Review on Pressure Sensors: A Perspective from Mechanical to Micro-electro-mechanical systems

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Abstract

Swiftly emerging research prospects in the Micro-Electro-Mechanical System (MEMS) enable to build of complex and sophisticated microstructures on a substrate containing moving masses, cantilevers, flexures, levers, linkages, dampers, gears, detectors, actuators, and many more on a single chip. One of the MEMS initial products that emerged into the micro-system technology is the MEMS pressure sensor. Because of their high performance, low cost, and compact size, these sensors are extensively being adopted in numerous applications viz., aerospace, automobile, and bio-medical domain, etc. These application requirements drive and impose tremendous conditions on sensor design to overcome the tedious design and fabrication procedure before its reality. MEMS-based pressure sensors enable a wide range of pressure measurements as per the application requirements. Considering its vast utility in industries, this paper presents a detailed review of MEMS-based pressure sensors and their wide area of applications, their design aspects, and challenges, to provide state of an art gist to the researchers of a similar domain in one place.

Keywords: *Micro Pressure Sensors, Sensitivity, Linearity, and MEMS*

1. Introduction

The MEMS industry has grown rapidly in recent years and more systems and devices are being developed utilizing MEMS technology. Some of the typical MEMS devices produced are pressure sensors, accelerometers, gyroscopes, micromirrors fluid pumps, Radio Frequency (RF) devices [1-2], etc. They find various applications in the aerospace, automotive, chemical, biological, and optical fields. Therefore, a considerable amount of research is directed towards developing and producing smaller and efficient MEMS-based devices and components. MEMS-based pressure sensors were the first devices that were fabricated successfully. Such pressure sensors are one of the most widely sold devices in the world market among all other devices made out of MEMS technology [3]. Current applications have emerged with miniaturization technology as a need to replace the huge conventional devices. Therefore, current research is progressing at developing and producing smaller and efficient MEMS-based pressure sensors. The production of MEMS pressure sensors will continue to increase in the future.

A prediction done using Moore's law that talks about the transistors requirement on a chip are twice in every eighteen months is applicable to MEMS sensors due to the advantage of batch processing and reduced cost, making the production of MEMS pressure sensors an increasingly attractive option.

There is a wide application of MEMS-based pressure sensors in order to measure, manage and monitor the pressure changes in aerospace, biomedical, automobile, and oceanographic applications where miniaturization and lightweight coupled with increasing reliability play a crucial role [4-7]. They are smaller, faster, and are less expensive than their macroscopic counterparts. The working procedure of most MEMS-based pressure sensors is based on the bending effect on a thin diaphragm due to the application of external pressure [8]. The thin diaphragm will be subjected to internal stress due to bending which can be sensed in form of an electrical signal employing different sensing mechanisms such as capacitive, optical, resonant, and piezoresistive.

2. The motivation of the Review Work

As the technology evolves, new and improved methods of accurate measurement of pressure in liquids/gases are constantly being developed. Most of the time, the pressure sensors need to be accommodated in large numbers in complex equipment viz., automobile, biomedical applications, etc. It is essential to design/select the correct device for the required range of input and accuracy, and also the device must be immune to service / operating conditions.

As the requirements widen, new challenges emerge such as wide pressure range, better sensitivity, and suitability to the application environment. The sensors need to be rugged and capable of withstanding temperatures and other harsh environmental factors in industrial applications. Whereas in biomedical applications such as in Intra-Cranial Pressure (ICP) sensors, ventricle sensors; biocompatibility and size less than 1 mm are the constraints imposed on the design. In ocean water applications the sensors need to survive in a corrosive atmosphere. For several other purposes, like a pressure sensor on the aerofoil of an aircraft, the sensor has to be restricted in dimensions. These restrictions on the size along with the requisites like sensitivity, linearity impose tremendous constraints on the pressure sensor design. As a result, the design/selection of pressure sensors is a challenging task and calls for a lot of time, a large number of alternatives have to be verified [9].

