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Carbon Nanotube based Piezoresistive Pressure Sensor for Wide Range Pressure Sensing Applications - A Review

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Abstract— **Pressure Sensors are very essential, and are used in various fields such as aerospace, barometry, industries, automobiles, medical, etc. There has been a great deal of developments in the design of pressure sensor beginning with metal strain gauges, square silicon diaphragm to recent pressure sensors developed using materials like nano wires, Carbon Nanotubes (CNT), etc. Due to its high gauge factor (200 to 1000), high sensitivity, temperature independency and many other advantages, CNT serves as a highly effective material to be used as a piezoresistive element in piezoresistive pressure sensors. This article provides a review of CNT based piezoresistive pressure sensors including their evolution, challenges, sensing mechanism, materials, applications, advantages and disadvantages.**

Keywords— ***Pressure Sensor; Piezoresistor; Carbon Nanotube (CNT); Wheatstone bridge; Gauge factor.***

I. INTRODUCTION

Earlier pressure sensors were in the form of strain gauges for several years. Advancements in the design and development of pressure sensors led to various pressure sensors with different sensing principles such as piezoresistive, capacitive, electromagnetic, piezoelectric, optical, potentiometric, resonant, thermal, ionization, etc. Due to its simple principle, Piezoresistive mechanism of pressure sensors are widely used in various applications that includes areas like aerospace, barometry, industries, automobiles, medical.

Piezoresistive pressure sensors use the piezoresistive effect of a material to detect strain due to applied pressure. Common technology types are silicon (monocrystalline), polysilicon thin film, bonded metal foil, thick film, and sputtered thin film, carbon nanotubes, etc. Generally, the piezoresistive materials are connected to form a Wheatstone bridge circuit to maximize the sensitivity and reduce nonlinearity. This is the most commonly employed sensing technology for general purpose pressure measurement.

Use of carbon nanotube as a piezoresistor element in the piezoresistive pressure sensor is the recent trend in sensor technology because of their remarkable mechanical, electrochemical, piezoresistive and other physical properties.

The major advantages that motivate the use of CNT based Piezoresistive pressure sensor instead of polysilicon based pressure sensors are:

1. Response of CNT sensor is independent of temperature.
2. CNT based sensors need not be fabricated at high temperature which allows the possibility of integrating polymer and CNT.

Apart from this, CNT based sensors have potential advantages such as high sensitivity, low cost, low power consumption, bio-compatibility, etc.

CNT based pressure sensors can sense a very low value of pressures and have high thermal conductivity.

II. EVOLUTION OF CNT BASED PIEZORESISTIVE PRESSURE SENSOR

Carbon nanotubes have drawn much attention since their discovery in 1991 because of their unique electronic and mechanical properties. In 1991, multi-walled nanotubes were first discovered by Ijima by arc-discharge technique when he saw fine threads in a bit of shoot under electron microscope. The strands were very thin and long tubes of pure carbon. SWNTs were synthesized for the first time by Ijima and Ichihashi [1] and Bethune et al. [2] in 1993 using metal catalyst in arc-discharge method. Laser-ablation technique was used by Thess et al. [3] in 1996 to produce bundles of aligned SWNTs. For the first time, catalytic growth of MWNTs by CVD was proposed by Yacaman et al. [4]. Liu [5] and Dai [6] demonstrated that piezoresistive pressure sensors can be realized with CNTs. They grew SWNTs on suspended square polysilicon membranes. When uniform air pressure was applied on the membranes, a change in resistance in the SWNTs was observed. Moreover, the membrane was restored to its original condition when the gas was pumped out, indicating that the process is reversible. Dharap et al.[7] argued that the conventional sensors have disadvantage that they are discrete point, fixed directional, and are not embedded at the material level. To overcome these limitations, they developed a CNT film sensor for strain sensing on macro scale. The sensor was based on the principle that the electronic properties of CNTs change when subjected to strains. As randomly oriented bundles of SWNTs were used by them, the film was isotropic in nature. The isotropic nature of CNT films helps in measuring strains in multiple locations and in different directions. The experimental results revealed nearly linear relationship between the measured change in voltage and the strains in CNT films when they are subjected to tensile and compressive stresses. Wu et al. [8] demonstrated using first-principle quantum transport calculations, molecular-dynamics simulation and continuum mechanics analysis that hydrostatic pressure can induce radial deformation, and therefore, electrical transition of SWNTs. A pressure-induced metal-to-semiconductor transition in armchair SWNTs was observed, which provides a basis for designing nanoscale tunable pressure sensors [9].

