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MEMS and NEMS - Micro (and Nano) Electromechanical Systems

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ABSTRACT

MEMS and NEMS use and application are growing and their market is expanding. With the development of 5G and IoT technologies, the number of MEMS components is always increasing.

In this paper gives an introduction of MEMS/NEMS definition, categories, and advantages. Fabrication techniques of MEMS/NEMS are also discussed. Finally, an elaborative analysis of the different applications of MEMS/NEMS is highlighted, followed by a discussion of the future of Micro/Nano electromechanical Systems.

Index Terms: MEMS; NEMS; Micro Electromechanical Systems; Nano Electromechanical Systems

1. INTRODUCTION

MEMS – Micro electromechanical Systems, aka MST - Microsystems Technologies in Europe, are manmade devices created by using compatible micro fabrication techniques that are capable of converting physical stimuli, events and parameters to electrical, mechanical and optical signals, as shown in Figure 1, performing actuation, sensing and other functions.

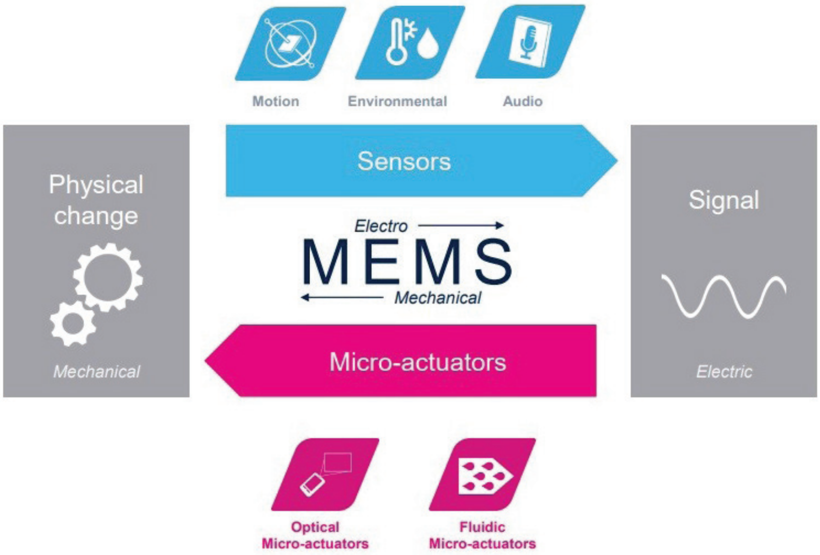


Fig. 1. MEMS sensors and actuators [1]

MEMS/NEMS are fabricated using micromachining technology, and are used for sensing, actuation or are passive micro-structures. They are usually integrated with electronic circuitry for control and/or information processing.

MEMS/NEMS range in size from a millionth of a meter (micrometer) to a thousandth of a meter (millimeter). Figure 2 shows the scale of things down to nanometer scale. They are manufactured onto semiconductor material (Si, silicon carbide, metals, plastics), integrating various sensing, computing and actuating elements into a single chip. Figure 3 shows a scanning electron microscope (SEM) photo of a part of a MEMS device under microscope. The size of the gear is 10 micrometers.