Since the design is carried out using equilibrium/static conditions; it is also a matter of importance that the dynamic analysis needs to be carried out to assess the performance of the sensor. With regards to the above-mentioned issues, the study of the performance of the sensors system is essential. The task of a design engineer will be made simpler if a proper review is in one place and is available to help them to design the sensor for optimal performance. The information in this reckoner needs to be designed to help the designer for trying a large number of options before freezing the design. A ready reckoner who helps to select sensors for optimal performance can ease the work of an instrument designer to a great extent. The information in this ready reckoner will help the designer for trying a large number of options before freezing the design. This present work aims to generate such a ready reckoner for the selection of pressure sensors for optimized performance by an instrument designer.

Keeping all these in mind, the present review work summarizes different design methods and models of various types of MEMS pressure sensors in view of their transduction and geometry.

3. Pressure Sensors

Typical large systems like the ones used in biomedical instrumentation are designed and prototyped by engineers before their implementation. The selection or design of these subsystems is a major challenge faced by instrumentation engineers. Generally, the design engineer in such cases resorts to virtual prototyping model of the subsystems before building them physically and testing prior to their incorporation into the final product.

Instrumentation systems used for measuring pressure for display or control are complex and thus require a variety of pressure sensors of different ranges and sensitivities. The design requirements may be in the form of input/output range, geometry, an area of the sensor, the linearity parameter, and sensitivity of the sensor, etc.

3.1. Pressure Sensors: Area of Applications

Three typical systems where pressure sensors of different ranges and sensitivities used are presented below:

3.1.1. Aircraft instrumentation system:

This consists of three categories of instruments based on function, namely; flight instruments, engine instruments, and navigation instruments. Engine instruments consist of devices such as exhaust gas and turbine inlet temperature, oil and fuel pressure sensors, flow sensors, speed & torque sensors, etc. There are various MEMS-based embedded sensors are being used in aircraft for health monitoring purposes [10]. The system comprises many pressure sensors of different pressure measuring areas like; Tyre Pressure (32 psi), Engine Oil Pressure (150 psi), Fuel Pressure (30 psi), etc. [11].

3.1.2. Automobile instrumentation system:

The operation of an automobile requires pressure measurement at different locations for indication/control. Automotive pressure sensors are required to have high accuracy and a low price. The system comprises many pressure sensors of different pressure measuring areas like; Manifold Pressure (120 kPa), Turbocharged pressure (250 kPa), Diesel pressure (300 kPa), Exhaust Gas Recirculation Pressure (250 kPa), Refrigerant Pressure (5 MPa), Brake Oil Pressure (5 MPa), Power Steering Oil Pressure(5MPa), etc. [11].

3.1.3. Biomedical System:

In the biomedical system, a large number of MEMS-based pressure sensors are in use, for the measurement of interface pressures and internal pressures. The system comprises many pressure sensors of different pressure measuring areas like; Blood Pressure (120 mmHg - Gauge), Intraocular Pressure (15 mmHg - Gauge), Respirator (4 kPa – Differential pressure), Ventilator (25 cm H2O – Differential pressure), Spirometer (4 kPa -Differential pressure), etc. [12].

In the above three cases, it could be noted that the task of design engineers is complicated, as they have to select a number of pressure sensors with the appropriate range and sensitivity that best suits the application.

3.2. Pressure Sensors: Primary Design Aspects

In designing a pressure measurement system, there are a number of steps that need to be considered as listed below:

3.2.1. Identifying the measurement requirements:

Before designing the pressure sensors, different measurement requirements have to be identified. Such measurement requirements are the range of measurements, variable of measurements, accuracy requirement for a specific application, working environment, speed of response, and nominal value, etc.

3.2.2. Identifying the sensor type:

A sensor has to be designed based on different design variables such as range, accuracy, linearity, sensitivity, reliability, ruggedness, life cycle, power supply requirement, maintainability, availability, and cost.

3.2.3. Identifying a suitable signal processing system:

The selection of signal processing is an important aspect of the sensing mechanism. The output signal needs to be processed in such a way that can understand by the user and further the control action might be required based on its signal output.

3.2.4. Identifying the appropriate display system:

The appropriate display system has to be decided for displaying the sensor out. The factors that affect the display system are compactness of display, display type, 3D/2D displaying image, recorder and also working environment, etc.

3.3. Pressure Sensor: Sensing Elements

A variety of mechanical elements have been used for this purpose, including (i) bellows, (ii) diaphragms, and (iii) Bourdon tubes [13]. Sensors belonging to the second category are suitable for miniaturization and have found wide applications.

