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CNT/Polymer Composite Strain Sensors

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Abstract—*Carbon nanotubes possess piezoresistive behaviour, according to which its electrical property changes even with the applied strain at nanoscale. Due to their high strain sensitivity, multidirectional sensing capability, flexibility, high dynamic range and low mass density they are turning out to be an ideal replacement to conventional strain sensors in many applications. CNT film can also be integrated into polymer to form a CNT/polymer composite strain sensor. Some of the most popular polymers used to produce CNTs/polymer composite strain sensors are thermosetting polymers (epoxy resins, polyurethanes etc.), thermoplastic polymers (poly methyl methacrylate, polystyrene, etc.), and polydimethylsiloxane (PDMS). The small addition of CNTs to polymer significantly increases their electromechanical properties by enhancing its tensile strength and young's modulus, which in turn improves their sensing performance. CNT/polymer composite strain sensor exhibits better strain transfer, gauge factor, linearity, repeatability and cost than that of pure CNT strain sensor. There are various parameters which are affecting the performance of CNT/polymer composite strain sensor they are quality and quantity of CNT filler particles in composite, type of fabrication technique adopted to form a composite, alignment and agglomerates of CNT in composite, cracks or defect in composite and environmental conditions. This paper reviews the performance of various different types of CNT/polymer composite strain sensors.*

1. INTRODUCTION

Carbon nanotubes (CNTs) are the strongest and stiffest material known due to its unique covalent bonding and seamless hexagonal network. They have novel properties such as high electrical conductivity (~1013 A/cm^2), high tensile strength (50 GPa or above) and elasticity (~1 TPa), high thermal conductivity (3500 W/mK) and high aspect ratio (about 1000:1). Due to its unique properties CNT based strain sensors are quite useful in many applications such as structural health monitoring, crack or defect detection in infrastructure, wearable electronic gadgets,biological monitoring of human body parts, luxury automobiles and also in highly strain sensitive applications. [1][2].

Carbon atoms in CNTs are bonded together using a strong sp^{2}hybridisation to form a hexagonal network, which result into a high tensile strength of 50 GPa or above. Due to their low mass density its stiffness is also very high (230–725 GPa).The mechanical properties of CNT depend strongly on the nanotube structure such as young's modulus of elasticity, tensile strength and toughness. The young's modulus of CNTincreases with the increase in aspect ratio and their tensile strength increases with the increase in tube diameter and reduces with the increase in defect. The addition of low concentrations of carbon nanotubes into fiber reinforced polymer composite improves its mechanical properties such as tensile strength, young's modulus and fracture toughness. [3].The electrical conductivity of CNTs depends on the orientation of hexagonal lattice around the tube axis. When the orientation of hexagons are parallel to the axis of tube it is labeled as armchair tube, which is metallic in nature and they are better conductor than metal such as silver and copper. Another two possible orientations of hexagon i.e. zigzag (one with the hexagons oriented in circle around the axis of tube) and chiral (one with hexagon not forming a line around the nanotube) show semiconducting behavior [4]. The unique electromechanical property of CNT is that its band structure changes with mechanical deformation, which is matter of interest for many researchers to use it in strain sensing applications [5].

This paper reviews the recent research outcome regarding CNT/polymer composite strain sensors. To discuss this, the review article is organized into three different sections. Section 1 gives an overview of polymers used by researchers in this field. Section 2 discusses the detailed description about the parameters affecting the sensitivity of composite strain sensors. Section 3 gives the performance analyses of recentcomposite strain sensors.

2. TYPES OF POLYMER USED [6]

Many recent researches in this field have shown that some of the most popularly used polymers to fabricate CNT/polymer composite strain sensors are:

- Thermosetting polymers such as epoxy resins, polyurethanes
- Thermoplastic polymers such as poly methyl methacrylate (PMMA),polystyrene(PS), polypropylene (PP)
- Polydimethylsiloxane (PDMS)

3. STRAIN SENSITIVITY OF CNT/POLYMER COMPOSITE STRAIN SENSORS[6][7][8][9]

The sensitivity of any strain sensor is given by their gauge factor (GF), which is the change in resistance divided by the strain.

