

A Critical Review of Carbon Nanotube based MEMS Piezoresistive Pressure Sensor for Medical Application

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Abstract: This paper discuss about the critical review on design of carbon nanotube based MEMS piezoresistive pressure sensors, use of different types of carbon nanotubes such as multi-walled carbon nanotubes (MWCNTs), single-walled carbon nanotubes (SWNTs) and vertically aligned carbon nanotubes (VANTs), sensing mechanism, applications, etc. The structural deformation of the piezoresistive nano structure will result in change of resistance. CNT is a sophisticated material with interesting electrical, mechanical, physical properties that can be used for fabrication of micro pressure sensors on different substrates, which may serve as alternative for silicon based pressure sensors when bio-compatibility and low cost applications are required.

Index Terms— Carbon Nanotube, MEMS, Piezoresistance, Pressure sensor, Sensitivity, Stress

I. INTRODUCTION

A pressure sensor measures pressure, typically of gases or liquids. Pressure is an expression of the force required to stop a fluid from expanding, and is usually stated in terms of force per unit area. Pressure sensors are used for control and monitoring in thousands of day today applications. Pressure sensors can be classified based on the sensing mechanism which is listed below:

1. *Force collector* -This type of electronic pressure sensors generally use a force collector (such a diaphragm, piston, bourdon tube, or bellows) to measure strain (or deflection) due to applied force (pressure) over specified area.
2. *Capacitive* - uses a diaphragm and pressure cavity to create a variable capacitor to detect strain due to applied pressure, capacitance decreases as pressure deforms the diaphragm. Common technologies use metal, ceramic and silicon diaphragms.
3. *Resonant* -uses the change in resonant frequency to measure stress, or changes in gas density caused by applied pressure.
4. *Thermal*-uses the change in thermal conductivity of a gas due to density changes to measure pressure.
5. *Ionization* - measures the flow of charged gas particles which varies due to density changes to measure pressure. Common examples are the hot and cold cathode gauges.
6. *Piezoresistive strain gauge* - it uses the piezoresistive effect of bonded or formed strain gauges to detect strain due

to applied pressure, resistance varies as pressure deforms the material. Common technology types are Silicon (Mono crystalline), Polysilicon, CNTs.

In piezoresistive pressure sensor, the piezoresistive effect is a change in the electrical resistivity of a piezoresistive material when mechanical strain is applied. In contrast to the piezoelectric effect, the piezoresistive effect causes a change only in electrical resistance, not in electric potential. The mechanism is in conducting and semi-conducting materials, changes in inter-atomic spacing resulting from strain affect the band gaps, making it easier for electrons to be raised into the conduction band. This results in a change in resistivity of the material. Within a certain range of strain this relationship is linear.

Existing simulation models for carbon nanotubes are grounded on two fundamental frameworks namely *discrete* and *continuum* models. The discrete models provide a valuable insight in analyzing the behavior of individual CNTs, but are restrained to small time and length scales due to immense computing power precincts. Though continuum models face a serious threat of break down in the Nano regime, many assumptions and designs for modeling macro and micro mechanics are valid at Nano scale to some extent [1]. Polysilicon is a well-known piezoresistive material for MEMS sensors because of its much higher sensitivity to strain changes than metals. However, the response of Polysilicon sensors is highly temperature dependent, which affect their abilities to sense true strain parameters [3].

S.H Abdul Rahman *et al* [8] gives an idea on Nano electromechanical sensors based on vertically aligned carbon nanotubes (VACNTs). At first, the VACNT films are synthesized on the pores anodic aluminum oxide (AAO) substrate by using chemical vapor deposition (CVD). AAO is used as a support to grow VACNTs. The advantages of the method are fast alignment, array design, mass production, high level structural diversity, and complexity. The excellent strain of CNTs produces a highly piezoresistive network, which benefits pressure sensors and micro scale/Nano scale strains with fine resolution. Many studies have examined the fabrication of highly sensitive pressure sensors by depositing piezoresistive CNTs onto the fixed silicon substrate in which single-walled and multi-walled carbon nanotubes are utilized as active sensing elements.

