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Carbon Nanotube Bucky Paper Based Strain Sensor

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Abstract—*Carbon nanotubes is turning out to be a replacement to all the existing traditional sensors because they have very high gauge factor (=~ 22.4), multidirectional sensing capability, high flexibility, low mass density, high dynamic range and highly sensitive to strains at nano and macro scales. The performance of CNT based strain sensors depends on number of parameters i.e. CNT type, polymer matrix, fabrication process and different type of nano-carbon fillers. Due to all these parameters the piezoresistive behavior of CNT is diversified. One of the diverse forms of CNT based strain sensor is buckypaper CNT film (BP-CNT film). Buckypaper is an attractive candidate material for strain sensing due to its lighter weight, high modulus, higher sensitivity and multidirectional sensing. Depending on the type of CNT film used it is classified as BP-SWCNT and BP-MWCNT sensors. Both these sensors have shown linear and fully reversible electromechanical characteristics for loading and unloading states. It has been found that both these sensor works well for lower strain (upto ±1,000 με) and their sensitivity is same as that of metallic strain gauge (k~=2) but at higher strain (between ±1,000 με to ±6,000 με) it results into permanent deformation. So, buckypaper strain sensor cannot be used in applications that require multifunctionality and repeatability. This review paper focuses on characterization, fabrication and performance of single walled buckypaper, multi walled buckypaper and buckypaper/polymer embedded strain sensors.*

1. INTRODUCTION

Carbon nanotubes (CNTs) are carbon allotropes, which are formed by wrapping a graphene sheet consisting of hexagonal lattices of carbon atoms into a seamless hollow cylinder. These are classified into two types: Single walled carbon nanotubes (SWNTs) and Multi walled carbon nanotubes (MWCNTs).The main structural difference between SWCNTs and MWCNTs is that the SWCNTs contain only single layer of graphene sheet with diameter around 1-3 nm and length in the order of ten micrometer rolled up to form a cylinder. While MWCNTs consist of multiple sheets of graphene layer of diameter typically around 10-200 nm rolled one inside another and bounded to each other by a weak vander wall forces [1]. CNTs structure depend on two parameters: Chiral vector C and Chiral angle θ. C depends on the way of wrapping graphite sheets and it is represented by a pair of chiral indices (n,m) or chirality where n and m are the integers associated with two unit vectors a_1 and a_2 respectively where

$$C = na_1 + ma_2 \quad (1)$$

While θ is an angle at which graphene sheet is rolled up to form a carbon nanotube as shown in Fig. 1.

Fig. 1: Illustration of how wrapping of graphite sheet form carbon nanotube [2]

On the basis of C and θ CNTs are classified into three types: ZigZag (θ=0, m=0) , Arm Chair (θ=30°, n=m) and Chiral CNTs ($0 < \theta < 30°$, $n \neq m$).The conductance, density, lattice structure and properties of CNTs are largely dependent on chirality. CNTs can be either metallic or semiconducting dependent on the chirality. A SWNT behave as metal if the value of n-m is divisible 3. Otherwise it behaves as semiconductor with small band energy gap varying from 0.1 to 2eV. As the diameter of CNTs increases, band energy gap decreases. Mostly all the armchair CNTs are metallic, one third zigzag and chiral CNTs are metallic while rest two third would be semiconducting with a very small band energy gap [2,3].

The unique electrical property of CNT is that it varies with the mechanical deformation, which is matter of interest for many researchers to use it in strain sensing applications [4,5]. The main advantage of using CNTs as strain sensor over conventional strain sensor such as PZT and strain gauge are: highly sensitive at nano and macro scale, smallest size, sense strain in multiple direction and in multiple location while other are fixed directional sensors, easily embedded into structural material and its gauge factor (change in resistance with respect to strain) is twice that of traditional strain gauge. Gauge factor for CNT can achieve a value greater than 2900 while that of silicon based strain sensor is nearly close to 200[5]. High gauge factor for CNT based strain sensor result into higher sensitivity and it can be positive or negative depending on the chirality of CNTs [6].