Inpil Kang et al [10] demonstrated the CNT based strain sensor for structural health monitoring applications. They fabricated SWNT strain sensor for their application using two methods, viz., Buckypaper fabrication and Fabrication of SWNT/Polymethylmethacrylate composite sensor. Experimentation showed that a buckypaper strain sensor has high sensitivity, but because of the weak axial van der Waals attraction Nanotube slippage degrades the strain response of the sensor which was linear only within the range of 500 microstrain whereas CNT/PMMA composite sensor improves the strain transfer across the sensor by means of stronger polymer interfacial bonding. Even though the composite strain sensor showed a lower sensitivity than the buckypaper sensor, it has a fairly linear symmetric strain response under static and dynamic strain.

Carmen K. M. Fung et al. [11] fabricated a novel polymer-based MEMS pressure sensor using bulk multi-walled carbon Nanotube (MWNT) as piezoresistive sensing elements. This was an era when a novel technique called Dielectrophoresis was employed to form MWNT bundles across the electrodes. Dielectrophoresis (DEP) is a phenomenon in which a force is exerted on a suspended particle, generally in a liquid, when it is subjected to a non uniform electric field [12]. It was discovered by Pohl in 1951.

Formation of composites of CNT with different polymer materials such as Polymethylmethacrylate, Polyimide, polydimethylsiloxane, poly (vinyl pyrrolidone), etc has made great impact on usage of pressure sensor for low pressure application. The Polymer/CNT composite based pressure sensors exhibited higher sensitivity than a polysilicon sensor, rapid response, and is thermally stable [13].

III. CNT AS PIEZORESISTIVE MATERIAL [14]

Correlation between mechanical deformation and conductivity behavior of free-standing membranes of CNTs is the preliminary interest.

CNT may be thought of as a graphene sheet rolled up to form a cylinder along the lattice vectors a1 and a2 as shown in Fig.3.1. The electronic states near the Fermi point may be analyzed using the first Brillouin zone of graphene as defined by the reciprocal-lattice vectors K_1 and K_2 as shown in Fig.3.2. In an undeformed lattice, the Fermi points lie on the vertices of hexagonal Brillouin zone. The allowed electronic states, given by the Bornvon Karman boundary condition, lie on parallel lines, k, that are perpendicular to the lattice vector C.

