CNT based Strain Sensor for Wearable Health Monitoring

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Abstract — Nanotechnology is a field of science and engineering that focuses on the creation and utilization of structures, devices, and systems at the nanoscale. This involves manipulating atoms and molecules to design and produce materials with dimensions of approximately 100 nanometers or smaller (which is about one hundred millionth of a millimeter). Within this broad field, one interesting application is the development of strain sensors using carbon nanotubes (CNTs). In this discussion, we will explore different methods and materials used in the manufacturing process, consider various parameters involved, explore modeling techniques on Solidworks software, and examine the basic structure of a multiwalled CNT strain sensor intended for healthcare applications.

Keywords – CNT Sensors, Nanotechnology

I. INTRODUCTION

The origins of nanoscience and nanotechnology can be traced back to a talk given by physicist Richard Feynman in 1959 at a meeting of the American Physical Society held at the California Institute of Technology (CalTech). Although the term "nanotechnology" had not yet been coined, Feynman discussed the possibility of manipulating individual atoms and molecules. Carbon nanotubes (CNTs) are cylindrical molecules composed of rolled-up sheets of single-layer carbon atoms, known as graphene. They exist in two main forms: single-walled nanotubes (SWCNTs) with diameters less than 1 nanometer (nm), and multi-walled nanotubes (MWCNTs) consisting of several concentrically interlinked nanotubes, with diameters exceeding 100 nm. The length of these nanotubes can range from several micrometers to millimeters.

Strain, in the context of materials, is a dimensionless measure that represents the ratio of the change in length to the original length of an object. When a material is stretched, it exhibits positive strain, while compression results in negative strain.

The natural tendency of carbon nanotubes to adhere to one another through weak van der Waals forces presents an opportunity to develop materials with exceptional strength-to-weight ratios and excellent electrical and thermal conductivity. These properties make carbon nanotubes highly desirable for a wide range of applications.

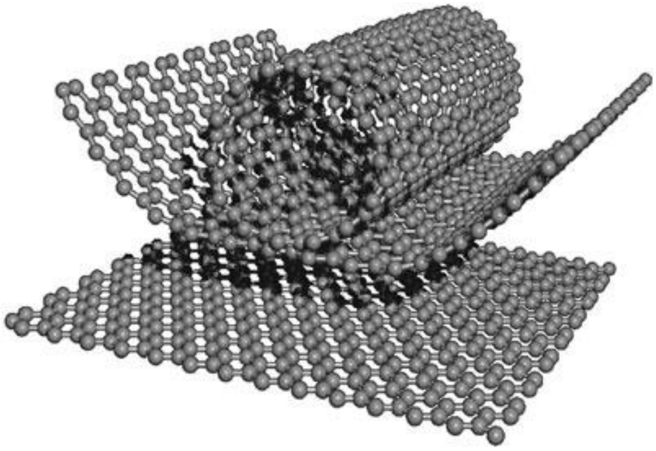


Fig. 1. Schematic of how graphene could roll up to form a carbon nanotube.

The utilization of carbon nanotubes (CNTs) in strain sensors is highly remarkable. Strain sensors have become increasingly prevalent in the modern era due to their ability to detect, respond to, and convert mechanical motion into an electrical signal, which can be interpreted based on changes in electrical resistance. This has expanded the scope of technology and allowed us to observe and understand our surroundings in new and distinct ways. In recent times, there has been significant growth in the development of advanced sensing materials based on carbon nanomaterials, owing to their exceptional properties. Among these materials, graphene, a type of carbon nanomaterial, has emerged as a promising choice for sensor development due to its unique combination of thermal, electrical, and mechanical strength. Graphene-based sensors offer numerous advantages across various fields of application.

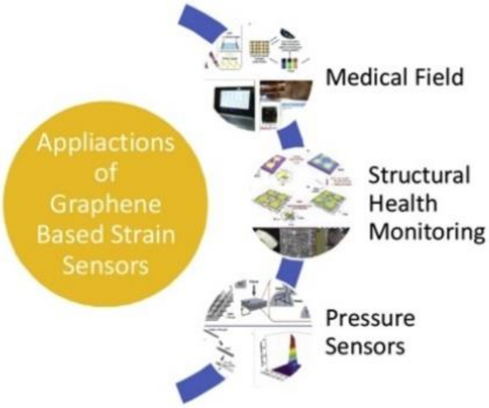


Fig. 2. Advantages of graphene in strain sensor in various fields.