II. EVOLUTION OF CNT BASED PIEZORESISTIVE PRESSURE SENSOR

In 1952 L. V. Radushkevich and V. M. Lukyanovich worked on clear images of 50 nanometer diameter tubes made of carbon. This discovery was largely unnoticed, it is likely that carbon nanotubes were produced before this date, but it was almost impossible to see them, as the transmission electron microscope (TEM) was not invented. When it was invented, during that time, it allowed direct visualization of these structures.

Carbon nanotubes have been produced and observed under a variety of conditions prior to 1991. A paper by Oberlin, Endo, and Koyama published in 1976 clearly showed hollow carbon fibers with nanometer-scale diameters using a vapor-growth technique. Additionally, the authors show a TEM image of a nanotube consisting of a single wall of graphene. Later, Endo has referred to this image as a single-walled nanotube (SWNT).

In 1979, John Abrahamson worked on the carbon nanotubes as carbon fibers that were produced on carbon anodes during arc discharge. A characterization of these fibers was given as well as hypotheses for their growth in a nitrogen atmosphere at low pressures.

In 1981, a group of Soviet scientists work with the results of chemical and structural characterization of carbon nanoparticles produced by a thermo catalytical disproportionation of carbon monoxide. Using TEM images and XRD patterns, the authors suggested that their "carbon multi-layer tubular crystals" were formed by rolling graphene layers into cylinders. They speculated that by rolling graphene layers into a cylinder, many different arrangements of graphene hexagonal nets are possible. They suggested two possibilities of such arrangements: circular arrangement (armchair nanotube) and a spiral, helical arrangement (chiral tube).

In 1987, Howard G. Tennett of Hyperion Catalysis was issued a U.S. patent for the production of "cylindrical discrete carbon fibrils" with a constant diameter between about 3.5 and about 70 nanometers, length 102 times the

diameter, and an outer region of multiple essentially continuous layers of ordered carbon atoms and a distinct inner core.

Two decades since their discovery by Iijima in 1991, CNTs have been subjected to extreme observations and detailed analysis owing to their remarkable properties. This unique allotrope of carbon due to its extraordinary electronic properties and peculiar mechanical properties has received much attention in the Nano-electro-mechanical systems (NEMS) community.

A coalescence of interesting properties makes the carbon nanotubes as potential Nano transducers in pressure sensing applications. Modern miniaturized pressure sensors have put piezoresistive and capacitive effects into play and a major area of concern has always been the low sensitivity of the piezoresistive materials employed. Theoretical and experimental analysis of the electromechanical properties of Single walled nanotubes (SWNT) highlights the materials' extraordinary potential and diversity.

III. PIEZORESISTIVE PRESSURE SENSING MECHANISM

The pressure sensor design consists of piezoresistive element resting on top of diaphragm. A contact is established with the electrodes, thus measuring the resistance of the nanostructure. The application of pressure underneath the sensor causes a deflection of the membrane and this causes a change in resistance of the carbon nanotube as shown in Figure.1. The optimal location to place the piezoresistive material 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.

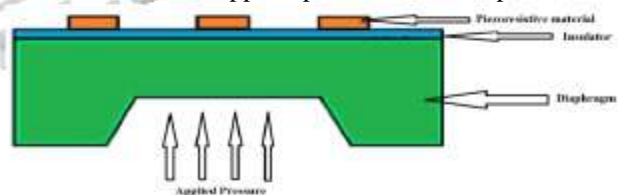


Figure.1 Conventional pressure sensor

IV. CONFIGUREURATION OF CNT BASED PIEZORESISTIVE PRESSURE SENSORS

There can be different types of CNT based piezoresistive pressure sensor designs possible depending on the number of CNTs used in the design, sensing mechanism, placements (position) of CNTs on the diaphragm of the sensor, etc. Figure 2 illustrates the pressure sensor design consists of piezoresistive CNT element resting on top of Silicon / Si₃N₄ diaphragm. A contact is established with the SWNT utilizing platinum electrodes, thus measuring the resistance of the nanostructure. The application of pressure underneath the sensor causes a deflection of the silicon membrane and this causes a change in resistance of the CNT. The optimal

location to place the CNT would be the region of maximum strain on the diaphragm. [1].