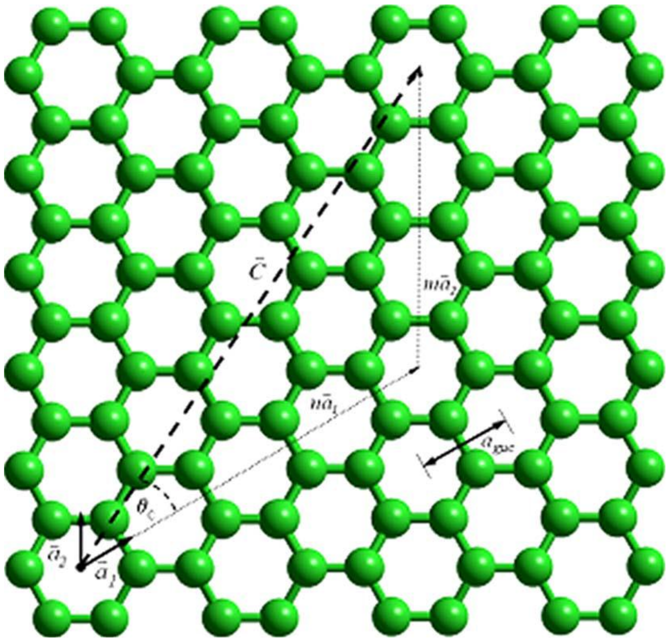

Fig.3.1. CNT Chiral Vectors

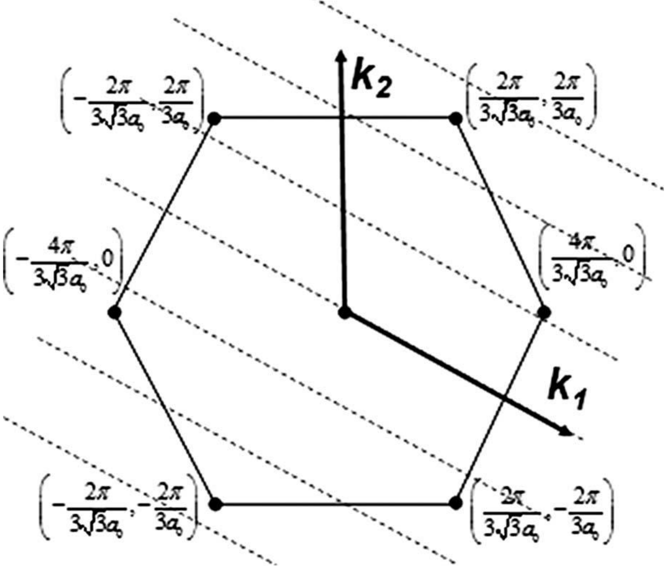

Fig.3.2. Graphene first Brillouin zone with allowed electronic states.

The change in band gap for small strains may be calculated as shown in Equation 1.

$$\Delta E_{gap} = sgn\,(2p+1)3t_0[(1+v)\varepsilon\cos 3\theta + \gamma\ \sin 3\theta]\_(1)$$

where v is the Poisson's ratio, θ is the chiral angle, ε is the axial strain, and γ is the torsional strain. The resistance of a CNT can be accurately modeled by considering electron transport to occur by thermal activation. [15] This model is given in Equation 2,

$$\mathrm{R} = \mathrm{R_c} + \frac{1}{|\mathrm{t}|^2}\frac{\mathrm{h}}{8\mathrm{e}^2}\left[1 + \exp\left(\frac{\mathrm{E^0_{Gap}} + \frac{\mathrm{dE_{Gap}}}{\mathrm{d}\varepsilon}\varepsilon}{\mathrm{kT}}\right)\right]\_\_\_\_\_\_\_\_\_\_(2)$$

where $|t|^2$ is the transmission probability of electrons with $|E-E_F| > E_{Gap}$ crossing the energy barrier, R_c is the contact resistance, h is plank's constant, e is the charge on an electron, k is Boltzmann's constant, and T is temperature in degree Kelvin.

The zero strain band gap, E^0_{Gap}, Is [16]

$$E^0_{Gap} = \frac{2t_0 a}{\sqrt{3}d} \qquad (3)$$

for a semiconducting CNTs and [17]

$$E^0_{Gap} = \frac{t_0 a^2}{4d^2} \qquad (4)$$

for a metallic CNTs.
where a is the length of the graphene lattice unit vector, d is the diameter of the CNT.
From the above equations it can be concluded that, as the strain applied increases, the band gap increases. Similarly as the diameter of the CNTs increases, the band gap decreases and the resistance of the CNTs increases. Thus, there is a change in the resistance of the CNTs when a strain is applied, hence making it an effective material to be used as a piezoresistor.

IV. CHALLENGES AND ISSUES OF CNT BASED PIEZORESISTIVE PRESSURE SENSOR

Before the CNTs are used in sensor applications to full potential, there are some challenges to be addressed. For example, the production of pure and uncontaminated nanotubes is very costly. In addition to it, there is a lack of detailed understanding of growth mechanism of CNTs. As a result, an efficient growth approach to structurally perfect nanotubes at large scales is currently not available. Secondly, it is difficult to grow defect-free nanotubes continuously to macroscopic lengths. Thirdly, control over nanotubes growth on surfaces is required in order to obtain large-scale ordered nanowire structures.
Another issue concerning the use of CNTs is their toxicity. On the basis of their experiments, researchers have suggested that CNTs possess health risks.
The major challenges and issues in the design and fabrication of MEMS based CNT piezoresistive pressure sensors are:

