistors present a scaling limitation for the pressure sensors. As the length of a resistor is decreased, the resistance decreases and the power consumption rises, which is not favorable. As the width is decreased, minute variations that may occur because of non-ideal lithography or other processing limitations will have a more significant impact on the resistance. These issues constrain how small a resistor can be made. As the size of the diaphragm is reduced, the resistors will span a larger area between its perimeter and the center. There are three general sources of noise that must be evaluated for piezoresistive pressure sensors, including mechanical vibration of the diaphragm, electrical noise from the piezoresistors, and electrical noise from the interface circuit.

### Capacitive Pressure Sensors

Capacitive pressure sensors were developed in the late 1970s and early 1980s.The flexible diaphragm in these devices serves as one electrode of a capacitor, whereas the other electrode is located on a substrate beneath it. As the diaphragm deflects in response to applied pressure, the average gap between the electrodes changes, leading to a change in the capacitance.

One of the drawbacks of capacitive pressure sensors is their inherent non-linearity. Piezoresistive pressure sensors offer better linearity without compensation, but these too need improvement for many applications. Digital compensation involves the correction of the non-linearity in software of the digital interface (or computer) by using polynomials or look-up tables. It is attractive because it is relatively easy to implement and reconfigure.

### Servo-Controlled Pressure Sensors

When a measured signal from a pressure change is used for feedback control to restore the signal to its reference, the pressure sensor is called a *closed-loop* or *servo-controlled* pressure sensor. Capacitive pressure sensors offer many attractive advantages such as high sensitivity, low temperature coefficients, and low power consumption. However, they tend to compromise linearity and dynamic range. Servo-controlled operation offers a solution to this problem. This concept has been widely used in micromachined inertial sensors to increase sensitivity, linearity, and dynamic range. To implement this concept, an actuator is necessary to drive the pressure sensor.

### Pirani Sensors

Pirani sensors are vacuum sensors that utilize temperature sensitive resistors as heating and sensing elements to measure pressure-dependent heat conduction across an air gap. This concept is widely used in conventional sensors, and micromachined versions have been reported as well.

### Optical MEMS Sensors

Optical MEMS sensors are highly adaptable to harsh environments, can measure displacement, pressure, temperature and stress, can be easily incorporated into sensor arrays by using multiplexing methods, and are suitable for liquid and gas measurements. In addition, they are highly resistant to electromagnetic interference (EMI) and radio frequency interference (RFI) and at the same time, they eliminate the necessity of onboard electronics. However, simpler processing techniques and therefore lower manufacturing costs are desirable. Moreover, simplification of the sensing elements and the fabrication processes will be helpful for their mass production and commercialization.

## 4.2 Actuators[4]

A micromachine is a system that uses small control energy to cause an observable (or controllable) perturbation to the environment. A machine able to generate a perturbation on environmental mechanical properties such as position, velocity, acceleration, force, pressure, and work. The actuator generates the mechanical work. A microactuator can have macro dimensions to generate a microenvironmental perturbation; however, for our purposes, we will consider actuators with at least one dimension in the order of microns (less than 1 mm), so we are referring to micromechanical actuators in the strictest sense.

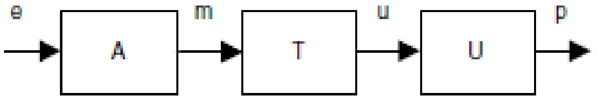


FIGURE 5.2 Functional definition of a mechanical machine. $A$ is the actuator, $T$ is the transmission, $U$ is the user, $e$ is an energy, $m$ is a mechanical function, $u$ is a usable mechanical function, and $p$ is an environmental perturbation.

The functional characteristics of an actuator are those of its mechanical output. On a bilogarithmic scale, it is possible to define three groups of ideal actuators: torque generators, speed generators and power generators.

Usually real actuators differ from ideal actuators; however, in some aspects of its actuator characteristics, ideal actuators can approximate real actuators. Usually the actuator output can be manipulated with a control variable, allowing the actuator characteristic to be changed.

Further, the actuator is also able to provide power for a limited amount of time, outside the standard field of the actuator characteristics, creating a joint field or an overloaded field.

### Piezoelectric Actuators

A piezoelectric material is characterized by the ability to convert electrical power to mechanical power (inverse piezoelectric effect) by a crystallographic deformation. When piezoelectric crystals are polarized by an electric tension on two opposite surfaces, they change their structure causing an elongation or a shortening, according to the electric field polarity. The electric charge is converted to a mechanical strain, enabling a relative movement between two material points on the actuator. If an external force or moment is applied to one of the two selected points, opposing a resistance to the movement, this “conceptual actuator” is able to win the force or moment, resulting in a mechanical power generation. Piezoelectric actuators are composed of elementary PZT parts that can be divided into three categories (depending on the used piezoelectric relation) of axial actuators, transversal actuators, and flexural actuators. Axial and transversal actuators are characterized by greater stiffness, reduced stroke, and higher exert able forces, while flexural actuators can achieve larger strokes but exhibit lower stiffness.

The primary design parameters of a piezoelectric actuator include:

- the functional parameters — displacement, force, and frequency
- the design parameters — size, weight, and electrical input power.

The most common internally force-leveraged actuators include:

(1) Stack actuators
(2) Bender actuators
(3) Unimorph actuators and
(4) Building-block actuators.

The externally force-leveraged actuators can be subdivided as:

(1) Lever arm actuators
(2) Hydraulic amplified actuators
(3) Flextensional actuators and
(4) Special kinematics actuators.