II. LITERATURE REVIEW

The evaluation standards for flexible sensors have not yet been established, despite the emergence of various types of flexible sensors [5]. However, in current research, several important factors are typically taken into consideration. These include sensitivity, stretchability, flexibility, and durability [6]. For flexible sensors intended for long-term skin applications, additional considerations such as biocompatibility, low energy consumption, and lightweight design are crucial [7]. Moreover, sensors intended for use in harsh environments, such as wet or corrosive conditions, should exhibit robustness [8]. In order to achieve commercial viability, the overall production process of flexible sensors should be simple, efficient, and economically feasible.

Flexible sensors generally consist of three main components: flexible substrates, active materials, and electrodes. The selection of suitable active materials and flexible substrates is essential for designing an optimal flexible sensor. The structure of these components also significantly influences the sensing performance. Flexible substrates such as polyimide (PI) [9,10], polydimethylsiloxane (PDMS) [11-13], polyurethane (PU) [14], and Ecoflex [15] are commonly chosen due to their excellent flexibility, stretchability, stability, and durability [16]. In practical applications, properties such as corrosion resistance, chemical resistance, thermal resistance, transparency, and reproducibility should also be taken into account.

Regarding active materials, extensive research has been conducted on advanced carbon materials and metal nanomaterials [17]. Among them, sensors utilizing metal nanoparticles [18,19] exhibit high sensitivity but have a limited sensing range and stretchability [20]. On the other hand, metal nanowires [21,22] face challenges related to poor chemical stability and reproducibility, limiting their applicability in flexible sensors [23]. In contrast, carbon materials offer several advantages. Due to their exceptional mechanical, electrical, thermal properties, high chemical stability, and ease of functionalization, carbon materials such as carbon nanotubes (CNTs) [24], graphene [25,26], and carbon black [27,28] have emerged as highly promising sensor materials.

According to information from US Research Nanomaterials INC., multi-walled carbon nanotubes have an outer diameter of 50-80 nm and an inner diameter of 5-15 nm, resulting in a wall thickness of approximately 45-65 nm. The distance between each wall is approximately 0.34 nm, allowing the estimation of the number of layers to be between 132 and 191. Consequently, the MWCT US4315 sample can be considered to consist of approximately 132-191 layers.

III. BACKGROUND

Strain is a metric that represents the change in length of an object relative to its original length, and it is expressed as a dimensionless quantity. Positive strain occurs when a material is stretched or elongated, while negative strain occurs when a material is compressed or shortened. On the other hand, stress is a measurement that quantifies the force applied to an object, divided by its initial cross-sectional area. In simpler terms, stress represents the internal resistance or capacity of an object to withstand external forces.

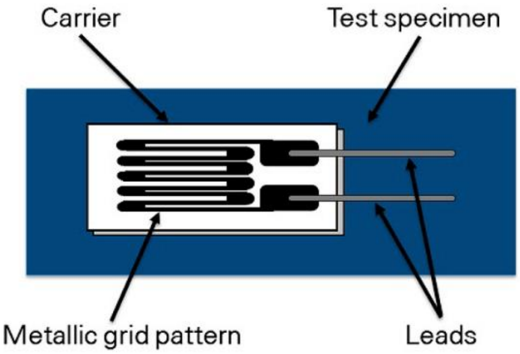


Fig. 4. Composition of Strain Gauge

A strain gauge typically consists of a metal foil that is insulated by a flexible substrate, as depicted in the accompanying illustration. The gauge is connected to a circuit through two leads, allowing a current to pass through it. When the surface of the object being measured experiences stretching or contraction, the strain gauge undergoes a change in resistance. This change in resistance is directly proportional to the alteration in length occurring on the surface of the object under test.

IV. METHODOLOGY

The strain gauge sensor is first designed in solidworks as a model to work on a nano scale.