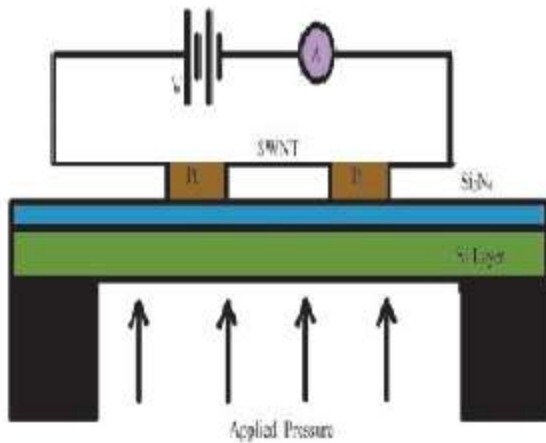


Figure. 2 The Pressure sensor model

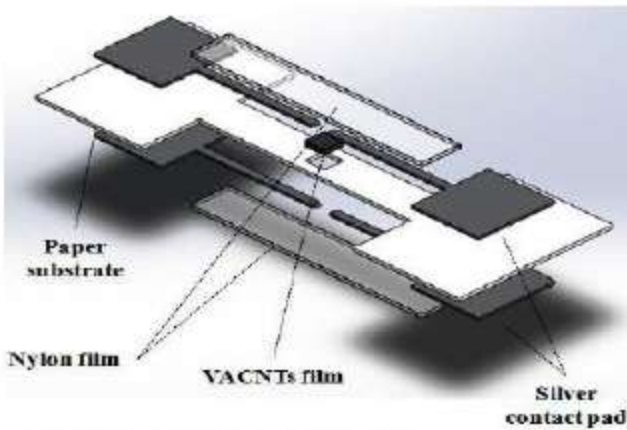


Figure.3 Schematic view of a VACNTs/paper-based load sensor

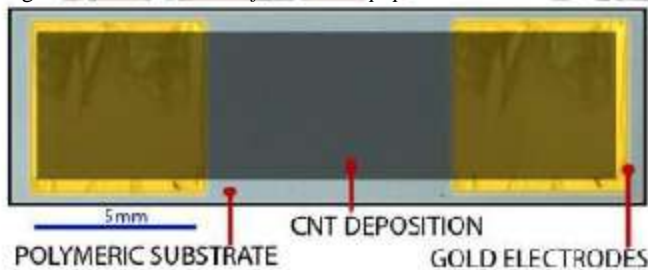


Figure.4 Layout of the CNT strain sensor

Figure.3. illustrates the vertically aligned carbon nanotube (VACNT) films are promising for use as piezoresistive based sensors. When VACNT is subjected to mechanical deformations, its resistance changes dramatically. This effect can be utilized for strain sensing, pressure sensing, and also for nano electro-mechanical transducers in micro electromechanical systems (MEMS). The VACNTs/paper-based load sensor, an A4 paper with a thickness of 340 μm was chosen as the substrate, and it was patterned to the required dimensions (80 mm \times 8 mm) using a laser cut with a precision of 0.12 mm. the electrical contact pads were

printed using a silver ink. Then VACNTs film (5 \times 5 mm) was attached to the paper substrate. In order to certify the connections between the printed contact pads and sensing components (VACNTs film) a small drop of silver ink was placed on the connections using a painting brush. Moreover, in order to protect the connections a nylon film was placed on the top and bottom of the sensor using a paste. At the end, by connecting the contact pads to the multimeter, it was possible to read the resistance change of the system [4].