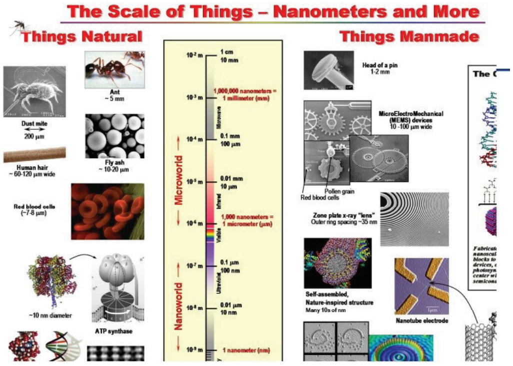
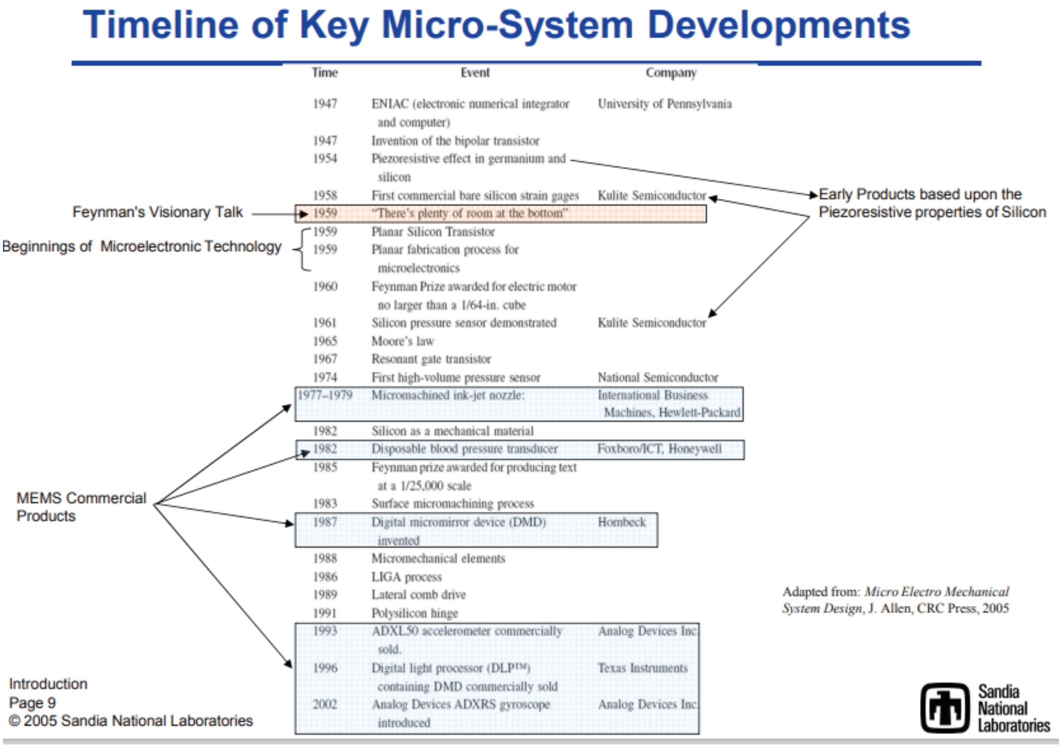


Fig. 2. The scale of things;
Natural and Manmade assembly. [2]

Fig. 3. Part of a MEMS device under microscope. [3]

Figure 4 shows a timeline of key microsystem developments, showing the start of MEMS commercial products in 1977.



Timeline of Key Micro-System Developments

Time	Event	Company
1947	ENIAC (electronic numerical integrator and computer)	University of Pennsylvania
1947	Invention of the bipolar transistor	
1954	Piezoresistive effect in germanium and silicon	
1958	First commercial bare silicon strain gages	Kulite Semiconductor
1959	"There's plenty of room at the bottom"	
1959	Planar Silicon Transistor	
1959	Planar fabrication process for microelectronics	
1960	Feynman Prize awarded for electric motor no larger than a 1/64-in. cube	
1961	Silicon pressure sensor demonstrated	Kulite Semiconductor
1965	Moore's law	
1967	Resonant gate transistor	
1974	First high-volume pressure sensor	National Semiconductor
1977–1979	Micromachined ink-jet nozzle:	International Business Machines, Hewlett-Packard
1982	Silicon as a mechanical material	
1982	Disposable blood pressure transducer	Foxboro/ICT, Honeywell
1985	Feynman prize awarded for producing text at a 1/25,000 scale	
1983	Surface micromachining process	
1987	Digital micromirror device (DMD) invented	Hornbeck
1988	Micromechanical elements	
1986	LIGA process	
1989	Lateral comb drive	
1991	Polysilicon hinge	
1993	ADXL50 accelerometer commercially sold.	Analog Devices Inc.
1996	Digital light processor (DLP™) containing DMD commercially sold	Texas Instruments
2002	Analog Devices ADXRS gyroscope introduced	Analog Devices Inc.