1. Deciding the range of pressure to be sensed by the designed sensor has been one of the major challenges because of the fact that a wide range of measurement will limit the miniaturization of the dimensions of the diaphragm.
2. A pressure sensor must be temperature independent; which means that as the temperature increases within the device, there is a possibility of change in the properties of the materials with which the sensor is designed. Due to this reason, there will be malfunctioning of the device. Hence designing a temperature independent pressure sensor is another challenge.
3. A pressure sensor should be linear over a wide range of pressure and temperature. Non-linearity in the output of a pressure sensor is a major issue and needs to be addressed.
4. A pressure sensor should be highly sensitive to the input pressure. Sensitivity depends on various factors such as positioning of the piezoresistors on the diaphragm, dimensions of the piezoresistors, thickness of the diaphragm, etc. In order to make the system to be highly sensitive, one has to go for a very thin diaphragm which will limit the use of sensor for larger pressure values. Thus there has to be a tradeoff between the thickness of the diaphragm and the range of pressure to be sensed which will decide the sensitivity of the device.
5. The designed pressure sensor should be optimized in order to produce optimum results. Optimization is largely dependent on the reliability of the simulation tools available.
6. Limitations in the fabrication facilities have been another challenge for the design and development of pressure sensors.

Another issue is the working environment of the pressure sensor. These sensors may need to operate in harsh environments such as in salt water, bloods, strong acid, alkaline or organic solutions. Overall, the issue is to package the device such that it must be able to withstand the environment(s).

V. CNT BASED PIEZORESISTIVE PRESSURE SENSOR

There are three basic aspects need to be addressed in order to study the CNT based piezoresistive pressure sensors, viz., the sensing mechanism, material used to design a sensor and the performance parameters.

A. *Pressure sensing mechanism*

The basic principle of CNT based piezoresistive pressure sensor is the measurement of change in the resistance across the CNTs due to the pressure applied. But the difference lies in the number of CNTs used as piezoresistors, their orientation and their location on the diaphragm.
The first theory provides the pressure sensor design that consists of piezoresistive CNT element resting on top of a diaphragm as shown in Fig. 5.1.

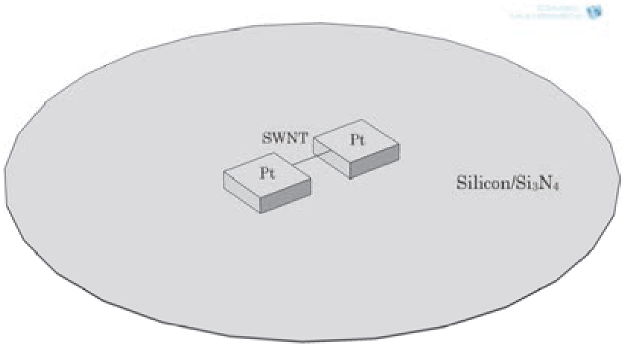

Fig.5.1. Single SWNT piezoresistive pressure sensor[18]

A contact is established with the SWNT utilizing Platinum electrodes, thus measuring the resistance of the nanostructure [18]. The application of pressure underneath the sensor causes a deflection of the silicon membrane and this causes a change in resistance of the Carbon nanotube. The optimal location to place the CNT would be the region of maximum strain on the diaphragm. As a result, the calculation of strain distribution and deflection in accordance with the applied pressure becomes pivotal.
Similar to a sensor shown in Fig.5.1, a bundled strands of CNT sensing elements on diaphragm can also be implemented as pressure sensor as shown in fig 5.2 [19].

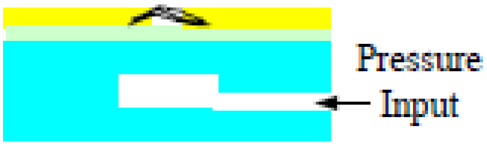

Fig. 5.2. Bundled strands of CNTs on diaphragm [19]

The second method describes the purely parallel ultrasmall piezoresistive pressure sensors with small bandgap semiconducting- SWNTs as active transducer elements which are aligned on the diaphragm as shown in Fig 5.3 is another method of positioning of the CNTs on the diaphragm.

