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High Performance SWCNT Pressure Sensor

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Abstract

In the current model, designed and simulated Carbon nanotubes (CNTs) on a circular diaphragm-based piezoresistive pressure sensor was studied. Single-walled Carbon nanotubes (SWCNTs) were used to check better sensitivity. The impact of altering the pressure on the displacement, current density, and von Mises stress was studied using a single CNTs and an array of CNTs. It was observed that increasing the pressure resulted in an increase in displacement, current density, and von Mises stress. The attained sensitivity of SWCNTs was 1.428*10^-11µA\Pa. Moreover, the effect of changing diameter on the resistance of CNT and the energy bandgap was studied. The design of the current study picked the diameter limits from 1nm to 4nm. It was found that raising the diameter led to reducing the energy bandgap from 0.426 eV to 0.10 eV and decreased the resistance from 2143kΩto 543kΩ at zero strain.

Keywords: Nanotechnology, Single-walled Carbon nanotube, Pressure sensor.

1. Introduction

A carbon nanotube pressure sensor is one of the favorable sensing components in sensing technology to transform a tactile input into electrical signals [1,2]. Carbon nanotubes are widely used as a piezoresistive element in piezoresistive pressure sensors due to their unique mechanical, electrochemical, piezoresistive, and other physical qualities [3,4]. Single-walled and multi-walled carbon nanotubes (SWNTs and MWCNTs,) have been used as active sensing components in pressure sensors to create devices that are very sensitive to changes in pressure [5,6].

In recent years, several pressure sensor designs have made the devices smaller, more sensitive, highly accurate, and less expensive [7,8]. Several pressure sensing methods are utilized, such as piezoelectricity, piezoresistive, and capacitive [9]. Piezoresistive pressure sensors exceed the opposition in applications used in everyday life due to their easy device form, simple signal collecting, low cost, and simple fabrication process.

T. Rijk et al. [10] presented a new pressure sensor that directly incorporates multi-walled carbon nanotubes (CNTs) into the polyimide sheet. The sensor is robust and can withstand pressures as high as the highest tested level of 55N. According to the primary findings, a linear pressure extent of up to 40N is measurable. Periodic pressure response tests demonstrate the sensor's recurrently and steady mechanical nature because of its robust polyimide foundation.

A. Gafar et al. [11] explain the analysis of two distinct CNT-based MEMS piezoresistive models. One has a square-shaped diaphragm, while the other has a circular diaphragm. Notice that a circular diaphragm is better than a square diaphragm because it has the lowest stress on its edges when applied pressure same pressure is to a square diaphragm. Additionally, a circular diaphragm's sensitivity is lower than a square diaphragm's sensitivity.

K. Balavalad et al. [12] describe developing and evaluating tiny piezoresistive pressure sensors utilizing Si, SOI, and CNT. Inspected sensor for sensitivity, output potential, and displacement characteristics. Findings demonstrate that the sensitivity of the CNT piezo resistor-based micro pressure sensor is higher than that of silicon and SOI-based sensors, at 308.7mV/MPa (30.8mV/bar) that the CNT sensor's output potential is superior to that of the other two sensors. The displacements for Si and CNT-based detectors are the same, whereas the removal for SOI-based sensors is lower.

This study proposed a simple and accurate method of modelling and simulating the SWCNT piezoresistive pressure sensor. The system was examined using COMSOL Multiphysics. Additionally, altering pressure that affected the displacement, current density, and von Mises stress was investigated, limiting the pressure from 0 to 300kPa, adding the mechanical and electrical properties of CNTs to the library of COMSOL Multiphysics, including young's modulus, passions ratio, transmission coefficient, density, and electron affinity.