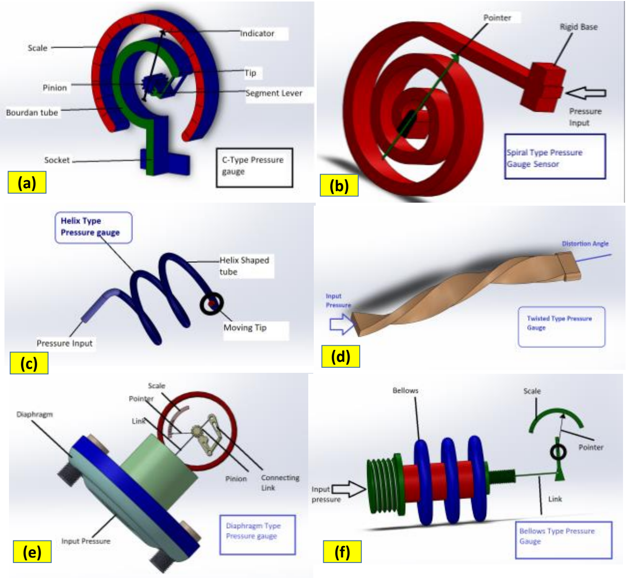


Fig. 1. Elastic elements used for pressure sensing

The diaphragms can be classified as flat, corrugated, capsules, etc., depending on physical realization. Sensing mechanisms using diaphragms are becoming more popular because they are very compact in size and they produce the required displacement/strain for the smooth operation of electronic transducers. There is a wide range of materials and shapes of the diaphragm are available for different applications. A typical set of elastic membranes used for macro-level pressure measurement are shown in Figure 1.

4. Miniaturization of Pressure Sensors

In the endeavor of instrumentation engineers to make the system compact, many of the above-mentioned macro pressure sensors are giving their way to micro pressure sensors. The benefits of miniaturized devices leading to a compact in size emerged with advanced functionalities and capabilities for meeting present engineering perspective are as follows [14]:

a) The system of small size moves fast as compared to bulk systems due to the smaller inertia effect.
b) Such miniaturized size devices encounter less vibration and thermal distortion because a resonant vibration of a system is inversely proportional to the mass.
c) The smaller size makes the devices particularly suitable for applications in medicine and surgery and microelectronic assemblies.

The background of micromechanical systems as pressure sensor and their working principles are discussed in the forthcoming section.

4.1. MEMS Pressure Sensors:

Micro pressure sensors are based on MEMS technology, which is essentially too small dynamic mechanical devices whose behavior is either controlled through electrical signal or they yield electrical signal from their deflection/straining. There is an enormous range of possible applications for microscale sensors and microscale tools. Microfabrication techniques are used to fabricate such miniaturized devices in MEMS technology. The size of a MEMS device can even less than one micron and also the structure can be varied from a simple to a complex structure. The elements in the simple structure are not movable type but in the case of complex structure, it has any numbers of moving elements controlled by an integrated microelectronics.

A MEMS-based device could be [15]:

a) A device, where microelectronics is used for monitoring and controlling the micromachines of the device. Normally, different microsensors are used for providing control signals to microelectronics.
b) A device, where the batch fabrication process (micromachining and IC making process) is used to fabricate different microstructure and microsensors.
c) A device, where different parts are integrated with the main parts, which does not require individual assembly.

MEMS devices have several distinct advantages. In the first place, the interdisciplinary nature of MEMS technology has a large diversity of devices. Secondly, MEMS-based devices are produced in batch fabrication which ensures the performance and also reliability of the component along with other advantages reduced weight, size, and cost. Thirdly, the manufacturing process adopted in MEMS cannot be achieved in other methods for performing such miniaturization jobs. However, there are many challenges and technological obstacles associated with MEMS viz., difficulties in visualization, dealing with fabrication and testing at miniaturized scale, which needs to be addressed and overcome before the potential can be realized. MEMS-based sensors and actuators can be found in a diversity of applications across multiple markets like automobile, communications, aerospace, defence, electronics, and medical applications [14].