Figure.4. shows that, a new type of low-cost strain sensor, based on piezoresistive carbon nanotube (CNT) network deposited on a flexible substrate. The substrate is a flexible polymer on which gold electrodes are deposited. The polymer is ETFE (Ethylene tetrafluoroethylene), is chosen for its high resistance to temperature, elevated pH aggressive chemicals, and for its high resistivity. Gold is chosen for its high conductivity and high resistance to corrosion. A layer of CNTs is then deposited both on top of the contacts and between the electrodes. The size the device is 5 x 17 mm (width x length) for a thickness of 0.15 mm [5].

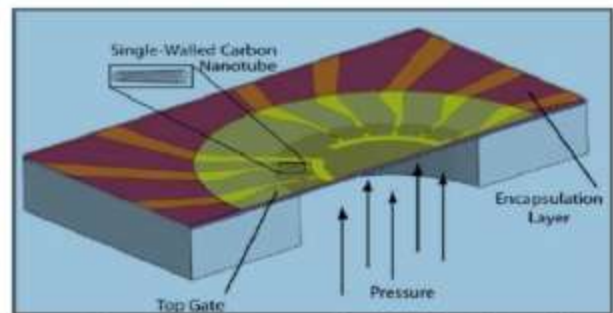


Figure. 5 Carbon nanotube are aligned in radial direction to the edge of circular membrane of the pressure sensor

Figure.5 shows the parallel fabrication of SWNT based piezoresistive pressure sensors consist of two essential elements. First, CNTs are dielectrophoretically positioned between predefined electrodes, before the pressure sensor membrane is released by bulk micro machining and final encapsulation and connections are made. When pressure is applied to the encapsulation layer, there will be change in the resistance of SWNT. To achieve even higher CNT gauge factors, contact resistance has to be minimized and CNT transmission increased [6].

Figure.6 (a) illustrates the simulation set up of the piezoresistive pressure sensor with square diaphragm. Four faces of the square silicon diaphragm are fixed. Force in the range of 2- 10 mmHg are applied along the z direction while the forces in x and y direction are zero. Figure.6 (b) shows the simulation set up of the Piezoresistive pressure sensor with slotted square diaphragm. Twelve faces of the square silicon diaphragm are fixed. The same force range and direction as square diaphragm are applied onto the slotted diaphragm [8].

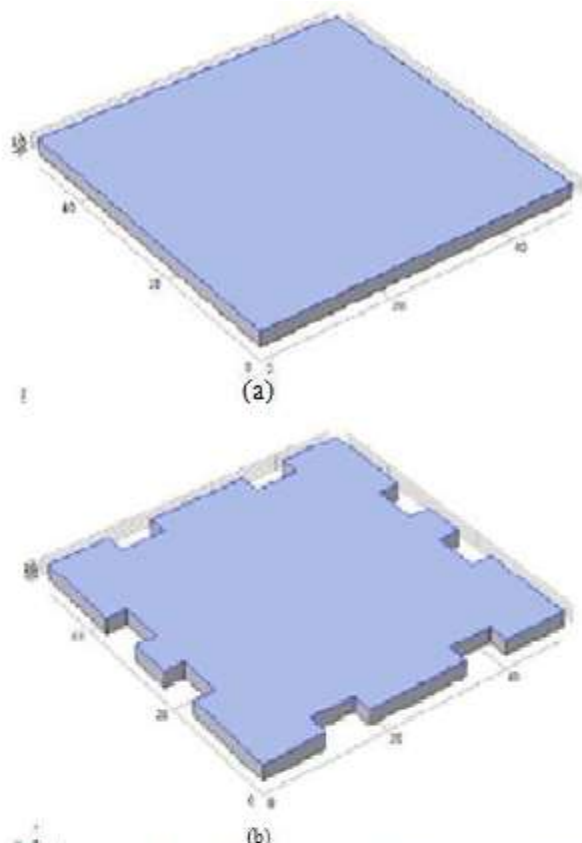


Figure.6 Simulation set up for a (a) square and (b) slotted square diaphragm pressure sensors.