2. Design of SWCNTs Piezoresistive Pressure Sensor

The geometry of SWCNTs pressure sensors was studied utilizing COMSOL Multiphysics. Figure 1 illustrates the geometry of the SWCNTs pressure sensor. In this design, the CNTs are placed between two metals (source and drain) in the diaphragm's (Si/SiO2) core, creating the two metals of gold. The thickness of the metal is 3µm while the substrate is 4µm.The CNTs function as a piezoresistive pressure sensor component to detect changes in pressure. The pressure of 300KPa has been applied at the backside of the circular substrate. The basic simulation procedures include the following: Modeling (geometry of the building), material selection, boundary condition setting (fixing support and load), initial condition, meshing, running the model, and viewing the results. One of the boundary conditions for the pressure sensor is the fixed edge of the circular diaphragm. The parameters utilized in this model are shown in Table 1.

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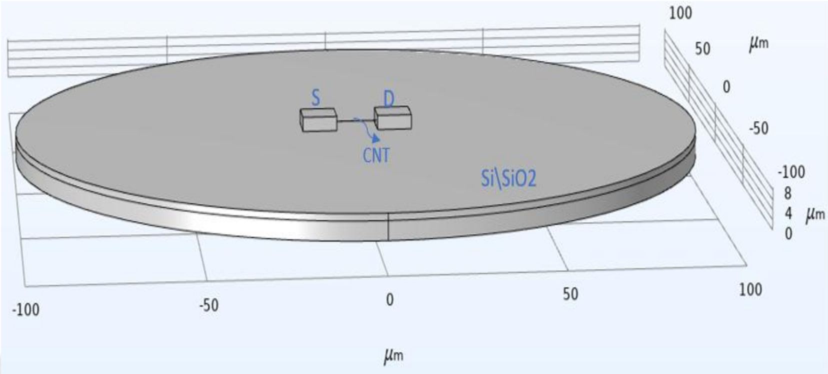