4.2. Design of MEMS Pressure Sensor: Diaphragm Geometry

Irrespective of the sensor type, improving the sensitivity has been the main concern in the research field of MEMS-based pressure sensors. The diaphragm geometry plays a significant role in finding the efficiency of the sensor. For a given pressure, the stress-induced at the edges of a circular diaphragm is lowest than the square diaphragm, but the center deflection is more in the case of the circular diaphragm. So, the circular diaphragm is recommended in those applications where the maximum deflection carries a key role. In general, the membranes used are rectangular or square since they occupy a lesser area, enable easier lithography and fabrication compared to circular ones. Since the stress induced in the square diaphragm is very high, therefore such diaphragm is more sensitive than others [8] but it also has a high-stress gradient and any shortcomings in the fabrication process will affect the sensor performance.

On the other hand, rectangular membranes have a lower stress gradient making the placement of piezoresistors less error-prone [16]. Apart from selecting a suitable diaphragm geometry different design modifications like dividing longitudinal and transverse gauges into two parts or using a bossed diaphragm [17] or a double diaphragm [18] have been employed to enhance the performance of the sensor. Some researchers have employed the burst pressure approach for designing diaphragms with greater sensitivity. Material modifications like using polysilicon piezoresistors or phosphorous diffused polysilicon piezoresistors or silicon on insulator (SOI) diaphragms have also been attempted to enhance the sensitivity of the sensor. Sensors containing alternate piezoresistive materials aligned on polymer diaphragms [19] have shown greater sensitivity than conventional sensors.

4.3. MEMS Pressure Sensor: Fabrication Techniques

The two main fabrication technologies which are commonly used are Bulk micromachining and surface micromachining.

4.3.1. Bulk Micromachining

Bulk micromachining is a MEMS fabrication technology that describes structures based on a particular etching process used in the bulk of a substrate. It is the most widely used micromachining technology. Silicon wafers are normally preferred for bulk micromachining. On these, a mask pattern is transferred using photolithography and 3D structures are formed by selective wet or dry etching processes combined with etch-stop techniques [20]. Wet etching like isotropic and anisotropic etching is generally done from the back surface of the substrate. Isotropic etching is done for amorphous or polycrystalline materials and anisotropic etching is used for single crystal silicon. Normally hydrofluoric acid-nitric acid–acetic acid (HNA) is used for isotropic etching [21] and the most common etchants are EDP (ethylene-diamine and pyrocatechol), TMAH (tetramethylammonium hydroxide), KOH (potassium hydroxide), and hydrazine [22]. The etch rate of these etchants depends on the crystal orientation and plays a crucial part in the formation of the structure. Silicon wafers with (100) and (110) orientations have been used in bulk micromachining [23]. Dry etching, classified as reactive ion etching (RIE) and deep reactive ion etching (DRIE) occurs through the removal of substrate materials by gaseous etchants. Plasma-based methods [24] and a high aspect-ratio silicon etching method DRIE in which alternating process of plasma etching of the substrate material and the deposition of etching protecting polymers on the sides. The majority of the MEMS devices like pressure sensors, accelerometers, gyroscopes, etc. have been fabricated using this technique.

4.3.2. Surface Micromachining

The surface micromachining process is a technique to develop the surface layer by layer on a substrate. These layers consist of thin films which can be either structural or sacrificial layers. The sacrificial layer is selected depending on the structural layer used. The use of an etchant that etches the sacrificial layer without affecting the structural layer plays an important role. IC compatible materials like silicon, polysilicon, silicon nitride polyimide, and metals like gold aluminum copper, etc. are used to form the structural/sacrificial films. In surface micromachining, the properties of substrates are not much important as bulk micromachining because the structures are made on the upper surface of the substrate, and also the expensive silicon wafers can be replaced by glass or a plastic substrate which are quite cheaper. This is in tune with the present IC fabrication technology. But there are limitations in forming 3-D complex structures in this method. Surface Micromachining requires more fabrication steps than Bulk Micromachining and hence is more expensive. This process can be used to fabricate much more complicated devices with sophisticated functionality [25-26].

4.4. Research Gap

Table-1 shows the summary of some of the review papers published in the area of MEMS-based pressure sensors.