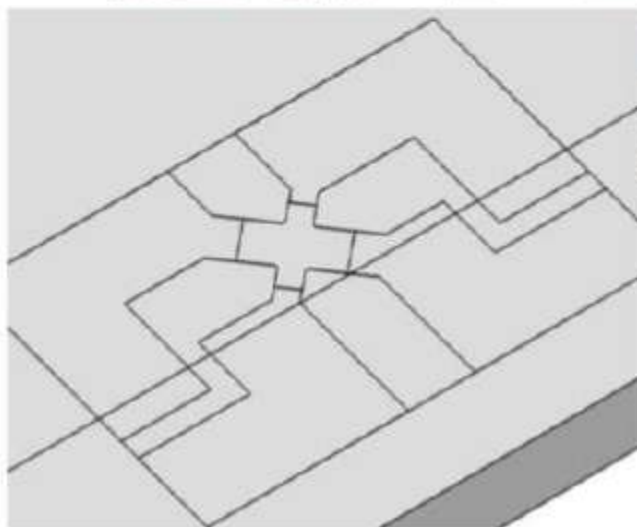


Figure.7 Geometry of piezoresistor.

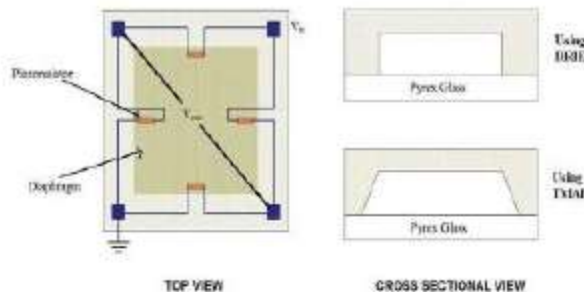


Figure. 8 A wheatstone bridge Piezoresistive pressure sensor.

From Figure.7.illustrates the diaphragm with a square membrane of side 1 mm and thickness 20µm around its edge by region 0.1mm wide was designed. The piezoresistor as in wheatstone bridge circuit is constructed using various predefined structures in geometry. The upper surface, lower surface and membrane lower are defined using geometry tool. The area of membrane lower surface is subtracted from upper surface using comsol and is fixed. The fixed area does not experience any change, whereas the remaining area experiences, when force is applied on the pressure sensor [9].

The work in [10] describes a pressure sensor consists of a diaphragm with four piezoresistors on top of it connected in a wheatstone bridge circuit arrangement. This is illustrated in Figure.8. The diaphragm is generally formed by dry etching using Deep Reactive Ion Etching (DRIE) or though wet bulk micromachining using alkali hydroxides like Potassium hydroxide (KOH) or Tetramethylammonium hydroxide (TMAH). The diaphragm is sealed from back side using anodic bonding in vacuum in order to measure the absolute value of pressure. The applied pressure causes diaphragm deflection and stress in diaphragm, which is sensed by the piezoresistors on top of the diaphragm. The piezoresistors are placed in regions of diaphragm where high stress is generated when a pressure is applied.

A. Material used for design of CNT based Piezoresistive pressure sensor

The diaphragm is used for mechanical support to sensor. The materials that are used for diaphragms are Silicon, Aluminum, PMMA, PDMS, and Polycrystalline. The insulator is placed between diaphragm and piezoresistive elements, which is in non-conductive state that reduce heat transfer. The materials are silicon dioxide (SiO₂), Parylene C. And the sensing materials are metals such as Platinum (Pt), gold (Au), copper (Cu). These are the materials used for design of diaphragm of CNTs based piezoresistive pressure sensors, and their properties are listed below.