Feynman's Visionary Talk

Beginnings of Microelectronic Technology

Early Products based upon the Piezoresistive properties of Silicon

MEMS Commercial Products

Adapted from: *Micro Electro Mechanical System Design*, J. Allen, CRC Press, 2005

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Fig. 4. Timeline of key microsystem developments [4]

2. ADVANTAGES OF MEMS/NEMS

MEMS/NEMS advantages include, miniaturized size, high sensitivity, low noise, reduced cost, and batch processing.
MEMS can be categorized into four categories: Fluidic, RF, optical, and Bio-MEMS, as shown in Figure 5.

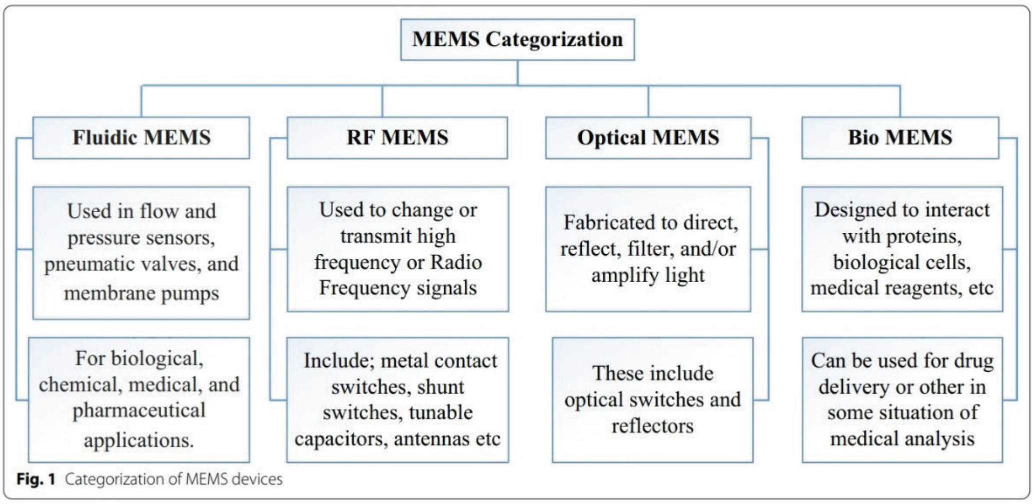


Fig. 1 Categorization of MEMS devices

Fig. 5. MEMS categories [5]

MEMS sensors and actuators are based on capacitive, piezoelectric/piezoresistive, electrothermal, electrostatic, electromagnetic, and optical mechanisms, as shown in Figure 6.

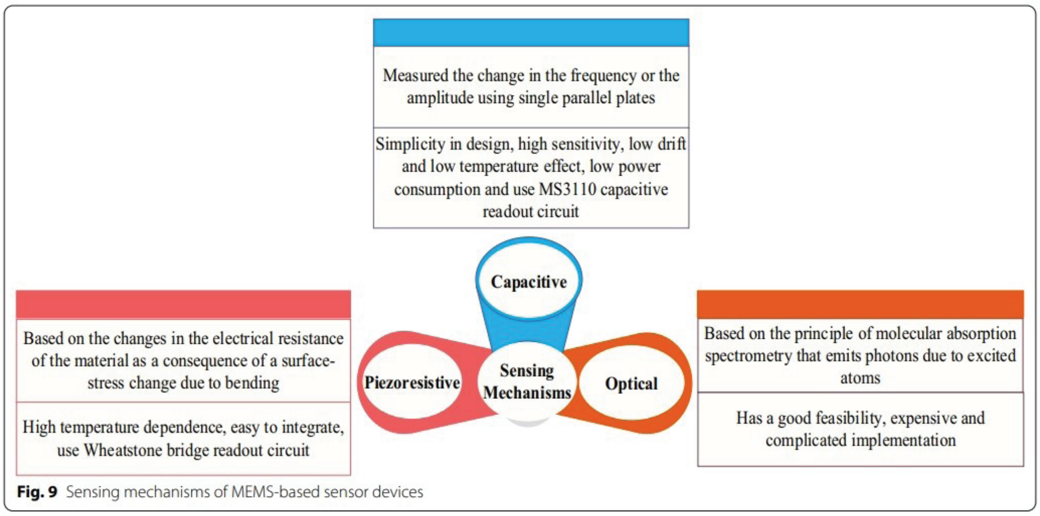


Fig. 9 Sensing mechanisms of MEMS-based sensor devices

Fig. 6.a. Sensing mechanisms of MEMS based sensors [5]