$$G = \frac{\frac{\Delta R}{R}}{\varepsilon} \quad (1)$$

Experimentally, it has been found that the strain sensitivity of CNT/polymer composite strain sensor is better than that of pure CNTs sensors i.e. without polymers. The best gauge factor of composite strain sensor i.e. 22.4 was reported by using epoxy as polymer. Apart from the type of polymers used there are various other parameters, which are affecting the strain sensitivity of composite sensors.They are:

- Quality and quantity of CNTs used ,
- Fabrication technique,
- Type of surfactants
- Type of dispersion technique,
- Alignment of CNTs ,
- Agglomerates of CNTs,
- Presence or absence of defects and
- Environmental conditions

Even a slight variation in any of these parameters can change the strain sensitivity of composite strain sensors.

4. CNT/POLYMER COMPOSITE STRAIN SENSORS

The characteristic curve and performance analysis ofCNT/polymer strain sensors using different types of polymers has been discussed below:

i) Using thermoplastic polymers:
a) SWCNT/PMMA composite strain sensors [10]:
SWCNT/PMMA composite film can be fabricated by dispersing single walledbuckypaper film in dimethylformaide(DMF) solvent and then bulk mixing the PMMA polymer to it. The strain sensitivity of SWCNT/PMMA strain sensor with different concentration of SWCNT in PMMA is shown in Fig. 1 [10].

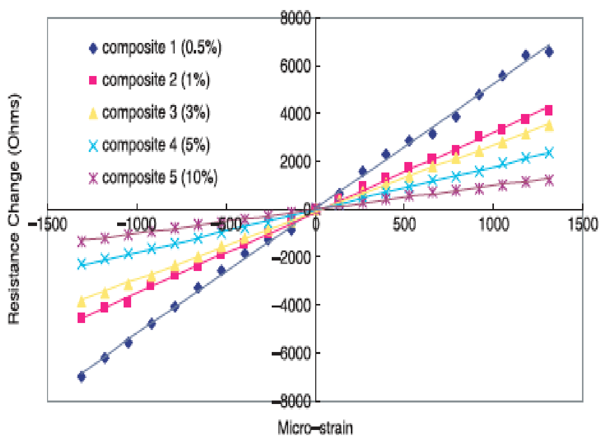

Fig. 1: Strain Response of SWCNT/PMMA Composite Strain Sensors[10].

Gauge factor of SWCNT/PMMA lie in range between1 to 5. For 0.5% wt of SWCNT in PMMA, the gauge factor of composite strain sensor is 5 and it decreases with the increase in CNT content.

b) MWCNT/PMMA composite strain sensor [11]:
MWCNT/PMMA composite strain sensor can be fabricated either by dry blended or solution based technique. In dry blended fabrication technique, MWCNTs are dry blended with PMMA powder and then hot pressed multiple times to fabricate the sample. While in the second method, MWCNTs are dissolved in solvent such as chloroform using mechanical stirrer and then polymer is added to the solution using ultrasound.Out of these two methods,solution based technique gives better dispersion and thus produces better strain sensitivity as shown in table1 [11].

Table 1: Strain Sensitivity factors of MWNT/PMMA films by using dry blended and solution based techniques [11].

MWCNT Loading (wt %)	1	3	5	6	8	10
Dry Blended	N/A	N/A	N/A	8.44	7.45	5.66
Solution Based	15.32	4.99	4.26	3.27	1.90	1.44

ii) Using thermoplastic polymers [12][13]:
a) MWCNT/epoxy composite strain sensors [12]
MWCNT/epoxy composite strain sensors can be fabricated by using two different types of MWCNT films i.e. MWCNT-7 and LMWNT-10 film. MWCNT/epoxy composite strain sensors can be prepared from these two MWCNT films by mixing epoxy and amine hardener by using planetary mixer and then adding MWCNT films into the mixture and then mixing it again at 2000 rpm for 1 minute. After mixing, the final mixture is then poured into silicon mould to form MWCNT-7/epoxy and LMWNT-10/epoxy strain sensors. The piezoresistivity curve of both these sensors are as shown below [12].