TABLE 1
SUMMARY OF REVIEW WORK

S. No	Title of the paper	Aim of the paper	Year	Ref
1.	Review of the potential of wireless MEMS and TFT microsystems for the measurement of pressure in the GI tract	Paper reviews of the capabilities of Micro Electro Mechanical Systems (MEMS) and thick film technology (TFT) for the fabrication of a wireless pressure sensing microsystem is presented	2005	27
2.	Modeling and analysis of MEMS sensor based on piezoresistive effects	The Paper has a detailed study and analysis of piezoresistive effects on a membrane suspended in an air-based sensor. The variation of its capacitance under the flow of stress or gas is investigated	2007	28
3.	Design and characterization of polymeric pressure sensors for wireless wind sail monitoring	This paper presents the design, fabrication, and experimental characterization of a capacitive differential pressure transducer, suitable to be implemented in a wireless sensor network for wind sail monitoring.	2011	29
4.	Tactile sensing for dexterous in-hand manipulation in robotics—A review	This paper reviews the state-of-the-art in force and tactile sensing technologies that can be suitable within the specific context of dexterous in-hand manipulation	2011	30
5.	An overview of micro-force sensing techniques	This paper presents a survey of the recent methods of micro-force sensing. The working principle, detection accuracy, advantage and disadvantage of seven widely used force-sensing methods are presented.	2015	31
6.	Evolution of micromachined pressure transducers for cardiovascular applications	Paper describes the eras of micromachining which contributed to progressive miniaturization, including early developments, early and late bulk micromachining, and surface micromachining. Characteristic microfabrication techniques and representative sensors per era are also detailed.	2015	32
7.	A review on coupled MEMS resonators for sensing applications utilizing mode localization	This paper reviews a recent technology development based on coupled MEMS resonators that have the potential of fundamentally transforming MEMS resonant sensors.	2016	33
8.	Shape memory alloy thin films and heterostructures for MEMS applications: A review	The article encompasses the new paradigms in the field of SMA thin films.	2016	34
9.	Theory, technology, and applications of piezoresistive sensors: A review	This paper focuses on the fundamentals of theory, materials, and readout–circuit design pertinent to the most recent developments in the field of piezoresistive sensors.	2018	35
10.	A review: crystalline silicon membranes over sealed cavities for pressure sensors by using silicon migration technology	The paper reviews the state-of-the-art technology for fabricating crystalline silicon membranes over sealed cavities by using the silicon migration technology in detail	2018	36
11.	Emerging Technologies of Flexible Pressure Sensors: Materials, Modeling, Devices, and Manufacturing	The paper reviews the recent progress in flexible pressure sensors based on their application and material aspects.	2019	37
12.	Recent Progress of Miniature MEMS Pressure Sensors	This paper reviews miniature MEMS pressure mainly in medical applications. The overall size of the pressure sensor focuses on 2 mmx2 mm with a diaphragm size of 1 mm x 1 mm	2020	38

The present paper discusses the basics of MEMS pressure sensors, their working principles, different design aspects, classification, type of sensing diaphragm used, and illustration of various transduction mechanisms. Moreover, this paper presents a comprehensive review on the present trend of research on MEMS-based pressure sensors, their applications, and the research gap observed to date along with the scope for future work, which has not been discussed in earlier reviews.

In a nutshell, the paper focuses on;

(i) Application and classification of MEMS pressure sensors based on diaphragm geometry and transduction mechanism.
(ii) Different sensing diaphragm geometry used in micro pressure sensors and its design challenges
(iii) Recent research on MEMS pressure sensors.
(iv) The present research gap and future scope of work on MEMS-based pressure sensors.

From the literature review and the study of the key results of research in the area of micro pressure sensors, the following areas have been identified for research.

a) Various researchers have employed the burst pressure approach to obtain the optimum dimensions of a pressure sensing diaphragm by considering the thickness and side length of the diaphragm for better sensitivity and safety factors [39]. However, data regarding a burst pressure approach including the maximum deflection of the diaphragm for obtaining greater linearity is scarce.
b) Reports emphasizing the effect of diaphragm geometry and the role played by the piezoresistor position in deciding the performance of the sensor [40], have been published but a study of the stress profile across the diaphragm of different geometries and the role played by the piezoresistor dimensions on the performance of the diaphragm is not available.
c) Comparison of capacitance evolution using different diaphragm geometry in order to decide proper sensing mechanism is not emphasized. Wheatstone bridge and Resonant frequency evaluation are also important in order to have a better accuracy output of sensors.
d) Though polymer-based pressure sensors have been fabricated [41] Data regarding the design of a SU-8 diaphragm for a piezoresistive pressure sensor is limited. But, by using the polymer SU-8 or some other functionalized polymers viz., PDMS, etc., as the pressure sensing diaphragm with CNTs or similar nanomaterial as piezoresistors, the sensitivity can be further enhanced and the pressure sensing ranges can be extended.