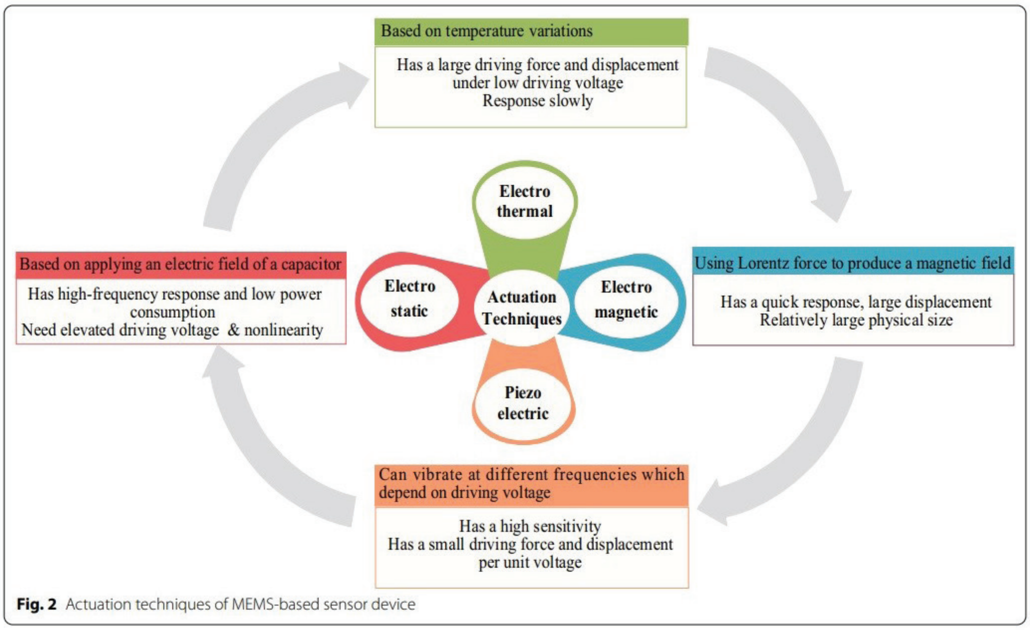
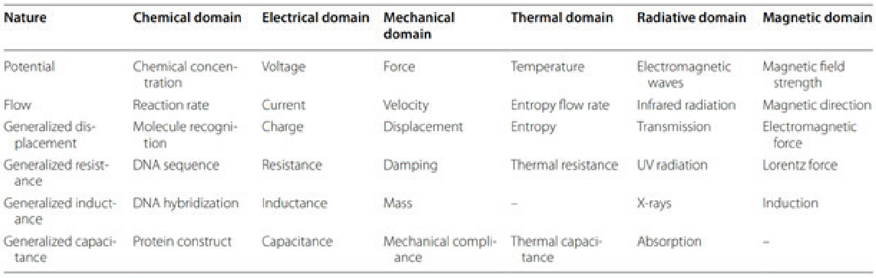


Fig. 2 Actuation techniques of MEMS-based sensor device

Fig. 6.b. Actuating mechanisms of MEMS based sensors [5]

Table 1 shows the different energy domains handled in MEMS.