Figure 1. Geometry of SWCNT pressure sensor

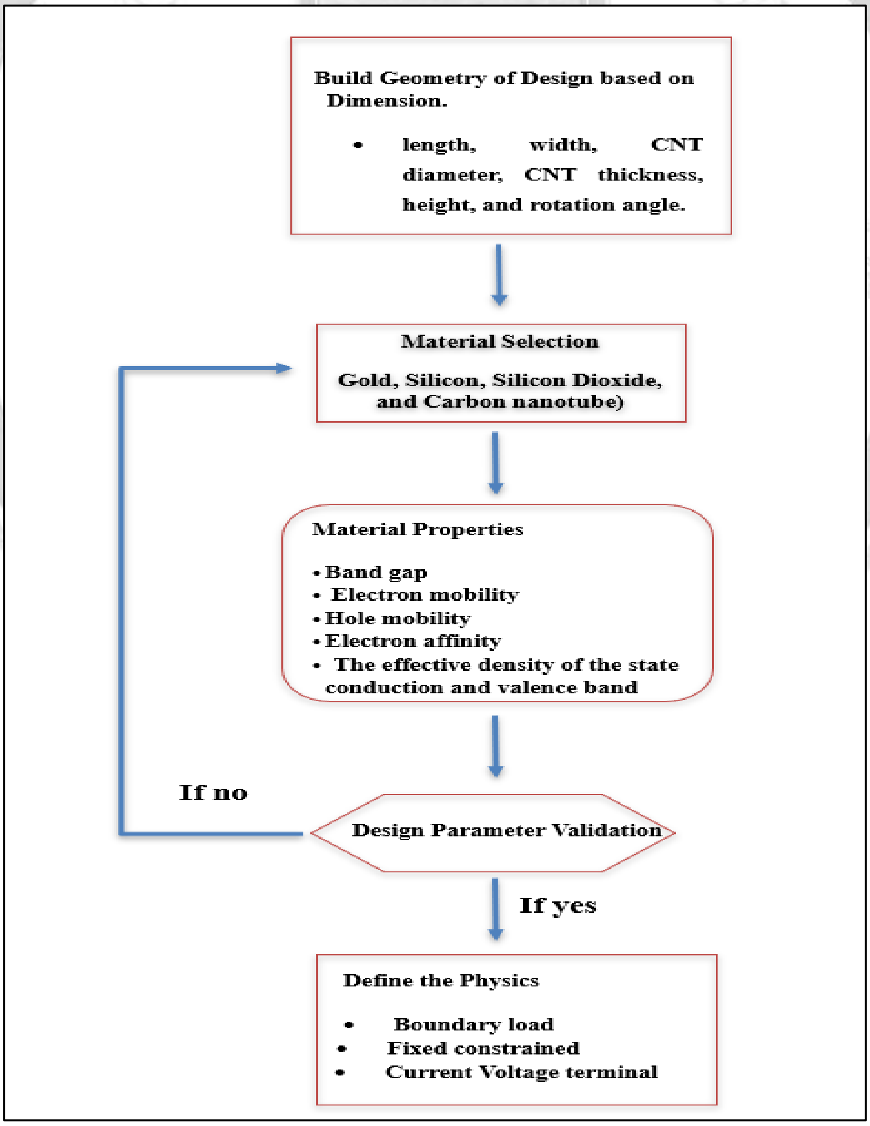

Figure 2. Flowchart of Simulation Work of SWCNTs based Pressure Sensor in COMSOL Multiphysics.

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Table 1. The Parameter of CNT Pressure Sensor Utilizing in COMSOL Multiphysics

Parameter	Value
Young modulus	1000GPa
Passion’s ratio	0.2
Thickness of diaphragm	4µm
Radius of diaphragm	100 µm
Thickness of SiO2	1.5 µm
Length of CNTs	14.99 µm
Temperature	293.15K
Transmission coefficient	0.5
Relative permittivity	5.7
Density	3515[kg/m^3]
Electron affinity	0.35[V]
Effective density of states, valence band	1e26[1/m^3]
Effective density of states, conduction band	1e25[1/m^3]

1. Mathematically Model of SWCNTs pressure sensor

The following equation describes the relationship between a carbon nanotube's resistance and its energy band gap. [13]:

$$R_{tot}(\varepsilon) = R_s + \frac{1}{t^2}\frac{h}{8e^2}\left[1 + \exp\left(\frac{E_g}{KT}\right)\right] \tag{1}$$

Where, R_s is the contact resistance, t is the transmission coefficient, h is Plank’s constant, e is the charge of an electron, is the energy band gap, T is absolute temperature, and K is Boltzmann’s constant.

Furthermore, the energy band gap of CNTs is dependent on its diameter estimated by the following equation [14]:

$$\mathrm{E_g} = \mathrm{E_g^{\circ}} + \frac{\mathrm{dE_g}}{\mathrm{d\varepsilon}}\varepsilon \tag{2}$$

Where,

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$$E_g^{\circ} = \frac{|P|2\gamma a}{\sqrt{3}d} \quad (3)$$

And

$$\frac{dE_g}{d\varepsilon} = \text{sign}\,(2p+1)3\gamma[(1+v)\cos 3\theta_t]$$

Where, ε is applied strain, γ =2.6 eV is a tight binding-overlap integral, a= 0.249nm is the graphene lattice unite vector length, d is the diameter of CNTs, v is a passion's ratio of CNTs, θ is a chiral angle. p=0,∓1 is the label's nanotube family is given by the chiral index (n, m) to determine p from n-m=3q+p, where q is an integer [15].

Additionally, the radial and tangential strains at the center of the diaphragm given by the equation [16]:

$$\varepsilon = \frac{3P\, r_0^2 (1-v^2)}{8\, h_2^2\, E} \quad (4)$$

Where P is the pressure applied, r_0 is the radius of the circular diaphragm E is young's modulus of SiO2, $h_2$is the thickness of SiO2, v is the Poisson's ratio of SiO2.

2. Results and Discussion

The resistance of the CNTs sensor varies depending on the applied pressure or strain. Moreover, the resistance of CNTs is directly proportional to the energy band gap, while the diameter is inversely proportional to the band gap. The proposed method of finding resistance and energy band gap was mathematically calculated using equations 1 and 2. Tables (2,3,4,5) explain the effect of changing strain on the energy band gap. At the same time, the energy bandgap is affected by the strain and the diameter of CNTs, whereas the resistance of CNT depends on the energy bandgap. When took specific values for the strain from 0 to 0.045, the energy bandgap was increased, and thus, the resistance increased.