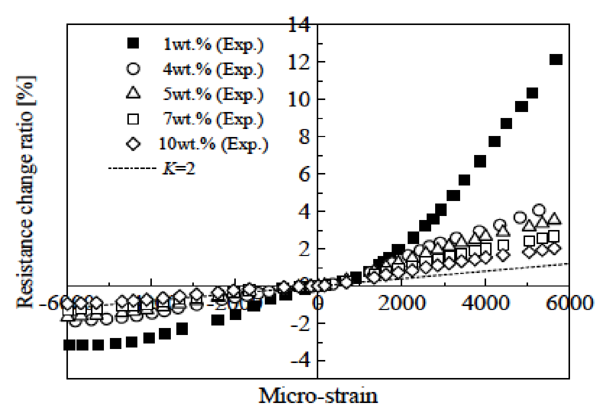

Fig. 2: Piezoresistivity of MWCNT-7/epoxy composite strain sensors[12].

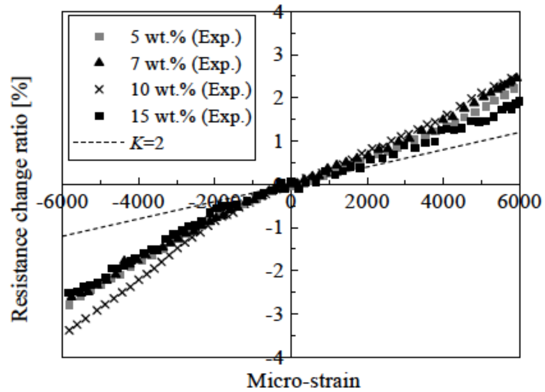

Fig. 3: Piezoresistivity of LMWCNT-10/epoxy composite strain sensors[12].

As shown in Fig. 2 and 3 the piezoresitivity characteristics of both these sensors are totally different. MWCNT-7/epoxy composite sensor possesses non-linear and antisymmetric piezoresistivity. On the other hand, LMWNT-10 /epoxy composite sensors shows linear and symmetricpiezoresistivity. The gauge factors of MWCNT-7/epoxy and LMWNT-10/epoxy strain sensors at different weight of CNT loading are shown in Table 2 and 3 respectively [12].

Table 2: Gauge factors of MWNT-7/epoxy strain sensors at various MWCNT loadings [12].

MWCNT Loading (wt %)		1	4	5	7	10
Gauge Factors	Compressive	7.1	3.5	3.0	2.2	2.1
	Tensile	22.4	7.6	6.2	4.8	3.2

Table 3: Gauge factors of LMWNT-10/epoxy strain sensors at various MWCNT loadings [12].

MWCNT Loading (wt %)		5	7	10	15
Gauge Factors	Compressive	3.8	4.1	4.3	3.2
	Tensile	4.9	4.5	5.8	4.4

b) MWCNT/PS composite strain sensors [13]:

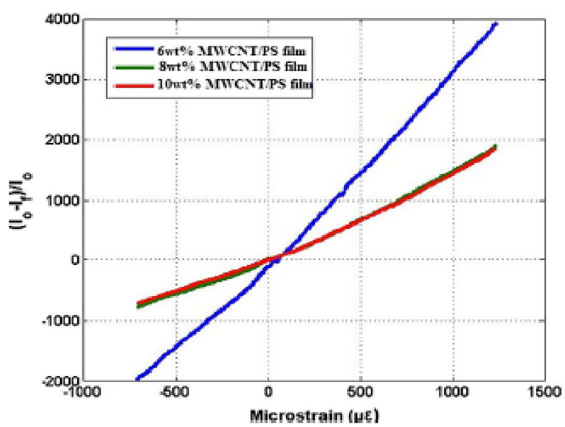

Fig. 4: Plot of normalized current response as a function of strain for different wt.% content of MWCNTs in the MWCNT/PS composite films [13].

MWCNT/ PS composite film is fabricated by mixing the functionalized MWCNT with PS solution in toluene. The mixture is stirred to form the homogenous solution, which is then poured onto flat plate to give flexible MWCNT/PS composite film. The strain sensitivity curve for MWCNT/PS composite film is shown in Fig. 4.The gauge factor of MWCNT/PS composite film decreases with the increase in CNT content as shown in Table 4.

Table 4: Gauge factors of MWNT/PS films at various MWCNT loadings [13].