5. Recent Research on MEMS Pressure Sensors

The real challenge lies in achieving high sensitivity with the best linearity is becoming the main research focus in the design and development of MEMS-based pressure sensors. Also, recent signs of progress in the materials, communication means, substrate flexibility have opened newer avenues in this area. In this context, different techniques have been proposed by researchers in order to achieve this, some of which are discussed as follows:

5.1. Optical Fiber Fabry-Perot(FP) Micro Pressure Sensor Based on Beam-Membrane Structure.

The Optical fiber Fabry-Perot(FP) micro pressure sensor is made of a single optical fiber and sensing silicon diaphragm. Single optical fiber is used for two-way light transmission. The sensing silicon diaphragm is designed of a beam-membrane structure in order to enhance the sensitivity and linearity of the sensor. This beam-membrane structure diaphragm is fabricated by MEMS technology. Tian et al. [42] reported the sensitivity of an FP micro pressure sensor using beam-membrane structure diaphragm can be reached up to 242 nm/kPa for an input pressure range of 0~10 kPa. As shown in figure 2, the complete setup is made of four parts: (i) Beam-membrane structure Si diaphragm, (ii) Single-mode fiber, (iii) Pyrex base, and (iv) ceramic ferrule. The light is passed through single-mode fiber vertically to the sensing head. During this process, a part of the light is reflected over the fiber and another part is transmitted to the beam-membrane Si diaphragm and reflected. Normally, the polychromatic light source is used and the optical signal is interpreted by the method of phase modulation technique. So the length of the FP cavity can be found out easily and the applied pressure on the beam-membrane Si diaphragm can be obtained from the optical spectrum by a spectrum analyzer.

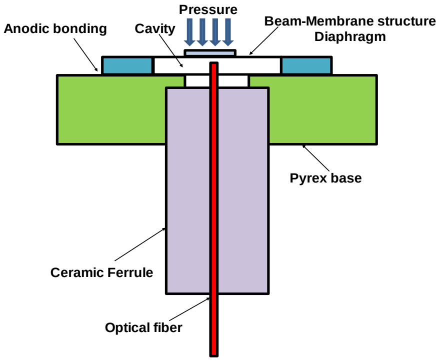
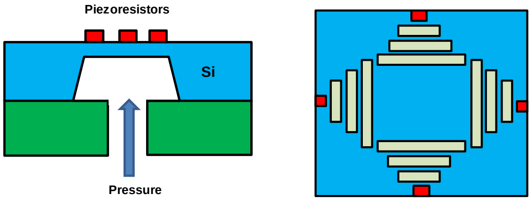


Fig.2. Optical fiber FP micro pressure sensor

5.2. Use of Striped Arrow Embossed Diaphragms in Low-Pressure MEMS-Based Piezoresistive Pressure Sensors.

A striped arrow embossed diaphragm is proposed by Angel et al. [43] for the design of a low-pressure piezoresistive pressure sensor. The analysis was made by the author that the use of a striped arrow embossed diaphragm can able to produce more stress than a flat diaphragm, hence improved the sensitivity of the sensors. At the same time author also given emphasized the design of an optimized structure in order to have a high degree of linearity in sensor output.



(a) (b)

Fig.3. (a) Cross-sectional view of the pressure sensor. (b) Top view of the pressure sensor.

A schematic of a typical MEMS-based pressure sensor is shown in figure 3 (a), which is working based on the principle of piezoresistive effect. The sensor chip is mainly fabricated with silicon material by MEMS technology. The sensing element of a MEMS pressure sensor is a silicon die with a thin etched diaphragm. In striped arrow embossed diaphragm is achieved by etching the flat diaphragm from the top surface as shown in figure 3 (b). Four tiny piezoresistors are diffused into the top surface of the silicon diaphragm in such a way that the maximum stress can be induced at that position. These piezoresistors are connected to an aluminum layer in order to establish the Wheatstone bridge configuration so as to convert the change in resistance value into electrical potential. The applied pressure onto the silicon membrane will lead to membrane deflection, the resistances will change accordingly, which also causes the change in output voltage.