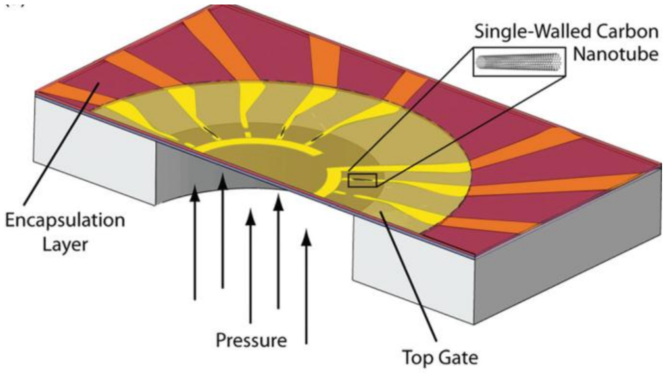

Fig.5.3 Piezoresistive pressure sensor with parallel integration of individual SWNT [20]

As shown in Fig 5.3, the individual small bandgap semiconducting carbon nanotubes are aligned in the radial direction on the edges of the circular membrane, the regions of maximum strain. The circular membrane is covered by a top gate and the SWNTs are protected by an encapsulating alumina layer. The radially arranged palladium electrodes are structured on silicon oxide. Purely parallel integration techniques are used in the sensor assembly [20].

Another theory of piezoresistive pressure sensing mechanism is fabrication of a piezoresistive composite using multi walled carbon nanotubes (MWCNTs) as a conductive filler and polydimethylsiloxane (PDMS) as a polymer matrix. A polymer wrapping method using poly (3-hexylthiophene) (P3HT) is used to modify the MWNTs in order to achieve a homogeneous dispersion of MWCNTs in PDMS [21].

These kind of polymer composite materials are basically used in the low pressure applications such as flexible finger-sensing devices, etc where the range of pressure is 0 – 0.12 MPa.

Placing of piezoresistive CNTs on the surface of diaphragm to form a Wheatstone bridge circuit for pressure sensing has been the recent advancement in sensor application. In this method, there will be four CNTs connected to form a Wheatstone bridge as shown in Fig.5.5.

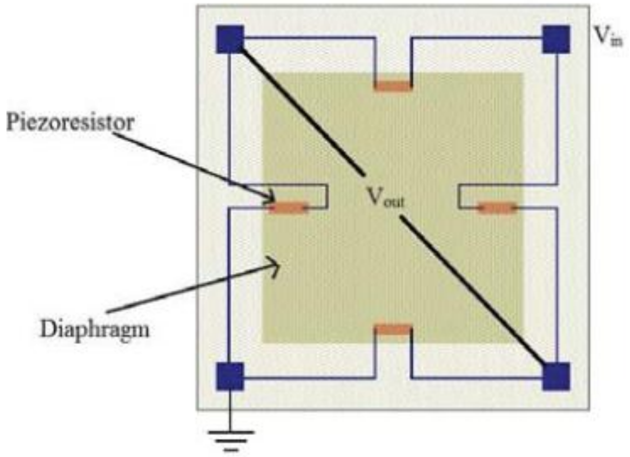

Fig.5.5. Piezoresistors connected in Wheatstone bridge circuit [22]

A typical Wheatstone bridge is as shown in Fig 5.6

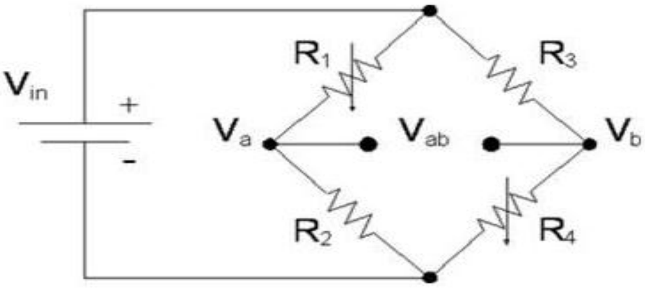

Fig. 5.6. Typical Wheatstone bridge circuitry

In Fig 5.6, the Wheatstone bridge consists of four piezoresistive material labeled as R_1, R_2, R_3 and R_4 respectively. The resistance [R] of a piezoresistive material is given by

$$R = \rho \frac{L}{A} \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ (5)$$

where ρ → Resistivity of a piezoresistor
L → Length of a piezoresistor
A → Area of a piezoresistor

Resistivity [ρ] of a piezoresistor is given by

$$\Sigma = \frac{1}{\rho} \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ (6)$$

where σ → Conductivity of a piezoresistor.