MWCNT Loading (wt %)		6	8	10
Gauge Factors	Compressive	2.55	1.04	0.998
	Tensile	3.28	1.55	1.49

iii) Using Polydimethylsiloxane (PDMS) polymers[14] [15]: MWCNT/PDMS composite strain sensors can be fabricated by using two methods i.e. shear mixing [14] and vacuum filtration [15].In shear mixing method, MWCNT films are mixed with the tetrahydrofuran (THF) solvent and sonicated in bath sonicator for 60 minutes. After that PDMS is added to the mixture by shear mixing to form the composite film.The fabrication of composite film using vacuum filtration method involve the use of MWCNTs film prepared by chemical vapour deposition (CVD) technique which is then sonicated in dimethylformamide (DMF) solvent and the solution is then ultrasonically treated to disperse the MWCNTs.The final solution is then passed through polyvinylidene fluoride (PVDF) filter to separate out CNTs in the film. CNTs are then transferred to flexible substrate by using PDMS molding.

The resistance-strain sensitivity curve of both these samples are shown in Fig. 5 and 6.The strain sensitivity of both these sample are different. MWCNT/PDMS composite sample by shear mixing technique shows a quasi-linear piezoresistive behavior with the gauge factors in the range of 0.8 to 2.3. While the composite fabricated by vacuum filtration shows linear piezoresistivity for a wider range of strain with a lower gauge factor (0.01 to 1.25) in comparison to the former sample.

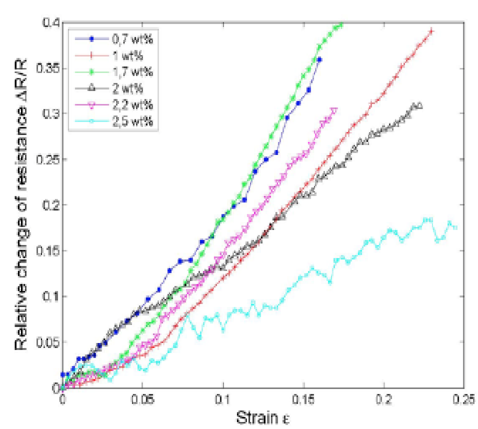

Fig. 5: Strain response of MWCNT/PDMS composite strain sensors (shear mixing) for different weight percentages of MWCNT[14].

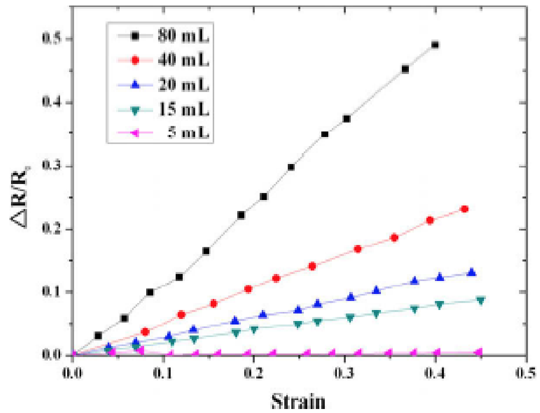

Fig. 6: The resistance–strain sensitivity of the CNTs/PDMS thin films (vaccum filtration) with different initial volume of CNTs suspension[15].

5. CONCLUSION

In this contribution, CNT/polymer composite strain sensors have been reviewed. To fabricate CNT/polymer composite strain sensor, most of the researchers useddifferent type of polymers such as thermosetting, thermoplastic, PDMS, vinyl etc. It was found that the strain sensitivity of CNT/polymer composite strain sensor depend on various parameters such as quantity and quality of CNT, fabrication parameters, polymer type, surfactant type, dispersion method, defects, environmental conditions, alignments and agglomerates of CNTs. By analysingthe piezoresistive curve of various composite strain sensors it can be concluded that they possess highest stain sensitivity in comparison to buckypaper, pure CNT and conventional strain sensors. It was also found that the sensitivity of composite strain sensor decreases with the increase in CNT loading. Among all these composite sensors, the best strain sensitivity(GF~= 22.4) was achieved with 1% wt MWCNT-7/epoxy composite strain sensor with tensile strain.

Although numerous researches have been conducted in the fabrication of CNT/polymer composite strain sensors. But still there were only very few studies reporting the practical usage of these sensors in commercial applications.

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