5.3. MEMS-Based Pressure Sensor with Photoresist Insulation Layer.

The online health monitoring of today's electronics which are very flexible and wearable is achieved through micro pressure sensing techniques. The current development in diaphragm structure design optimized to obtain high sensitivity, flexibility with self-healing capability. However, the fabrication process of many pressure sensors is too complicated and difficult to integrate with traditional silicon-based Micro-Electro-Mechanical System (MEMS). Liang et al. [44] demonstrate a scalable and integratable contact resistance-based pressure sensor based on a carbon nanotube conductive network and a photoresist insulation layer. They have achieved high sensitivity up to 95.5 kPa−1, a very low sensing threshold below 16 Pa, quick response time which is less than 16 ms, and zero power consumption when without loading pressure. The sensitivity, sensing threshold, and dynamic range are all tunable by conveniently modifying the hole diameter and thickness of the insulation layer.

5.4. MEMS piezoresistive pressure sensors based on large-area layered PtSe2 films

Generally, the diaphragm is considered to be 2D layered materials for micro/nanosystems application due to their ultimate thickness. Platinum diselenide ($PtSe_2$), an exciting and unexplored 2D transition metal dichalcogenides (TMD) material, is particularly interesting because its low-temperature growth process is scalable and compatible with silicon technology. Wagner et al. [45] have reported the potential use of thin PtSe2 in MEMS piezoresistive pressure sensors. They have conducted all the experiments with semi-metallic PtSe2 films grown by thermally assisted conversion of platinum at a CMOS-compatible temperature of 400°C. From the experimental setup of a bending cantilever beam, they found a very high negative gauge factor of up to - 84.8 from PtSe2 films measured using strain gauges. This negative gauge factor exhibits a very high sensitivity of the sensors. Authors use density functional theory (DFT) in order to understand the origin of the measured negative gauge factor. The results of these experiments explored the promising use of PtSe2 in MEMS/NEMS in the future.

5.5. InAlN/GaN High Electron Mobility Micro-Pressure Sensors for High-Temperature Environments.

A micro-scale pressure sensor leveraging a ring-shaped InAlN/GaN high electron mobility transistor (HEMT) sensing element was fabricated and characterized under applied pressure. AlN/GaN is used on Si material in order to enable monolithic integration with electronics which makes it capable to operate in a high-temperature environment. Chapin et al. [46] developed an analytical model of pressure transduction system in order to compare the change in the 2D electron gas sheet carrier concentration for InAlN and AlGaN heterostructures upon applied pressure. The model confirms that the high aluminum content of InAlN and large piezoelectric constants of AlN results in a larger pressure response in InAlN/GaN heterostructures, in comparison to AlGaN/GaN heterostructures. To experimentally examine the InAlN/GaN pressure sensor architecture, a 500-µm-radius pressure sensor was electrically characterized under applied pressures from 0 to 28.5 psig. The sensitivity of the sensor increased as the gate voltage reached the threshold voltage. The authors demonstrated the sensitivity (change in current) was 0.64% / psig at VGS = -5 V, VDS = 2.2 V. To observe the influence of temperature, the current-voltage (ID-VDS) response of released and unreleased ring-shaped devices was measured up to 3000C. At all temperatures, the current of the released ring-shaped devices decreased when compared to the solid-state device, which is attributed to reduced thin film tensile stress between the underlying GaN buffer layers and the silicon. This work demonstrates the feasibility of using InAlN/GaN sensor architectures for high-temperature applications (space exploration, nuclear energy, downhole, and combustion).

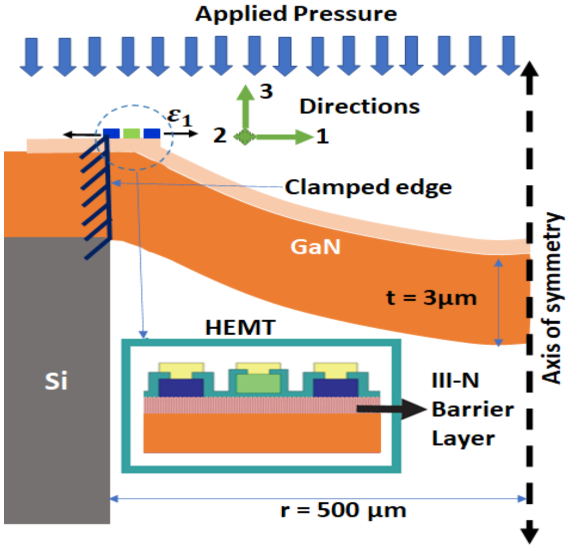


Fig 3: Schematic illustration of the InAlN/GaN-on-Si micro-pressure sensor under applied pressure.