Although recent studies had shown that carbon nanotube buckypaper could be utilized as a strain sensor. However to the best knowledge of authors, review article discussing about fabrication techniques of carbon nanotube buckypaper based strain sensor is absent in the literature. So this motivated authors to write a review article in this relatively new era of research. Aim of this review article is to provide a well-knitted knowledge bank about buckypaper strain sensor and their fabrication methods. It also analyses the characterisation, performance, advantage and disadvantages of each one of them, which would be an immense help to practitioners and researchers working in this field.

2. BUCKYPAPER STRAIN SENSOR

Buckypaper is a macroscopic aggregate of carbon nanotube. It is a macroscopic ensemble of nanotubes in which tube form bundle and bundle form paper like fleece. It can be formed either from SWNTs or from MWNTs as shown in Fig. 2. On this basis it is divided into two types: single walled carbon nanotube buckypaper (SBP) and single walled carbon nanotube buckypaper (MBP). Strength of SBP is 250 times and its weight is 10 times lighter than that of steel [7].

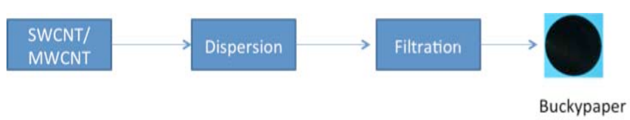
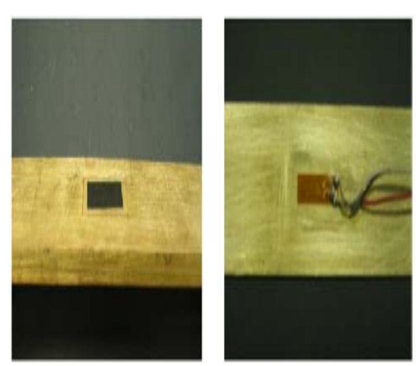


Fig. 2: Schematic representation of the fabrication process of buckypaper from CNTs

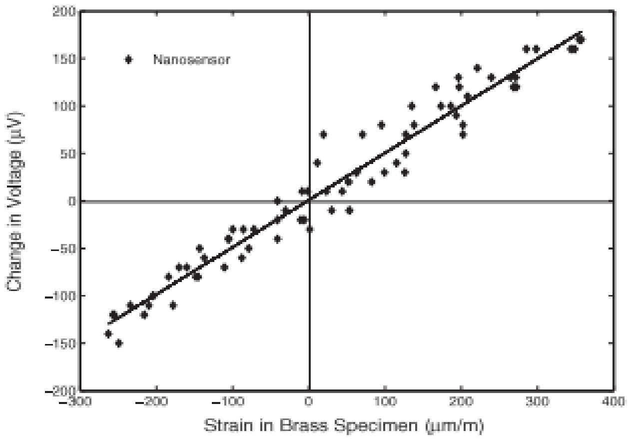
The electrical conductivity of SBP is on the same line as that of silicon and copper and its thermal conductivity is two times better than that of diamond. SBP and MBP sensor differ in terms of volume, cost and resistivity[8]. Resistivity of BP depends only on the contact resistance between the carbon nanotubes[9]. BP strain sensors are found to be sensitive with local defects in the material which open their scope in variousstrain sensingapplications such as structural health monitoring, finding defects and analyzing the material structure[7]. There are many advantages of using buckypaper as strain sensor: flexible enough to be molded into any shape and size, homogenous nanotube dispersion is possible unlike nanocomposite strain sensing elements, sense strain in multiple directions due to its isotropic structure and also it possesses higher sensitivity than conventional strain gauge[7,8]. There are various strain measurement tests available to analyse the effect of strain on buckypaper such as raman spectroscopy [8], two point probe method and four point probe method[9]. Raman wavenumber G band peak shift downward as the tensile strain increases and this relation is utilized for measuring strain of SBP using Raman spectroscopy [8]. But it is practically not viable approach for strain measurement at remote location due its bulky and expensive hardware. While the other two tests is used to measure the change in electrical properties of CNTs with respect to mechanical deformation. Out of these two, four point probe method is considered to be nearly 15 times [9] more sensitive as it do not include change in contact resistance between nanotubes. So this method is preferred over two point probe method.