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Table 2. The SWCNTs Results with Different Parameter at Diameter =1nm

Strain	Energy band gap (eV)	Resistance (KΩ)
0	0.426	2143
0.005	0.4728	2377
0.01	0.5196	2611
0.015	0.5664	2845
0.02	0.6132	3079
0.025	0.660	3313
0.03	0.706	3547
0.035	0.753	3781
0.04	0.800	4015
0.045	0.847	4249

Table3. The SWCNTs Results with Different Parameter at Diameter =2nm

Strain	Energy band gap (eV)	Resistance (KΩ)
0	0.213	1078
0.005	0.259	1312
0.01	0.306	1546
0.015	0.353	1780
0.02	0.400	2014
0.025	0.447	2248
0.03	0.493	2482
0.035	0.540	2716
0.04	0.587	2950
0.045	0.634	3184

Table 4. The SWCNTs Results with Different Parameter at Diameter =3nm

Strain	Energy band gap (eV)	Resistance (kΩ)
0	0.142	723
0.005	0.188	957
0.01	0.235	1191
0.015	0.282	1425
0.02	0.329	1659
0.025	0.376	1893
0.03	0.422	2127
0.035	0.469	2361
0.04	0.516	2595
0.045	0.563	2829

Table5. The SWCNTs Results with Different Parameter at Diameter =4nm

Strain	Energy band gap (eV)	Resistance (kΩ)
0	0.106	543
0.005	0.152	777
0.01	0.199	1011
0.015	0.246	1245
0.02	0.293	1479
0.025	0.340	1713
0.03	0.386	1947
0.035	0.433	2181
0.04	0.480	2415
0.045	0.527	2649

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The Tables (2,3,4,5) illustrate that the increasing diameter from 1nm to 4nm led to decrease in energy bandgap from 0.426eV to 0.106 eV and a reduction in the resistance from 2143KΩ to 543KΩ at zero strain. Rolling a single wall nanotube graphene sheet allowed to change the diameter in this study. The current system observed that the resistance and energy band gap changes from 543kΩ to 2143 and 0.106eV to 0.426Ev, respectively. Figure 3 illustrates the effect of changing diameter on the resistance and energy band gap with different strain.