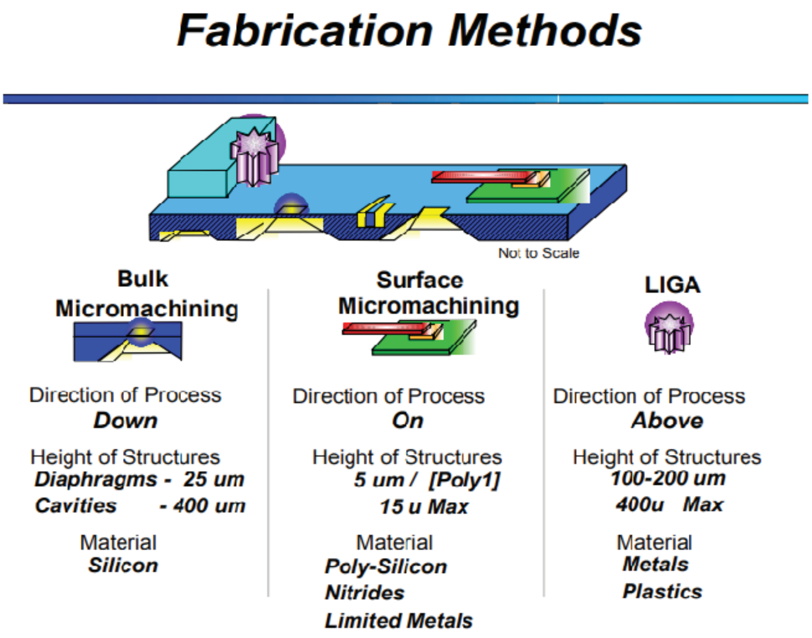
Table 1
Different energy domains handled in MEMS [5]



Nature	Chemical domain	Electrical domain	Mechanical domain	Thermal domain	Radiative domain	Magnetic domain
Potential	Chemical concentration	Voltage	Force	Temperature	Electromagnetic waves	Magnetic field strength
Flow	Reaction rate	Current	Velocity	Entropy flow rate	Infrared radiation	Magnetic direction
Generalized displacement	Molecule recognition	Charge	Displacement	Entropy	Transmission	Electromagnetic force
Generalized resistance	DNA sequence	Resistance	Damping	Thermal resistance	UV radiation	Lorentz force
Generalized inductance	DNA hybridization	Inductance	Mass	–	X-rays	Induction
Generalized capacitance	Protein construct	Capacitance	Mechanical compliance	Thermal capacitance	Absorption	–

3. MEMS/NEMS FABRICATION

MEMS/NEMS fabrication can be divided into surface micromachining and bulk micromachining. A third process was developed specifically for MEMS and is called LIGA, as shown in Figure 7.



Fabrication Methods

Not to Scale

Bulk Micromachining

Direction of Process
Down

Height of Structures
Diaphragms - 25 um
Cavities - 400 um

Material
Silicon

Surface Micromachining

Direction of Process
On

Height of Structures
5 um / [Poly1]
15 u Max

Material
Poly-Silicon
Nitrides
Limited Metals

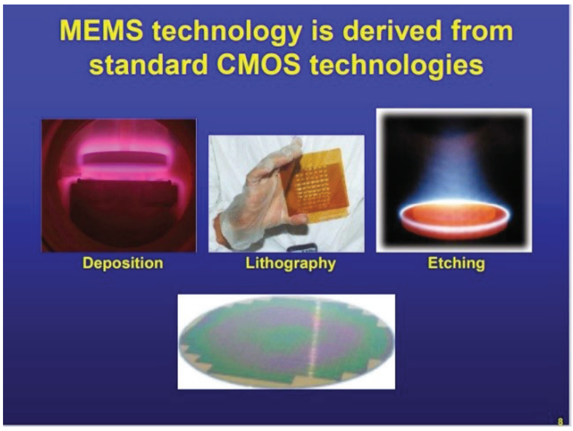
LIGA

Direction of Process
Above

Height of Structures
100-200 um
400u Max

Material
Metals
Plastics

Fig. 7. Bulk-, surface micromachining and LIGA. [6]



MEMS technology is derived from standard CMOS technologies

Fig. 8. MEMS fabrication processes. [7]

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The three basic fabrication processes used in integrated circuit fabrication are also the basic processes in MEMS/NEMS fabrication, namely, Deposition, Patterning, and Etching, as shown in Figure 8.

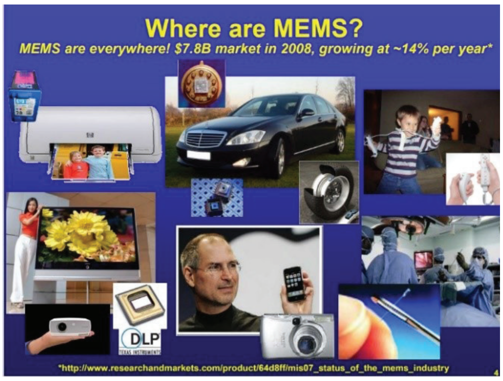
DEPOSITION is the addition of layers of materials, including oxidation, epitaxy, evaporation, sputtering, spin-on methods, chemical-vapor deposition (CVD/PECVD/LPCVD), diffusion, and ion implantation.