Electromagnetic Actuators

Electromagnetic actuators can be classified according to four attributes: geometry, movement, stroke, and type of electromagnetic phenomena. We will use the Lagrange equations of motion or Newtonian equations of motions to derive the models of each single type of actuator:

$$\frac{d}{dt}\left[\frac{\partial(\Gamma + D)}{\partial \dot{q}_i}\right] - \frac{\partial(\Gamma - \Pi)}{\partial q_i} = Q_i, \quad i = 1,2 \ldots n$$

$$\sum_{j=1}^{m} F_j(t, r) = m\frac{d^2r}{dt^2}$$

Where the first and second equation represents, respectively, Lagrangian and Newtonian approach; while *qi* and *Qi* represent, respectively, the generalized coordinates and the generalized forces applied to the system.

Induction Mini and Microactuators

Induction actuators consist of a mobile and a static part and the transformation from electric to mechanical energy due to the inductance of each part of the microactuator. This section will address a cylindrical rotary actuator with unlimited stroke and, to simplify the analysis, only a common configuration is considered: three phase, two pole actuation system. The mobile part (the rotor) has a cylindrical shape and is able to rotate around its axis; the static part (the stator) has the same axis as the rotor and is separated from it by an air gap. Both are composed of ferromagnetic material and incorporate lengthwise holes carrying conductive wires that are close to the air gap.

Shape Memory Actuators

A shape memory alloy that deforms at a low temperature will regain its original undeformed shape when heated to a higher temperature. This behavior is due to the thermoelastic martensitic phase transformation and its reversal. Many alloys exhibit shape memory effect and the level of commercial interest of each and every alloy is correlated with its ability to easily recover its initial position or to exert a significantly high force.

## 5. Software tools

Researchers in MEMS use various engineering software tools to take a design from concept to simulation, prototyping and testing. Simulation of dynamics, heat, and electrical domains, among others, can be performed by ANSYS, COMSOL and CoventorWare.

### 5.1 CoventorWare[5]

The CoventorWare MEMS product suite incorporates system- to physical-level modeling and simulation solutions for the MEMS industry. The comprehensive product suite provides integrated multi-physics analysis capabilities encompassing the mechanical, electrical, optical, fluidic and electromagnetic domains, as well as package analysis. CoventorWare is comprised of four major modules that can be used individually to complement an existing design flow, or jointly to provide a complete MEMS design flow:

ARCHITECT: simulation tool that quickly evaluates the behavior of MEMS devices and surrounding electronics within a schematic-based system-level modeling environment. Design engineers can efficiently simulate complex MEMS devices and MEMS-based products, including inertial sensors, RF switches, resonators and oscillators, and optical mirrors.

DESIGNER: With this tool, you can create layout masks, define the fabrication process, automatically generate and visualize 3D solid models for input into field solvers. DESIGNER is tightly integrated with ARCHITECT and ANALYZER.

ANALYZER: Analyze, understand and verify any MEMS or microfluidic design using these best-in-class 3D field solvers optimized for MEMS-specific coupled physics. You can, simulate the physical behavior of your MEMS or microfluidics design; perform multi-physics simulations that are critical to MEMS, such as coupled electro-mechanics and fluid-structure interaction; explore a variety of design concepts to find out which ones work; perform parametric studies to optimize your design; predict or validate experimental measurements;

INTEGRATOR: Create complex linear and non-linear reduced-order MEMS models that are compatible with standard IC simulators.

## 5.2 ANSYS[6]

ANSYS is a general purpose finite element modeling package for numerically solving a wide variety of mechanical problems. These problems include: static/dynamic structural analysis (both linear and non-linear), heat transfer and fluid problems, as well as acoustic and electro-magnetic problems. ANSYS is a finite element analysis (FEA) software package. It uses a preprocessor software engine to create geometry. Then it uses a solution routine to apply loads to the meshed geometry. Finally it outputs desired results in post-processing. In general, a finite element solution may be broken into the following three stages. This is a general guideline that can be used for setting up any finite element analysis.

1. **Preprocessing: defining the problem**; the major steps in preprocessing are given below:
    - Define keypoints/lines/areas/volumes
    - Define element type and material/geometric properties
    - Mesh lines/areas/volumes as required

The amount of detail required will depend on the dimensionality of the analysis (i.e. 1D, 2D, axi-symmetric, 3D).

2. **Solution: assigning loads, constraints and solving**; here we specify the loads (point or pressure), constraints (translational and rotational) and finally solve the resulting set of equations.
3. **Postprocessing: further processing and viewing of the results;** in this stage one may wish to see:
    - Lists of nodal displacements
    - Element forces and moments
    - Deflection plots
    - Stress contour diagrams

## 5.3 COMSOL[7]

COMSOL is a finite element analysis, solver and simulation software package for various physics and engineering applications, especially coupled phenomena, or multiphysics. COMSOL also offers an extensive interface to MATLAB and its

toolboxes for a large variety of programming, preprocessing and postprocessing possibilities. MEMS Module:
Represents coupled processes in microelectromechanical and microfluidic devices. Incorporates specific multiphysics couplings for applications such as electroosmotic flow, film damping, piezoelectricity and fluids-structure interaction.

[1] http://www.memsnet.org

[2] http://faculty.bus.olemiss.edu/

[3] Sensors & Transducers Journal, Special Issue

[4] The MEMS Handbook (Applications) edited by Mohamed Gad-El-Hak

[5] http://www.coventor.com/

[6] http://www.ansys.com/

[7] http://www.comsol.com/