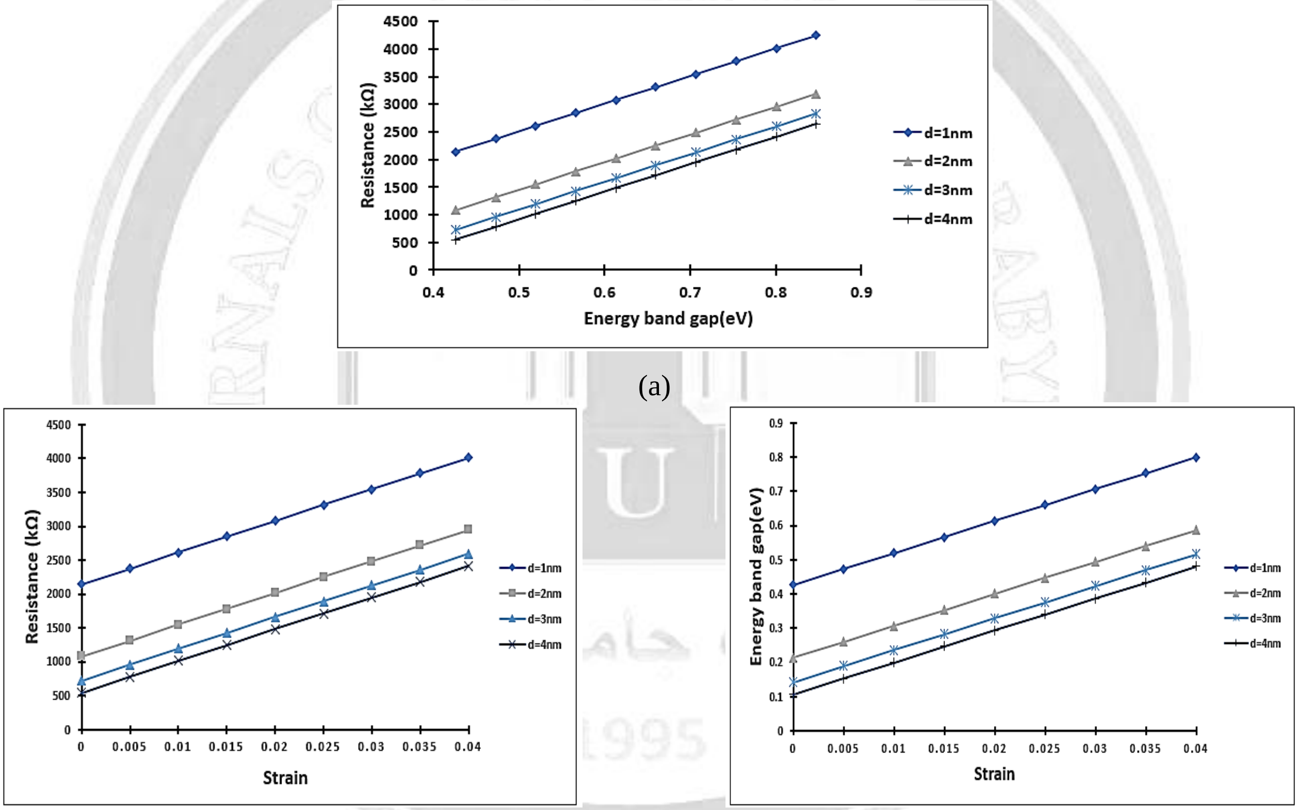

Figure 3. The SWCNTs Results (a) Resistance vs Energy Band Gap (b) Strain vs Resistance (c) Strain vs Energy Band Gap

4.1 Effect of Pressure on Von Mises Stress.

This section shows the effect of changing pressure on von Mises's stress. Number of single-walled CNT (one, two, four) walls were analysis and the relationship was plotted as shown in Figure 4. The applied pressure range was 0 to 300 kPa. The results show that Von-mises stress is in a linear relationship with pressure. It was also observed that increasing the number of CNTs increases von-Mises stress. High stress is usually not recommendable as it increases the chance of failure of the material. It was noticed that the diaphragm edge experiences more von-mises stress than the other geometry parts. These results show that the 4SWCNTs are greater than 1SWCNTs.

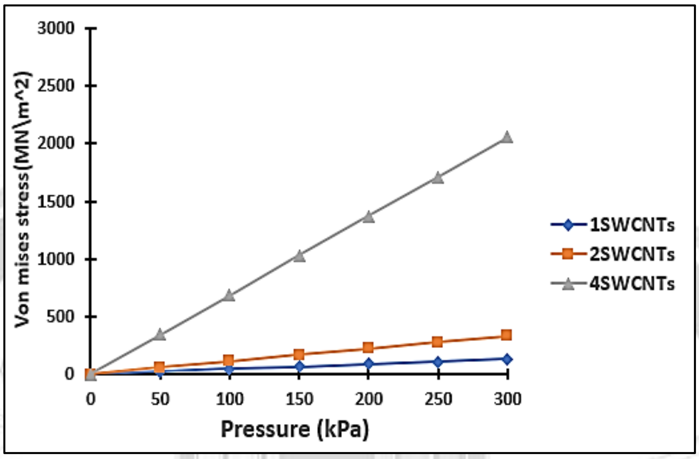

Figure 4. Pressure vs Von Mises Stress at Single-walled CNT

4.2. Effect of Pressure on Displacement of CNTs.

Figure 5 presents the relationship between pressure and displacement for several numbers of single-walled CNTs. From the result, the displacement is directly proportional to the applied pressure. The applied pressure increased from 0 to 350kPa, this leads to increase the displacement from 0 to 0.5µm. The results showed that increasing the number of CNTs does not affect its displacement. The deviation of the displacement was minimal in the numbered of SWCNTs.