PATTERNING is done using Photolithography, electron-beam (e-Beam) lithography, and X-ray lithography.

ETCHING is removal of material by wet etching (Isotropic), and dry etching (anisotropic), including plasma etching and reactive ion etching (RIE), and deep reactive ion etching (DRIE).

4. APPLICATIONS OF MICRO/NANO ELECTROMECHANICAL SYSTEMS (MEMS / NEMS)

MEMS/NEMS have a lot of applications and are found almost everywhere around us, as shown in Figure 9, with a market share of $7.8B in 2008, growing at about 14% every year.



Where are MEMS?

MEMS are everywhere! $7.8B market in 2008, growing at ~14% per year*

*http://www.researchandmarkets.com/product/64d8ff/mis07_status_of_the_mems_industry

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Fig. 9. MEMS are everywhere. [7]

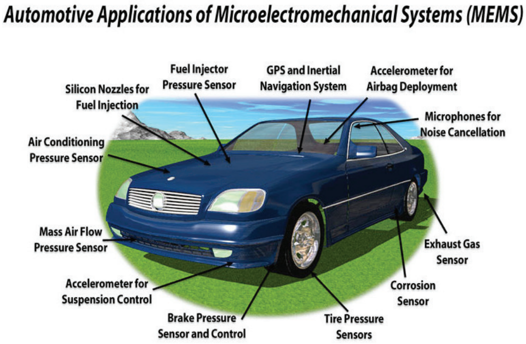

Fig. 10. Automotive applications of MEMS/NEMS. [8], [9]

MEMS/NEMS applications include AUTOMOTIVE APPLICATIONS, as shown in Figure 10, like sensors, accelerometers (Figure 11) – air bag crash sensing – seat belt tension – automobile suspension control, vibration – engine management – security devices, angle of inclination, vehicle stability and roll.

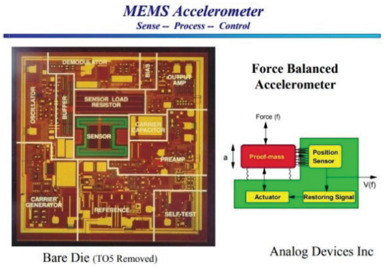

Fig. 11. MEMS accelerometer. [6]

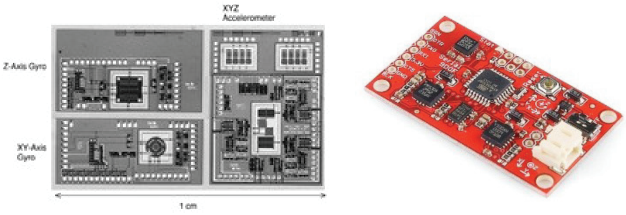

Fig. 12. MEMS inertial measurement unit (IMU). [10], [11]

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Fig. 13. MEMS gyroscope. [6]

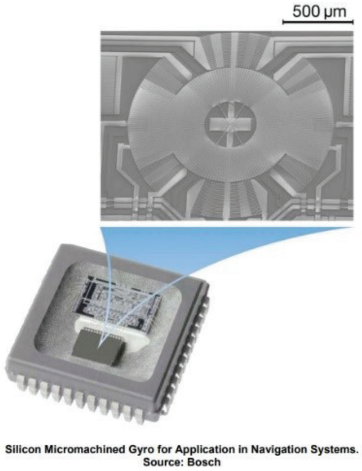

Fig. 14. MEMS gyro used for navigation systems. [6]

Biological applications, including microfluidics, Lab-on-a-Chip, micropumps, resonant microbalances, and Micro Total Analysis systems,

Wireless communications, including micromechanical resonator for resonant circuits and filters, and RF switches, inertial measurement unit (IMU) shown in Figure 12,

Optical communications, including optical switching,

Transportation, including gyroscopes (Figure 13),

Aerospace, including gyroscopes (Figure 14), deformable mirrors first developed in the 1990's (Figure 15),