Table 1: Properties of various materials

S.No	Material	Density (kg/m ³)	Young's Modulus(Gpa)	Poisson's ratio	Pressure range (Pascal)
1	Silicon	2330	160	0.22	1-(500*10 ³)
2	Platinum	2145	168	0.38	1-(550*10 ⁶)
3	Polydimethylsiloxane	965	360	0.5	1-(3*10 ⁶)
4	Polymethyl Methacrylate	1190	3	0.40	1-(14*10 ⁹)
5	Anodic aluminium oxide	3965	400	0.20	1-(10*10 ⁶)
6	Ethylene Tetrafluoroethylene	1.75	1.5	0.21	1-(23*10 ⁶)
7	Parlyene C	2.4	2.8	0.29	1-(69*10 ⁶)
8	Silicon dioxide	2.17	66.3	0.15	1-(400*10 ²)
9	Gold	1930	70	0.44	1-(120*10 ⁵)
10	Poly crystalline Si(n,p type)	2320	160	0.22	1-(500*10 ²)

B. Performance Parameter and Mathematical analysis

The gauge factor of the piezoresistive CNT sensing element can be estimated in the following equation [3]

$$GF = \frac{\Delta R}{R} \left(\frac{1}{\epsilon} \right) \dots \dots \dots (1)$$

Where R_0 are the initial resistance of the sensor without applying pressure, resistance change of the piezoresistor. Under applied pressure, and the strain of the sensor, respectively. R is the resistance of the sensor under applied pressure. The sensitivity of a pressure sensor is defined as the relative change in the output voltage per unit of applied pressure [10]

$$S = \frac{\Delta V_{OUT}}{\Delta P} \frac{1}{V_{in}} = \frac{\Delta R}{R} \frac{1}{R} \dots \dots \dots (2)$$

The maximum deflection of the square diaphragm due to pressure applied is

$$w_{max} = \frac{0.00126Pa^4}{D} \dots \dots \dots (3)$$

Where a is side length of diaphragm and P is applied pressure. The D is the flexural rigidity, and is given by [12]

$$D = \frac{Eh^3}{12(1-\nu^2)} \dots \dots \dots (4)$$

Where E , h and ν are Young's modulus, plate thickness, and Poisson's ratio, respectively. Eq. (3) and (4) implies that the diaphragm will exhibit a maximum strain at the center and would therefore be the ideal place for the nanotubes to lie. To find the analytical solution, the deflection in the linear region of operation can be expressed as follows for a square diaphragm [13]

$$\frac{w_0}{h} = \frac{Pa^4}{Eh^4g_1} \dots \dots \dots (5)$$

The maximum stress, which occurs in the center at the edge of the square diaphragm, can be expressed by the analytical expression for a square diaphragm as [13]

$$\sigma_{max} = p \left(\frac{a}{h} \right)^2 \dots \dots \dots (6)$$

V. APPLICATIONS OF PRESSURE SENSORS

The pressure sensors are used in many applications such as barometric applications, industrial, automobile's, touch screen and medical field etc. In barometric applications Using barometric pressure and the pressure tendency (the change of pressure over time) has been used in weather forecasting since the late 19th century. Simultaneous barometric readings from across a network of weather stations allow maps of air pressure to be produced, which were the first form of the modern weather map when created in the 19th century.

In Medical applications such as Non-invasive and invasive blood pressure monitors, Fetal heart rate monitors Inhalers and ventilators, Wound management, Patient monitoring systems, Spirometer and respiratory therapy devices, Dialysis systems, Drug delivery systems, a pressure sensor is required. In this article, a focus is on use of pressure sensor in Patient Monitoring Systems.

A. Patient Monitoring Systems

Remote patient monitoring (RPM) is a technology to enable monitoring of patients outside of conventional clinical settings, which may increase access to care and decrease healthcare delivery costs. Incorporating RPM in chronic disease management can significantly improve an individual's quality of life. Figure.9 illustrates the various types of sensors that are used in patient monitoring system. The purpose is to monitor the patient's vital factors such as blood, pressure, temperature, reading them at specified frequencies from analog devices and storing readings in a db. If readings fall outside the range specified for patient or device fails an alarm must be sent to a controller.