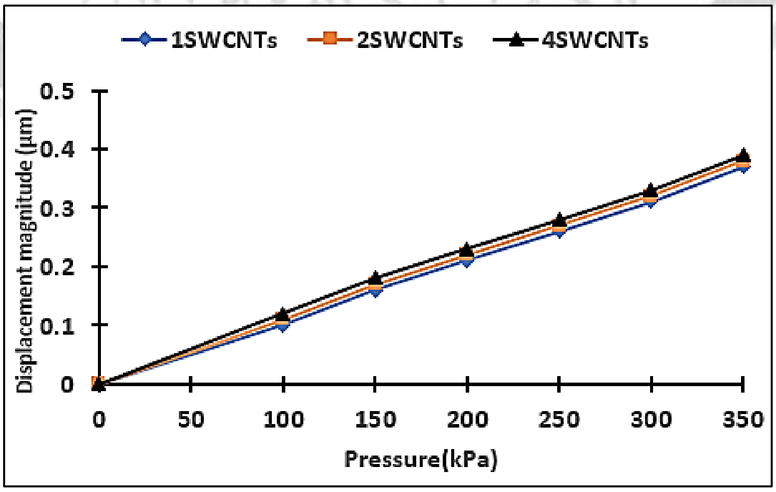

Figure 5. Pressure vs Displacement of Single-walled CNT

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4.3. Effect of Pressure on Current Density

This section presents the effect of pressure changes on the current density of carbon nanotubes in Figure 6. The results show that the current density increases linearly with increased pressure. The spacing between the particles decreases, and the particles become closer to each other due to the increasing pressure. The current density of SWCNTs is greater than that of MWCNTs due to the big diameter of CNTs.

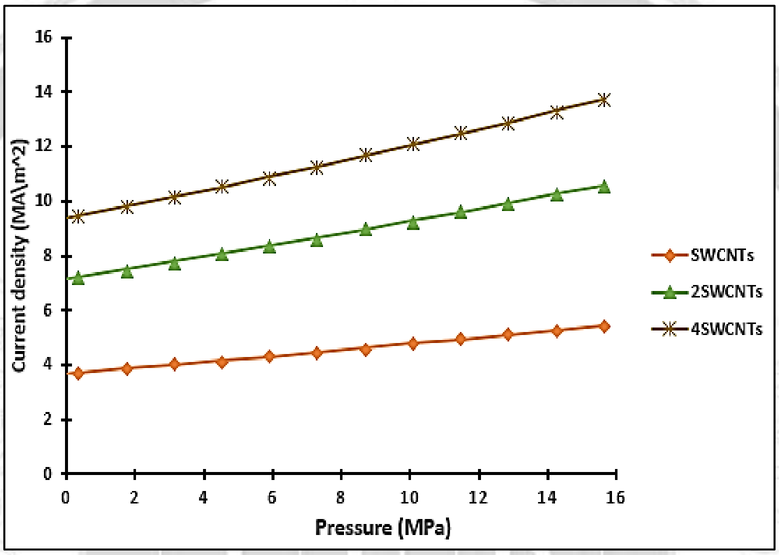

Figure 6. Relationship between Pressure and Current Density of SWCNTs

4.4. Relationship between Arc Length and Von Mises Stress.

This line plot shows the von-mises stress effect along the length of the carbon nanotubes. Results show that the stress initially increases, becomes stable, and rises again at the second end. The total length of CNT is 14.99µm; the von Mises stress fluctuates only at the endpoints and remains the same at the middle part of the carbon nanotube, as shown in Figure 7. This Means that von Mises's stress is in control and will not be led to the failure of stress in this selected range of applied pressure.