Wheatstone bridge is mounted on a membrane or diaphragm. When a pressure to be sensed is applied on to the diaphragm, the diaphragm experiences the sheer stress due to which, the diaphragm deforms in the direction of pressure applied. Due to the deformation of the diaphragm, the carbon nanotubes mounted on the diaphragm in a Wheatstone bridge format, stretches. As the carbon nanotubes stretches, the length increases while the area decreases. From equation (5), if length increases and area decreases, there will be incremental change in the resistance of a carbon nanotube and effectively decreases the output voltage.

When carbon nanotube stretches due to pressure applied, overall mass of CNT does not change and even the density of material also does not change, thus the volume of the CNT has to remain constant. Since Vol = L × A, as length increases, Area has to decrease to keep the volume constant. This is the reason, how the area of a CNT decreases as the length increases.

The four CNTs forming Wheatstone bridge can also be configured differently as shown in Fig.5.7.

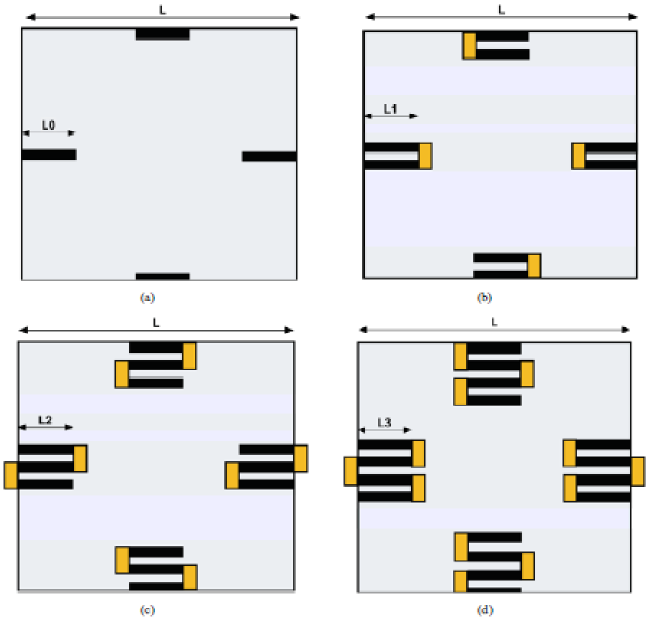

Fig.5.7. Piezoresistor configurations to form Wheatstone bridge [22]

However the sensing mechanism remains the same irrespective of the configurations, whereas the sensitivity and the nonlinearity differ from one configuration to the other. It is proved in [22] that the two turn configuration is found to have the best sensitivity of 4.181 mV/V/bar and the one turn configuration gives the least non-linearity of 0.5051 %.

Compared to the various piezoresistive pressure sensing mechanisms discussed above, Wheatstone bridge mechanism is most suitable and widely used technique because of the fact that it is easy to analyze, highly accurate, simple in design, low-cost, low input voltage and high sensitivity.

B. Materials for design of sensor

In the above discussion it is clear that the piezoresistive material is a Carbon nanotube (Metallic or Semiconducting), but depending on the application, different types of CNTs can be used as piezoresistive material such as Single Walled CNTs, Multi Walled CNTs, Vertically Aligned CNTs or even the composite of CNTs and Polymers. However the principle remains the same which is piezoresistive mechanism of pressure sensing.

The material used to design the diaphragm on which the CNTs are placed, plays a very important role in deciding the application of a pressure sensor and the range of pressure the sensor can sense. Table 1 lists a few of the materials that can be used to design the diaphragm of a pressure sensor along with the range of pressure it can withstand and the respective application area.

TABLE I. LIST OF MATERIALS USED TO DESIGN THE DIAPHRAGM

Sl. No.	Material	Pressure Range	Major area of Application
1	Silicon	0-1 Mpa	1.Medical field for Spirometers, Patient Monitoring Equipments. 2.Barometric Applications
2	Titanium	Upto 20 Mpa	Hydraulics in Aerospace Applications
3	Stainless Steel	Upto 20 Mpa	Hydraulics in Aerospace Applications
4	Silicon Nitride	1 to 500 kPa	Intracranial Pressure sensing Application
5	Polymethylmethacrylate	0-60 kPa	Biological Pressure sensing Application
6	PolyDimethylsiloxane	0-0.12 MPa	Artificial skin, Intelligent textile

However the list is not exhaustive with respect to the material used to design the diaphragm and it depends on the application area and the range of pressure to be sensed.