3. FABRICATION OF SINGLE WALLED BUCKYPAPER

To fabricate Single walled Buckypaper (SBP) as a strain sensor, first of all SBP film is purchased or prepared from SWNT and then poly vinyl chloride (PVC) is attached between SBP film and a brass specimen of specifications (length= 12 inches, breadth=1.5inches and height=0.065 inches and Young's modulus close to 100 GPa). The main drawback of SBP strain sensor is the poor strain transfer capability because of slippage between nanotube bundles at higher tensile strain [8]. Attachment of PVC is done by using vaccum bonding approach which makes sure that a high strength epoxy provides a firm bond to prevent slippage with better strain transfer capabilities. For strain measurement, a cycle of tensile and compression strain is imposed on a brass specimen by using servo hydraulic machines and change in voltage of SBP film with respect to strain can be recorded either by using two point or four point probe method. For doing the comparative analysis of strain measurements between SBP strain sensor and strain gauge, other side of a brass specimen is connected to a conventional strain gauge as shown in Fig. 3 (a) [10]. In four-point probe method[9], two outer probes are connected to a constant current source supplying 100 mA constant current to the specimen and two inner probes are used for measuring the change in voltage with respect to strain. There exists a linear relationship between change in voltage measured across two inner probes with respect to both tensile and compressive strain as shown in Fig. 3(b)[10].



(a) (b)



(c)

Fig. 4. (a) Picture of SBP film with insulating PVC attached to the brass specimen; (b) picture of metal strain gauge attached on the opposite side of the brass specimen;(c) Linear relationship between change in voltage in SBP film with respect to both tensile and compressive strain subjected to brass specimen [10].

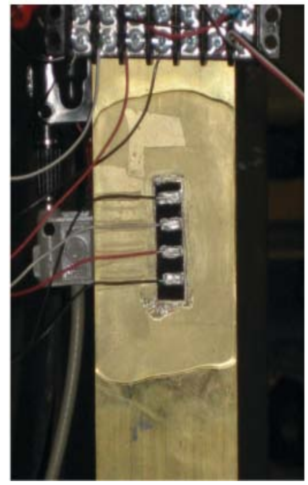
The major contribution of change in voltage is due to resistivity (~91%) and rest due to change in dimension in SBP films (~9%).The resistivity measured using four- point probe method is given by

$$\rho = \frac{V}{I} C\left(\frac{a}{d}, \frac{d}{s}\right) \quad (2)$$

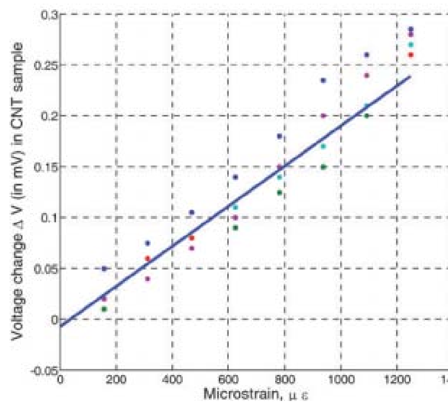
whereρ is the resistivity of the SBP film, $V$is the voltage across two inner probe , I is current applied to two outer probes and $C\left(\frac{a}{d}, \frac{d}{s}\right)$is factor related to dimensions a is the length ofSBP film; d is thewidth of SBP film, s is the distance between the two probes[10,11].

4. FABRICATION OF MULTI WALLED BUCKYPAPER

Multi walled Buckypaper (MBP) strain sensor can be fabricated by using MBP film which can be purchased or prepared from MWNTs. MBP film is then cut into a sensor strip of size (50.8mm x 12mm x 0.1mm). After cutting into strips, next step is to symmetrically deposit aluminum electrodes of diameter =1.78mm at both the end of strips by using vaccum thermal deposition method. Then the sensor strip is attached at the top of test specimen by using adhesive layer as shown in Fig. 5(a)[11].



(a)



(b)

Fig. 5: (a) Experimental set up of MBP film attached to the brass specimen with silver epoxy lead (b) Linear relationship between voltage change in MBP film with respect to tensile microstrain [11].