5.6. Flexible Pressure Sensors

A lot of research focus in the sensing domain has been shifted from rigid substrate-based sensors to flexible ones. Herein the base over which all functional modules are supposed to be developed is chosen to be well fit in any kind of surface area of interest. Flexible sensors have moderate deformability. [47] Liu et al. reported a flexible pressure sensor which was made up of a piezoelectric sensor and a piezoresistive sensor to measure pulse wave and static pressure discretely. In this work, poroelastic materials were used to attain flexible connections and reduce interference among sensors. This study showed that the flexible pressure sensor array not only reflects depth information of radial artery pulse waves under a wide range of static pressures but also has good repeatability and anti-interference performance [48]. Important characteristics in a pressure sensor that determines the efficiency of sensors have also been investigated via different routes by various researchers. These routes may be; exploring the enhanced properties of small-scale materials, such as graphene, carbon nanotubes, other functionalized materials, as well as various other signal transduction mechanisms.

5.7. Advantages and Disadvantages of recently reported work on MEMS pressure sensor

TABLE 2
ADVANTAGES AND DISADVANTAGES OF MEMS PRESSURE SENSOR OF RECENT RESEARCH WORK.

Recent Research on MEMS Pressure Sensors	**Advantages**	**Dis-advantages**
Optical fibre Fabry-Parot (FP) micro pressure sensor based on beam-membrane structure.	1. Used in harsh places because of their good immunity to electromagnetic interference and high insulation capacity. 2. Cross-Beam Membrane structure diaphragm is to have good stiffness which resists failure.	1. Fabrication risk to make microstructure beam. 2. Initial manufacturing cost is high due to the rate of failure.
Use of Striped Arrow Embossed Diaphragms in Low-Pressure MEMS-Based Piezoresistive Pressure Sensors.	Using striped arrow embossed diaphragms to have high sensitivity, better linearity, and low fabrication cost over other existing structures.	Small pressure range of application.
MEMS-Based Pressure Sensor with Photoresist Insulation Layer.	The use of a photoresist insulation layer in MEMS pressure sensors has improved the sensitivity and better response time of the device.	The fabrication process is too complicated and difficult to integrate with traditional silicon-based MEMS devices.
MEMS piezoresistive pressure sensors based on large-area layered PtSe2 films.	Platinum diselenide (PtSe2), an exciting composition because its low-temperature growth process is scalable and compatible with silicon technology.	Low linearity
InAlN/GaN High Electron Mobility Micro-Pressure Sensors for High-Temperature Environments.	Best preferred for high-temperature operation environment.	1. Increase bias due to sudden rise of current. 2. Poor packaging
Flexible Pressure Sensors	has good repeatability and anti-interference performance	Signals may interfere with the vibration environment because of small gaps between the sensors (less than 1 mm).

6. Conclusion

This review article focuses on the fundamental aspects of pressure sensors, classification of MEMS pressure sensors based on diaphragm geometry and transduction mechanism, its design challenges, etc. It also summarizes the recent research on micro pressure sensors which shows that the real challenges lie in the optimum design of the sensing diaphragm in order to obtain not only high sensitivity but also excellent linearity in MEMS-based pressure sensors.

The present research work focuses more on application-based design e.g., InAlN/GaN high electron mobility micro-pressure sensors is designed for high working temperature areas. Similarly, MEMS-Based pressure sensor with photoresist insulation layer is designed to use where better response time is a demand whereas micro pressure sensor based on the beam-membrane structure is designed to use for high sensitivity and linearity requirements. Though, some disadvantages are there in each technique, so these can be envisioned as future research work for coming researchers.

In nutshell, this article also provides a comprehensive review on the present trend of research on MEMS-based pressure sensors, their advantages, and their applications along with the research gap observed.

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