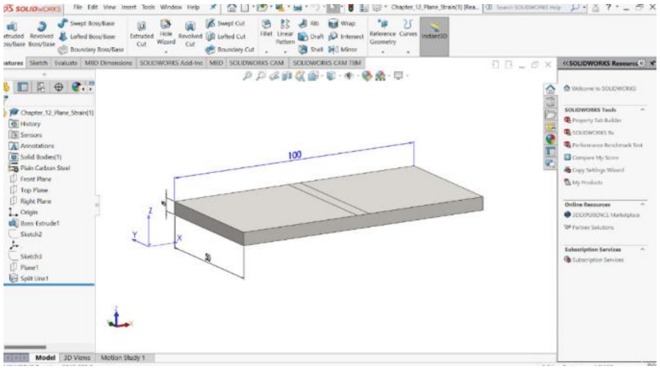


Fig. 5. Basic solidworks model of strain sensor film

Further we designed the basic structure of the CNT on Furious Atoms, by referring to the model of CNT US4315**,** which has the parameters. Where N = 37, M =37, with a diameter of about 50 Armstrong.

Material	Structure	Sensitivity	Work range
CNT/PDMS/polyethylene	Micro-pyramid arrays	-3.26 kPa^{-1} in 0-300 Pa -0.025 kPa^{-1} in 600-2500 Pa	0-300 Pa 600-2500 Pa
CNT/Au	Au island patterns	0.06 kPa^{-1} at 400 kPa	0-400 kPa
CNT/PDMS	Cobweb-like network	39.4 kPa^{-1} in 10 Pa-1.6 kPa	10-1600 Pa
CNT/PDMS	Irregular surface morphology	0.3 kPa^{-1} up to 0.7 kPa	0-5 kPa
CNT/PI	Porous structure	11.28 kPa^{-1} at 0-5 kPa 0.3 kPa^{-1} at 20-60 kPa	0-60 kPa

Table 1. Main sensing performance of sensor with microstructure

Considering the inner diameter to be around 1-2 µm.

Gauge factor (GF) or strain factor of a strain gauge is the ratio of relative change in electrical resistance R, to the mechanical strain ε. The gauge factor is defined as:

$$GF = \frac{\Delta R/R}{\Delta L/L} = \frac{\Delta R/R}{\varepsilon} = 1 + 2\nu + \frac{\Delta\rho/\rho}{\varepsilon}$$

Material Selection and Fabrication Process

Recent advancements in the field of strain sensors have demonstrated the exceptional performance of 1D carbon nanotube (CNT) fibers with core-sheath structures and helical properties. These structures offer high sensitivity, stretchability, and linearity. Tang et al. [28] developed a multi-walled CNTs (MWCNTs)-based core-sheath fiber with a protective layer, exhibiting remarkable properties such as 300% stretchability and a gauge factor of 1378. The protective layer ensured the sensor's performance in harsh environments, while also providing resistance against bending and torsion. Zhou et al. [29] utilized a coaxial wet-spinning approach and post-treatment to create thermoplastic elastomer (TPE)-wrapped single-walled CNTs (SWCNTs) fibers. These fibers exhibited a high density of cracks beyond their crack-onset strain, with entangled SWCNT networks bridging the cracked fragments, which played a key role in sensing performance. The inclusion layer offered protection, stability, and durability, and the production process was continuous and scalable, promising mass production. Cai et al. [30] employed core-spun spinning technology to fabricate a cotton/CNT sheath-core yarn with polypyrrole (PPy) deposition. This yarn possessed a unique spring-like structure, allowing for great stretchable capacity and a large work range of 350%. Gao et al. [31] reported a CNTs/polyurethane (PU) nanofiber composite helical yarn produced through electrospinning, spray coating, and twisting processes. The stretchability was enhanced by the synergistic effect between the polymer chain and the helical coil structure, while a firmly winding-locked CNT network contributed to a stable conductive network. This yarn demonstrated conductivity and recoverability within a 900% deformation range and remained conductive under strains up to 1700%.

However, there has been relatively less focus on the behavior of strain sensors in challenging environments such as high humidity, strong acidity, and high temperature, which are crucial for practical applications [31]. Therefore, the development of CNT-based strain sensors that are flexible, soft, and resistant to corrosion holds promise. In addition to core-sheath structures, alternative approaches have been proposed. For instance, ultrasonication has been used to decorate CNTs onto nanofiber surfaces [32]. Building upon this technique, Wang et al. [33] designed a superhydrophobic strain sensor. By decorating CNTs onto the surface of a thermoplastic polyurethane (TPU) nanofiber and modifying it with polydimethylsiloxane (PDMS), they achieved a conductive network and superhydrophobicity. The fabrication process is illustrated in Figure 5. Different patterns have been explored to enhance flexibility in SWCNT membranes, with Pattern P being identified as one of the most efficient options (Fig. 6).