By using four-point probe method[9], a constant current is supplied to two inner probe and change in voltage is measured at two outer probe by using microscale voltage measurement device. An incrementing tensile load (0-8klbf) in elastic range at a rate of 1klbf/min is applied to brass specimen using servo hydraulic machine. The voltage across the two outer probe in four-point probe method varies linearly upto 1000 microstrain and then it become nonlinear as shown in Fig. 5(b). The major contribution of change in voltage is due to resistivity (~76%) and rest due to change in dimension in MBP films (~24%). On applying repeatedly loading and unloading test conditions to brass specimen, linear change in voltage of MBP film attain during loading fully reverse itself on unloading. During unloading, change in voltage of MBP film decreases linearly with respect to strain and finally reaches a value equivalent to zero load conditions. This means that MBP film shows fully reversible electromechanical characteristics [11].

5. FABRICATION OF BUCKYPAPER/POLYMER EMBEDDED STRAIN SENSOR

Buckypaper film is prepared or purchased from SWNTs and MWNTs. SBP/MBP film is then cut into a square piece of length ~10mm and width ~4mm.High purity silver paint is used to bind the copper wire on BP surface. This sensor is then encapsulated into three different dog bone shaped epoxy polymer tensile specimen. Out of these three polymers, polymer 1 and 2 fail at lower value of strain (~2 % and ~4% respectively) while polymer 3 fails at a very high value of strain (~40%). The benefit of BP enclosed into epoxy matrices is that it secures sensor and electrodes from damage and attains consistent deformation for BP sensor. Resistance of BP film can be measured by using four-point probe method [9] and it varies non-linearly with respect to applied strain for all the three different BP epoxy polymer matrices. This non-linearity factor is reported due to the interaction between BP film and epoxy polymer [7].

6. PERFORMANCE OF BUCKYPAPER STRAIN SENSOR

Performance of Buckypaper strain sensor is analysed by its sensitivity. Sensitivity of sensor is defined as the rate of change of resistance with respect to change in applied strain .It is denoted by S where

$$S = \frac{\frac{\Delta R}{R}}{\frac{\Delta \epsilon}{\epsilon}} \quad (3)$$

whereΔR is the change in resistance after deformation, ε is applied strain [7]. Sensitivity of a BP strain sensor depends on: bonding between polymer and sensor, amount of strain transfer, effect of strain on electrical properties and modulus of elasticity of epoxy specimen. As modulus of elasticity decreases, the sensitivity of sensor also decreases because lower the value of modulus of elasticity lesser will be the effect of strain on electrical properties resulting into lower sensitivity. Sensitvity of SBP is higher than MBP sensor. Sensitivity of SBP and MBP sensor is same as that of conventional metallic strain gauge for low range of strain (upto 15% for SBP and upto 7.5 % for MBP). As the value of strain increases, sensitivity of both SBP and MBP sensor increases. MBP sensor possesses very high sensitivity for higher value of strain (~30%) while SBP cannot function as strain sensor for high strain(~ above 15%)[7,9].

7. CONCLUSION

This review covers fabrication, characteristics and performance of SBP, MBP and Buckypaper/polymer embedded strain sensor. It has been observed that one can simply design buckypaper strain sensor either from SBP/MBP and can also encapsulated them into epoxy matrices. But due to its lightweight it resulted into poor strain transfer and slippage losses at higher value of strain. Hence to prevent slippage and provide better strain transfer, designers must use high strength epoxy coating between buckypaper and brass specimen. Among the entire available strain measurement test, four-point probe test gives the best result and is consider to be the most preferred test on buckypaper by the practitioners of this field. There exist a linear characteristic between the changes in voltage with respect to measured strain in brass specimen for both SBP and MBP film. But for buckypaper/polymer embedded strain sensor this curve possesses nonlinearity and the major contributor to this is the interaction between carbon nanotube bundles. The performance of buckypaper sensors can be analysed by finding their sensitivity. It has been found that the SBP sensor is more sensitive than MBP sensor and it possesses highest sensitivity in brittle polymer. At lower value of strain, the sensitivity of both SBP and MBP sensors is same as that of metallic strain gauge and at higher value of strain, MBP strain sensor is more sensitive than SBP sensor.

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