Fig. 15. MEMS deformable mirror. [12]

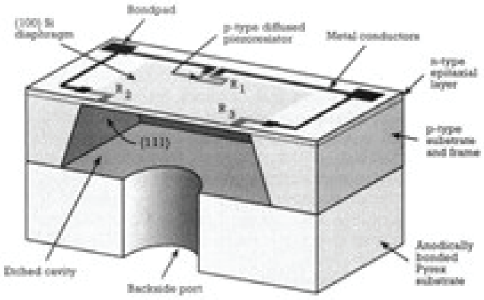

Fig. 16. MEMS Piezoresistive pressure sensor. [2]

Healthcare, including blood pressure sensor, human activity for pacemaker control, wearable health monitoring,

Industry applications, including pressure sensors (Figure 16), manifold absolute pressure (MAP) sensor,

Computing, including inkjet print heads (Figure 17), magnetic read/write heads for hard disks, Digital Micromirror Device (DMD) used in projection systems (Figure 18).

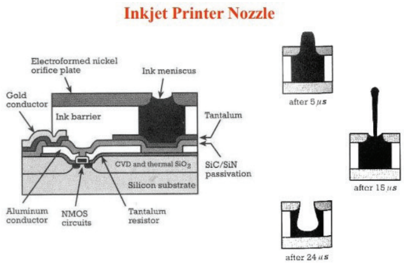

Fig. 17. MEMS inkjet print head. [2]

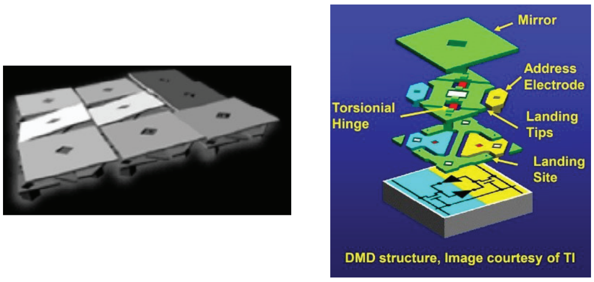

Fig. 18. MEMS Digital Micromirror Device (DMD). [7]

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ENVIRONMENTAL APPLICATIONS, including air quality monitoring, toxic gas detection, monitoring of seismic activity, RFID systems (Figure 19), and energy harvesting (Figure 20), using electromagnetic energy, acoustical energy and vibrational energy.

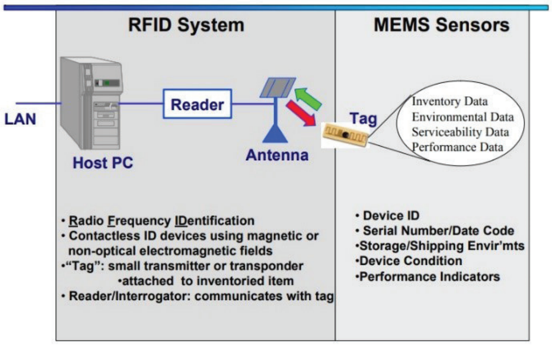

Fig. 19. MEMS RFID system. [6]

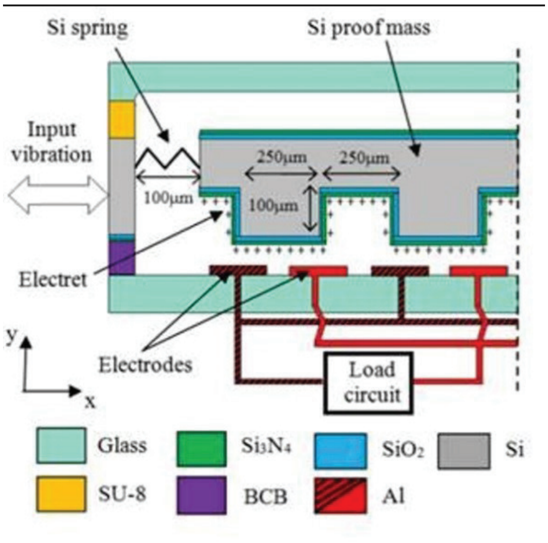

Fig. 20. MEMS energy harvesting system. [13,14]

5. FUTURE OF MICRO / NANO ELECTROMECHANICAL SYSTEMS (MEMS/NEMS)

Figure 21 shows the number of mechanical components versus the number of transistors for different MEMS applications, showing the location of the majority of existing MEMS systems.
Figure 22 shows the development trends and perspectives of future MEMS/NEMS systems.