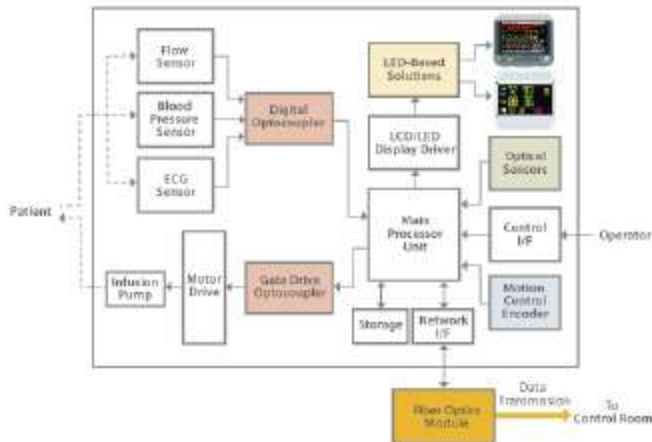


Figure. 9 Block diagram of a typical Patient Monitoring System.

Physiological data such as blood pressure and subjective patient data are collected by sensors on peripheral devices. Examples of peripheral devices are blood pressure cuff, pulse oximeter and glucometer. The data are transmitted to healthcare providers or third parties via wireless telecommunication devices. The data are evaluated for potential problems by a healthcare professional or via a clinical decision support algorithm, and patient, caregivers, and health providers are immediately alerted if a problem is detected. As a result, timely intervention ensures positive patient outcomes. The recent applications also provide education, test and medication reminder alerts, and a means of communication between the patient and the provider.

VI. ADVANTAGES AND DISADVANTAGES

CNTs have several unique chemical, sizes, optical, electrical and structural advantages that make an attractive. In electrical and structural the nanotube is semiconducting with a very small band gap otherwise the nanotube is a moderate semiconductor. Some nanotubes have conductivities higher than that of copper, while others behave more like silicon. In dimensions of CNTs are smaller in size, due to their Nano scale dimensions, electron transport in carbon nanotubes will take place through quantum effects and will only propagate along the axis of the tube. The fact that CNTs are small allows them to deliver smaller doses of drugs to specific disease cells in the body thus reducing side effects and harm to healthy cells unlike conventional drugs, whilst improving disease cell targeting efficiency. In chemical, CNTs have been observed to have enhanced solubility when functionalized with lipids which would make their movement through the human body easier and would also reduce the risk of blockage of vital body organ pathways. The disadvantages of CNTs are lifetime, reliability, difficulties in mass production, production cost. In lifetime the carbon nanotube degrades in a few days when exposed to oxygen. There have been several works done on the nanotubes with different polymers and increasing their lifetime. In with respect to reliability Carbon nanotubes have shown reliability issues when operated under high electric

field or temperature gradients. In with respect to difficulties in mass production, production costs the CNTs have unique properties such as stiffness, strength, and tenacity compared to other materials especially to silicon, there is currently no technology for their mass production and high production cost. To overcome the fabrication difficulties, several methods have been studied such as direct growth, solution dropping, and various transfer printing techniques.

CONCLUSION

The modeling of a CNT based piezoresistive pressure sensors and their pressure sensing mechanisms have been discussed. In all the CNT based models, pressure sensing mechanism is piezoresistive. Such that a structural deformation of the piezoresistive Nano structure placed above the diaphragm will result in a change of resistance, which is in direct accordance with the applied pressure. To achieve the better sensitivity of a pressure with CNTs located so as to harness high strain transition is evaluated. Di-electrophoresis can be a potential technique to disperse CNTs between electrodes for these studies. By optimizing parameters like voltage, frequency and time one can fine tune the density and alignment of CNTs between electrodes. Further this technique can be used to selectively decompose metallic tubes by passage of a high current to enrich the abundance of semiconducting tubes. The various advantages and disadvantages of pressure sensors have been discussed along with the potential applications with an emphasis on the use of pressure sensor in medical field.

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