CARBON NANOTUBES BASED PIEZORESISTIVE PRESSURE SENSOR

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Abstract—Piezoresistive sensors are the sensors which convert the pressure applied into the change in the resistance. It involves the silicon substrate that bends with the applied pressure that gives the overall change in the resistance. Nowadays, although piezoresistive pressure sensor has a wide range of applications, the materials with which it is formed makes this pressure sensor to act more effectively with high sensitivity. This paper describes the relative comparison of different materials with respect to the carbon nanotubes and also elaborates the working mechanism of this carbon nanotubes piezoresistive pressure sensor.

Index Terms—Carbon Nanotubes, Piezoresistive pressure sensors, Mechanical stress.

I. INTRODUCTION

A pressure sensor measures pressure, typically of gases or liquids [2]. 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 as Force collector, Capacitive Resonant, Thermal, Ionization, Piezoresistive strain gauge.

II. PIEZORESISTIVE PRESSURE SENSOR

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. 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.

III. PIEZORESISTIVE PRESSURE SENSING MECHANISM

The pressure sensor design consists of piezoresistive element resting on top of diaphragm [1]. 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

Figure.1 Conventional Pressure Sensor

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.

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 in Figure.2

Figure.2 Single SWNT piezoresistive pressure sensor

A contact is established with the SWNT utilizing Platinum electrodes, thus measuring the resistance of the nanostructure [3]. 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.

In this paper a critical review on CNT as piezoresistive is carried.

IV. EVOLUTION OF CARBON NANOTUBES

In 1952 L. V. Raduskevich 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 thermocatalytical 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.

V. CARBON NANOTUBE USED AS PIEZORESISTIVE MATERIAL [4]

In this section we find the co-relation between mechanical deformation and conductivity of membranes of CNT. Nanotubes are the members of fullerene structural family, there name is derived from long hallow structures with the walls formed by one atom thick sheet of carbon called graphene. These sheets are rolled at specific and discrete (“Chiral”) angles.

Lattice vectors: Any lattice vector ‘r’ in a real lattice can be written as:

\[ r = n_1 a + n_2 b + n_3 c \]

Where \( n_i \) are integers a, b and c are the unit vectors describing the lattice. From Figure.3 lattice vectors is the resultant of unit vectors describing the lattice. CNT may be thought of as a graphene sheet rolled up
to form a cylinder along the Lattice Vectors \( a_1 \) and \( a_2 \) as shown in the figure below:

**Figure.4 CNT Chiral Vectors**

Chiral vector \( C \): It is defined as the resultant of lattice vectors \( a_1 \) and \( a_2 \) given by \( C = m a_1 + n a_2 \), where \( m \) and \( n \) are integers. Carbon nanotubes are described by the chiral indices \( (n,n) \).

The coordinates of the Hexagonal lattice can be found by Chiral Vectors as shown in the Figure.5 below:

**Figure.5 Graphene first Brillouin zone with allowed electronic states**

Reciprocal lattice vectors:
The reciprocal lattice vectors can be defined as:
\[
r^* = m a_1^* + n b_2^* + p c_3^*
\]
Where \( m, n, p \) are the integers, \( a_1^*, b_2^*, c_3^* \) are the reciprocal unit vectors.

**Figure.6 Reciprocal Lattice Vectors**

The reciprocal lattice vector represents the Fourier transform of another lattice. The reciprocal lattice plays a fundamental role in most analytic studies of periodic structures, particularly in theory of diffraction.

Fermi level/point: It represents the maximum energy any electron can possess, at absolute zero and the energy at this level/point is called Fermi energy. Fermi level is in-between Valence band and conduction band. The energy state near the Fermi point may be analyzed using the first Brillouin zone of Graphene as defined by reciprocal lattice vectors \( K_1 \) and \( K_2 \). The energy band structure describes the range of energy the electron has.

The Fermi points lies on the vertices (carbon atom) of the Hexagonal Brillouin zone. At this point, electronic states given by Bornvon Karman boundary condition which lies on parallel lines \( K \), perpendicular to chiral vector \( C \). Where \( K \) is the resultant of reciprocal vectors \( K_1 \) and \( K_2 \).