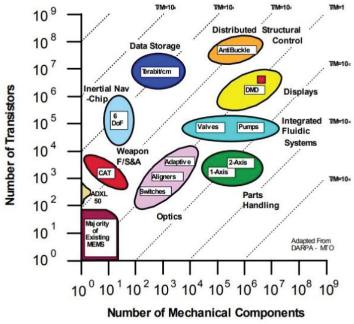

Fig. 21. Number of mechanical components vs number of transistors for different MEMS applications. [6]

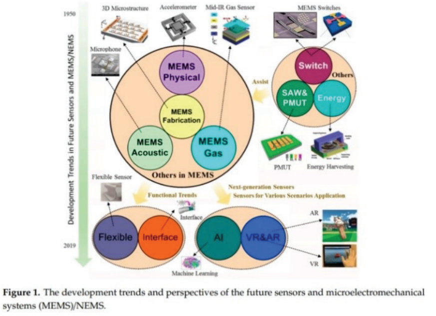

Figure 1. The development trends and perspectives of the future sensors and microelectromechanical systems (MEMS)/NEMS.

Fig. 22. Development trends of future MEMS/NEMS systems. [15]

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MEMS market is growing and expanding, as is evident from Figure 23, which shows the 2020 Top MEMS manufacturers, and Figure 24 which shows the MEMS market Forecast.

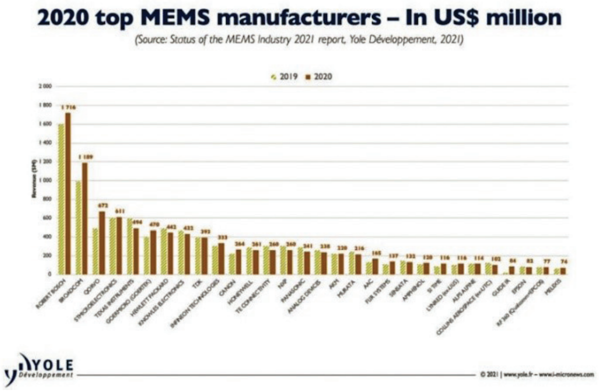

Fig. 23. 2020 Top MEMS manufacturers. [15]

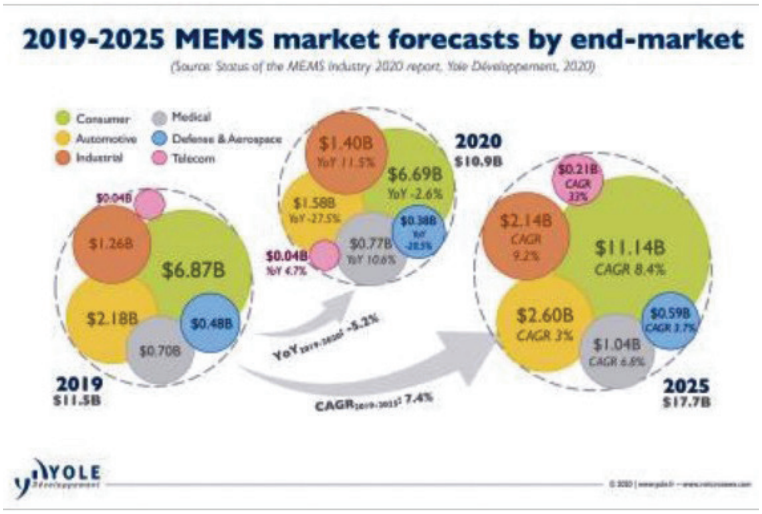

Fig. 24. MEMS market Forecast. [15]

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BIOGRAPHY

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Dr. Roshdy's current research interests include Nanoelectronics, VLSI, Integrated circuit fabrication, analog and mixed-circuits, semiconductor devices, and photovoltaics.