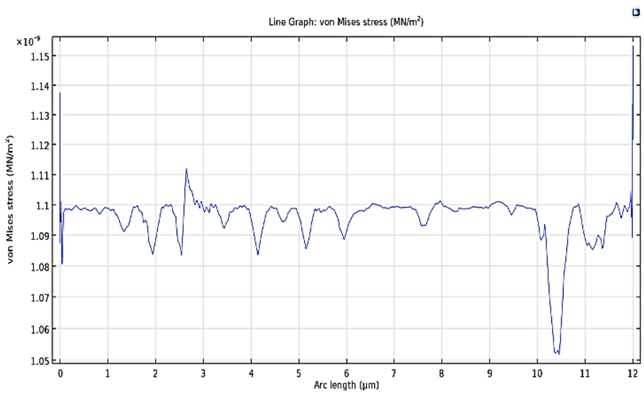

Figure 7. Arc Length vs Von Mises Stress of SWCNTs

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5. Comparison with Previous Results

The comparison between these results and previous results is tabled in Table 2. The sensitivity of these results was observed to be equal to **1.5×10^-11µA/Pa**, While the previous results were equal to **2kΩ/Pa** due to the different dimensions. Additionally, the displacement equal **0.5 µm** for our result and **9.35 µm** for previous result.

Table 2. Comparison of the results with previous Results

Parameters	Our results	Previous results [17]
Diameter of CNTs	**1nm**	**5nm**
Length of CNTs	**14.99µm**	**14.99µm**
Thickness of diaphragm	**4µm**	**1 µm**
Metal contact	**Gold contact**	**Platinum contact**
Sensitivity	**1.5×10^{-11}µA/Pa**	**2kΩ/Pa**
Total displacement	**0.5 µm**	**9.35 µm**

Conclusion

This work aims to study and analyses array of single-walled CNT piezoresistive pressure sensors. In this study, a substrate is a circular diaphragm and studied the effect of changing pressure on the von Mises stress at the pressure range of 0 to 300kPa. Observe the pressure is directly proportional to the von Mises stress. The displacement increased from 0 to 0.5µm while the pressure climbed from 0 to 350kPa. The maximum displacement is the same because of the pressure remaining in the same place. In the proposed method, the diameter increases, decreasing the bandgap. As a result, the resistance decreases. Additionally, the sensitivity of SWCNTs was $1.428*10^{-11}$µA\Pa. This sensor is promising for practical applications and batch production based on these results.

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مستشعر ضغط SWCNTs عالي الاداء

زهراء عيسى محمد حيدر المؤمن

جامعة بابل/ كلية الهندسة/ قسم الهندسة الكهربائية

الخلاصه

في هذا النموذج ، تمت دراسة تصميم ومحاكاة أنبوب نانوي كربوني على مستشعر ضغط دائري قائم على الحجاب الحاجز. تم استخدام الأنابيب النانوية أحادية الجدار للتحقق من حساسية أفضل. تمت دراسة تأثير تغيير الضغط على الإزاحة وكثافة التيار وإجهاد فون ميزس باستخدام CNTs واحد ومجموعة من الأنابيب النانوية الكربونية. وقد لوحظ أن زيادة الضغط أدى إلى زيادة الإزاحة وكثافة التيار وإجهاد فون ميزس. كانت الحساسية المحققة لـــ 1.428 * 10 ^ -11µA \ Pa SWCNTs. علاوة على ذلك ، تم دراسة تأثير تغيير القطر على مقاومة الأنابيب النانوية الكربونية وفجوة الطاقة. اختار تصميمنا حدود القطر من ١ نانومتر إلى ٤ نانومتر. وجد أن رفع القطر أدى إلى تقليل فجوة نطاق الطاقة من ٠.٤٢٦ فولت إلى ٠.١٠ فولت ، كما أدى إلى تقليل المقاومة من ٢١٤٣ كيلو أوم إلى ٥٤٣ كيلو أوم عند الصفر.

الكلمات الداله: تقنيه النانو , الانابيب النانويه احاديه الجدار, حساس الضغط .