Bornvon Karman boundary condition are periodic boundary condition which imposes the restriction that wave function must be periodic on a certain Bravias lattice.

The Bornvon Karman boundary condition is important in solid state physics for analyzing many features of crystals such as diffraction and band gap. Whenever stress is applied, the electronic states/energy state varies and the material gets compressed/stretched, therefore the electrons in the carbon atom gets repelled and energized. Hence the Fermi point gets changed, using this change in Fermi point we can measure the change in energy states.

The variations of electronic/energy states are obtained by measuring the Fermi point which moves with respect to lines as strain is applied. The Fermi point is found by solving the tight binding equation (1):

\[
E(K_F) = \sum \frac{r_0^2}{r_i^2} e^{ik_i R_i} \quad (1)
\]

Where \( r_0 \) is the original bond length, \( r_i \) is the deformed bond length, \( t_0 \) is the tight-binding Overlap integral, \( R_i \) is the Deformed bond vector. Tight binding overlap integral describes the properties of how electrons are tightly bounded in solids under the influence of stress applied. Deformed bond vector is the chiral vector after deformation.

Yang solved the above equation, and showed that,

\[
\Delta K_F t_0 = (1 + \nu) \varepsilon \cos 3\theta + \gamma \sin 3\theta \quad (2)
\]

Where \( \nu \) is the Poisson’s ratio, \( \theta \) is the chiral angle, \( \varepsilon \) is the axial strain, and \( \gamma \) is the torsional strain, \( \Delta K_F \) is the difference between Fermi points before and after applying stress.

Axial strain \( (\varepsilon) \) is the measure of deformation to the member due to the force applied along the axis.

Axial strain is given by: \( \varepsilon = \frac{d}{L} \)

Where \( \varepsilon \) represents axial strain, \( d \) represents the change in length, \( L \) represents the original length.

Torsional strain is the increase in potential energy of the molecule due to the repulsion between electrons in bonds that do not share an atom. After applying
pressure the electron outside the molecule exerts repulsion to the electrons in the neighboring carbon atoms, thereby increasing potential energy of the molecule. Dispersion is the fraction of atoms of the material exposed to the surface where stress is applied.

The dispersion relation of the deformed graphene may then be found by expanding $E(k)$ at $kF$.

$$E(k - k_F) = \pm \frac{3}{2}t_0\rho [k - k_F]$$ (3)

Before applying the stress, the initial length of CNT is $P_0$ say. After applying stress, the length of the wire gets changed given by $P_{new} = P_0 (1 - \alpha)$.

Where $\alpha$ is the stress applied. Due to the repulsion of the electrons in the carbon atom under the influence of stress, the electron jumps from valence band to conduction band. Therefore the energy gap gets changed.

Combining equations (2) and (3), the change in band gap for small strains may be calculated as shown in Equation (4).

$$\Delta E_{\text{gap}} = \text{sgn}(2p + 1)3t_0[(1 + v)\varepsilon \cos 3\theta + y\sin 3\theta]$$ (4)

The sign of the band-gap change is determined by the chiral indices such that 

$p = -1$, 0, 1 depending on the value of mod $(n-m, 3)$.

Where $p = \text{sgn}(x) = -1$ if $x<0/ (m>n)$

$0$ if $x=0/ (m=n)$

$1$ if $x>0/ (m<n)$

The equation (4) works well for semiconducting and armchair CNTs with diameters larger than 1 nm. For smaller CNTs and for primarily metallic CNTs, curvature plays a vital role in the gauge factor and therefore must be accounted for in the band-gap theory. For primarily metallic CNTs, Kleiner and Eggert showed that

$$\Delta E_{\text{gap}} = -\text{sgn} \left( \frac{t_0a^2}{4d^2} - \frac{ab\sqrt{3}}{2} \right) \frac{a\sqrt{3}}{2} \varepsilon \cos 3\theta$$ (5)

Where $a$ is the length of the graphene lattice unit vector, $d$ is the diameter of the CNT, and $b$ is the change in the transfer integral with change in bond length. Transfer integral is the change in transfer of electrons with change in bond length upon applying stress. The energy band gap decreases linearly with the stress applied. By comparing with the other materials like silicon etc, slope of the band gap changes rapidly with the diameter and the strain.