Here we finalized the materials for the strain sensor i.e., CNT along with a polymer composite of PDMS.

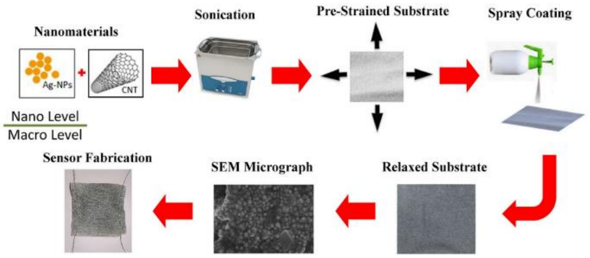


Fig. 5. The finalized way for manufacturing

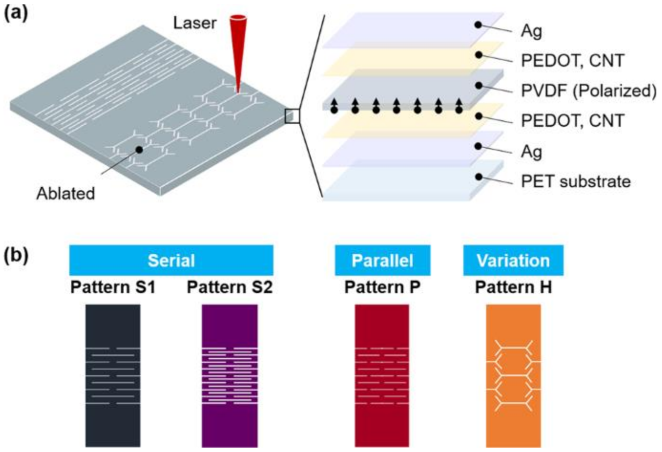
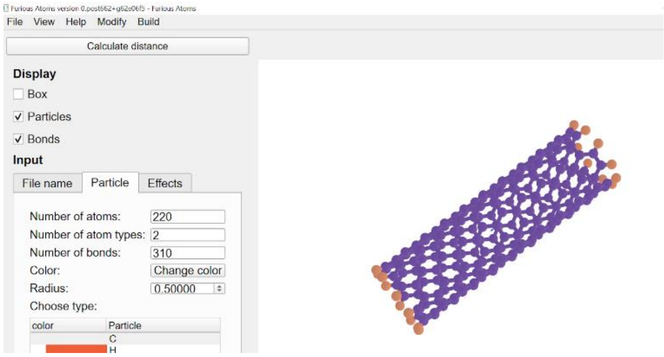


Fig. 6. The patterns available for stretchability of SWCNT

V. RESULTS AND DISCUSSIONS

Detailed study of Nanotechnology uses in CNT strain sensor and various methods of manufacturing the SWCNT, finalization of materials i.e., polydimethylsiloxane (PDMS) to be used and the overall fabrication process mentioned above in Fig. 5 along with the pattern P for stretchability.



☐ Box
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Number of atoms: 220
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Fig. 5. Model of SWCNT in Furious Atoms

The model made in Furious Atoms by finalizing the dimensions of the SWCNT.

VI. FUTURE SCOPE

CNTs and nanotechnology offer vast possibilities for diverse applications, including the development of various types of sensors using CNTs and polymer composites. Among these applications, SWCNTs hold significant promise for the fabrication of flexible strain sensors due to their unique geometry and exceptional intrinsic properties. Enhancing the sensing performance from a materials perspective can be achieved through several potential approaches. One such approach is utilizing SWCNT networks composed of isolated semiconducting SWCNTs with an appropriate level of functionalization, which offers a balance between cost-effectiveness and efficiency as a sensing material. By combining the structural design and configuration of the sensor with the flexibility and transparency of SWCNTs, strain sensors based on SWCNTs can find extensive utility in the Internet of Things (IoT), wearable devices, and aerospace applications.

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