Apart from the piezoresistive CNTs and diaphragm materials, other materials such as Parylene C, SiO_2, TiO_2, etc., are used as insulating layer to protect the diaphragm and improve the adhesion of electrodes to the substrate.

Finally the materials used for designing of electrodes in the later part of design of pressure sensor can be made up of aluminum, platinum, gold, etc. However gold is rarely used as an electrode material, since it also is a piezoresistive material, which leads to nonlinearity in the graph of Change in resistance v/s pressure applied.

C. Performance parameters

When a pressure is applied onto the diaphragm, it tends to get deformed (displaced), with maximum displacement at the centre of the diaphragm. The value of displacement decreases near the fixed ends of the diaphragm. The quantity of displacement is measured at the centre of the diaphragm using the following equation,

$$x = \frac{0.00126\,P\,L^4}{D} \_\_\_\_\_\_\_\_\_\_\_\_ (7)$$

where P → Pressure applied on the diaphragm,
L → Length of the diaphragm
D → Bending rigidity of the diaphragm material and is given as

$$D = \frac{Et^3}{12\,(1-v^2)} \_\_\_\_\_\_\_\_\_\_\_\_ (8)$$

where E → Young’s Modulus of the diaphragm material
t → Thickness of the diaphragm
v → Poisson’s ratio of the diaphragm material

The amount of sheer stress experienced at the mid-point of the diaphragm is given as:

$$\gamma = \left(\frac{L}{t}\right)^2 \_\_\_\_\_\_\_\_\_\_\_\_ (9)$$

It can be concluded from equation (7) and (9) that, increase in the pressure applied on the diaphragm increases the sheer stress at the mid-point of the diaphragm, also increases the displacement (deformation) of the diaphragm. The displacement of the diaphragm also depends on the dimensions of the diaphragm as well as the stiffness property (Young’s modulus) of the material with which the diaphragm is prepared.

When a pressure is applied on the diaphragm with four CNT blocks as piezoresistors, the stress induced causes change in resistance of piezoresistors due to piezoresistive effect. This change in the value of resistance of the CNT bundles is denoted by ΔR. Due to the deformation of the diaphragm in the direction of pressure applied, it is said that the length of the CNT blocks increases which in turn increases the resistance of the CNTs blocks (using equation 5). Thus it can be concluded that, as the applied pressure increases, there is a linear increase in the resistance of the piezoresistors.

The third parameter used for sensing the pressure applied is the output voltage across the Wheatstone bridge. The output voltage of the Wheatstone bridge depends on the input voltage applied to the bridge circuit and also the resistance values of all the four piezoresistive materials. Hence, as the resistance of the piezoresistive materials changes due to the pressure applied, the output voltage of the Wheatstone bridge also varies. The output voltage [Vout] across the Wheatstone bridge circuit is given by,

$$V_{out} = V_{in}\left[\frac{R_2R_3 - R_1R_4}{(R_1 + R_2)(R_3 + R_4)}\right] \text{ Volts } \_\_\_\_\_\_\_\_\_\_\_\_ (10)$$

where Vin → Input voltage applied to Wheatstone bridge circuit.
R_1, R_2, R_3, R_4 → Resistance values of 1st, 2nd, 3rd and 4th CNT blocks respectively.

From equation (10), when $R_2R_3 = R_1R_4$, Vout = 0. This means that the bridge is in the balanced state and theoretically no pressure is applied onto the diaphragm. When no pressure is applied onto the diaphragm, the resistance values of all the CNT blocks will be theoretically identical, hence $V_{out} = 0$.

But practically it may be difficult to fabricate the CNT blocks of equal resistances, due to which the output voltage may not be zero when no pressure is applied. From equation (10), it can be concluded that, as the applied pressure increases, resistance of the CNT blocks (bundles) increases, hence the output voltage decreases.