The change in electrical resistance due to strain can be calculated based on band-gap changes. The energy band gap changes because of the transfer of electrons from one carbon atom to another upon applying the stress. The resistance of a CNT can be accurately modeled by considering electron transport to occur by thermal activation.

This model is given in Equation (6),

$$R = R_c + \frac{1}{4\pi^2} \frac{h}{ae^2} \left[ 1 + \exp \left( \frac{\Delta E_{\text{Gap}}^0 + \frac{d\Delta E_{\text{Gap}}}{dx}}{kT} \right) \right]$$ (6)

Where $|\varepsilon|^2$ is the transmission probability of electrons with $|E-E_F| > E_{\text{Gap}}$ 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.

Transmission probability of electrons is the square of ratio of transmitted and incoming probability of electron energy.

The zero strain band gap

$$E_{\text{Gap}}^0 = \frac{t_0a^2}{24d^2}$$ (7)

For a semiconducting CNTs

$$E_{\text{Gap}}^0 = \frac{t_0a^2}{4d^2}$$ (8)

For a metallic CNTs.

The gauge factor for any set of chiral indices may be calculated using Equations (8) to (10). Gauge factor for any material is defined by,

$$GF = \frac{1}{R} \frac{\Delta R}{R}$$ (9)

Substituting equation (8) in equation (11), it can be shown that when $R_c \ll R$,

$$GF = \frac{1}{\varepsilon} \frac{\Delta \varepsilon}{\varepsilon}$$ (10)

Using this equation, the gauge factor for a specific CNT may be calculated by inserting equations (4) and (7) for semiconducting CNTs, or equations (5) and (8) for metallic CNTs, into equation (10).

**VI. ADVANTAGES OF CNT BASED PIEZORESISTIVE PRESSURE SENSOR**

As a sensor material, the linear variation of the film resistance with the pressure force of carbon nanotubes is much superior to the nonlinear behavior of silicon rubber. This suggests that the resistances of the composites are dominated by the nanotubes, not the resistance in the gap width between neighboring carbon nanotubes.
Carbon nanotubes represent a new class of semiconductor materials whose electrical properties are more attractive than silicon, particularly for building nanoscale transistor devices that are a few tens of atoms across. Electrons in carbon transistors can move easier than in silicon-based devices allowing for quicker transport of data.

Advantage of carbon nanotubes over silicon are:
- High electrical and thermal conductivity, very high tensile strength, high flexible and elastic, high aspect ratios, good field emission.
- CNTs with particular combinations of N and M (structural parameters indicating how much the nanotube is twisted) can be highly conducting, and hence can be said to be metallic. The conductivity and resistivity of ropes of SWNTs has been measured by placing electrodes at different parts of the CNTs. The resistivity of the SWNT ropes was in the order of 10−4 ohm-cm at 27°C. This means that SWNT ropes are the most conductive carbon fibers known. The current density that was possible to achieve was 107 A/cm², however in theory the SWNT ropes should be able to sustain much higher stable current densities, as high as 1013 A/cm².
- Ultra-small SWNTs have even been shown to exhibit superconductivity below 200K. Research suggests that these exotic strands, already heralded for their unparalleled strength and unique ability to adopt the electrical properties of either semiconductors or perfect metals, may someday also find applications as miniature heat conduits in a host of devices and materials.
- The carbon nanotubes have high sensitivity, linearity than the silicon. The output voltage in the carbon nanotubes is much superior and accurate than the silicon and other materials. Silicon exhibits the non-linearity due to the temperature factors but carbon nanotubes are less dependent on temperature factors so the linearity is greater in carbon nanotubes.

Carbon nanotubes with its properties like electrical conductivity are better than the silicon and hence the output voltage of the CNT based piezoresistive pressure sensor is better than the silicon based pressure sensor. Silicon is now replaced with the carbon nanotubes in all the fields due to its extraordinary properties.

CONCLUSION

From the above information, we can conclude that the change in resistance of CNT depends on the change in the energy band gap upon applying the pressure on CNT. The energy band gap changes due to the shift of electrons from one carbon atom to another upon applying the pressure.

REFERENCES