Another parameter used for measuring the amount of pressure sensed is the electric field in the vicinity of surface of diaphragm. The relation of electric field in the vicinity of surface of diaphragm with applied stress is given in equation 11.

$$E = \rho J + \Delta\rho J \_\_\_\_\_\_\_\_\_\_\_\_ (11)$$

where ρ → resistivity of nanotubes,
J → current in piezoresistors,
Δρ → induced change in resistivity which is given by the equation,

$$\Delta\rho = \pi.\gamma \_\_\_\_\_\_\_\_\_\_\_\_ (12)$$

where π → piezoresistance tensor, a material property.
γ → shear stress given by equation (9).

The performance of the proposed model can be estimated based on the sensitivity of the sensor to the pressure applied and the gauge factor of a structure.

The sensitivity of a pressure sensor is defined as the relative change in the output voltage per unit of applied pressure. The sensitivity of the proposed piezoresistive pressure sensor is given by

$$S = \frac{\Delta V_{out}}{\Delta P}\frac{1}{V_{in}} \text{ mV/V/Bar} \_\_\_\_\_\_\_\_\_\_\_\_ (13)$$
$$= \frac{\Delta R}{\Delta P}\frac{1}{R}$$

Where S → Sensitivity of the pressure sensor
ΔVout → Change in the output voltage
ΔP → Change in the pressure applied
Vin → Input voltage
ΔR → Change in the resistance of CNTs
R → Initial resistance of the CNT block when no pressure is applied.

For the system to be better, it should be highly sensitive. In other words, there should be large decrease in the output voltage and large increment in the resistance of CNT blocks due to a small increase in the pressure applied to call a proposed device as highly sensitive.

Gauge factor is another parameter which determines the performance of the proposed piezoresistive pressure sensor. The Gauge factor of a structure is the change in resistance to the amount of volumetric strain acting on it. It is given as

$$GF = \frac{\Delta R/R}{\varepsilon} \_\_\_\_\_\_\_\_\_\_\_\_ (14)$$

where ε → Strain of the pressure sensor.

The strain of the pressure sensor is computed from simulation. The Gauge factor value should be large (in the range of 500 to 1000) to indicate the better performance of the proposed model.

VI. APPLICATIONS OF PIEZORESISTIVE PRESSURE SENSOR IN MEDICAL FIELD

Pressure sensors find its application in almost all the fields. Piezoresistive pressure sensing is the most widely used pressure sensing mechanism. Pressure sensors are most widely used in medical applications for various measurements. Few of them are listed in table 2:

TABLE. II. APPLICATIONS OF PRESSURE SENSOR IN MEDICAL FIELD

Sl. No	Measurements	Type	Pressure range
1	Barometric pressure	Absolute	101.3 kPa
2	In vivo blood Pressure	Absolute	Upto 40 kPa max
3	Ex vivo blood pressure	Gauge	Upto 40 kPa max
4	Intraocular pressure (IOP)	Gauge	2 kPa
5	Vacuum (light-medium)	Gauge	100 Pa to 3 kPa
6	Liquid or gas flow	Differential	Application dependent
7	Drug delivery (liquid flow)	Differential	flow rates (0.5-10.0 microliters/min)
8	Respirator (airflow)	Differential	4 kPa
9	Ventilator (airflow)	Differential	2.5 kPa
10	Spirometer (airflow)	Differential	4 kPa
11	Oxygen concentrator	Gauge	4 kPa
12	Hyperbaric oxygen (HBOT) hard	Gauge	600 kPa
13	Hyperbaric oxygen (HBOT) soft	Gauge	30 kPa and 50 kPa
14	Oxygen tank	Gauge	Upto 14 MPa
15	Sleep apnea (CACP)	Differential	4 kPa

VII. CONCLUSIONS

Research activity in the areas related to CNT based piezoresistive pressure sensor has had a phenomenal growth over the last decade. In this paper, an attempt is made to provide the most contemporary review on CNT based pressure sensors, their various sensing mechanisms, materials used to design and their potential applications in a medical field. The Piezoresistive pressure sensor based on Wheatstone bridge circuit is widely used by many reported works.

The exceptional properties, which allow CNTs to be used in sensors, has also been reviewed. The use of CNTs will increase the sensitivity and dynamic range of pressure sensing. Dielectrophoresis is the fabrication technique to place the CNTs on the diaphragm of the sensor. However, CNTs have yet to cross many technological hurdles in order to fulfill their potential as the preferred material for sensor applications.

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