Functionalized Carbon Nanowalls Materials for Biomaterial Applications

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Summary of Doctoral Thesis

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Biomaterials based devices have been fabricated using Carbon nanomaterials (CNMs), among these Graphene and Carbon Nanotubes (CNTs) have been used the most extensively. Graphene and CNT possess unique properties that are ideally suited for use in the fabrication of electrodes that have been instrumental in the development of photovoltaic cells, capacitors, batteries, fuel cells, biomedical and biosensor related devices. One of the major drawbacks while using Graphene and CNTs have been the difficult in their difficult reproducibility and replicability. These CNMsare difficult to grow uniformly and their properties are easily affected by changes in the growth and nucleation conditions. Generally, Chemical Vapour Deposition (CVD) systems are used to produce Graphene and CNT films. When using the CVD method of production, Graphene substrates made of Copper metal are used from epitaxial growth on the other hand for the growth of CNTs, metallic nanoparticles are required nucleation, in order to use CNT and Graphene in biological devices, extensive purification procedures are required particularly in the case of CNTs, where removal of the metallic nanoparticles catalysts. These nanoparticles are usually Co and Ni based and require strong oxidizing agents such as acids to remove them. These nanoparticles still linger after the purification process and thus may not be suitable in biological applications due to their toxicity. Furthermore, these solutions not only cause defects in the materials but also cause environmental damage if used in large-scale production. In the case of Graphene, the difficulty is in isolating single unbroken layers of monoatomic thick graphene. This causes reproducibility issue in devices fabricated with graphene, as the device performance may vary from batch to batch. In order to mitigate these factors, another method of fabricating electronic and biological devices is required. One method is by using a material that is already deposited as a thin film layer such as epitaxially grown graphene, which can then be utilized without any further purification. Another material that can be used in such application are Carbon Nanowalls. Carbon Nanowalls (CNW), can be prepared with good reproducibility using CVD systems and without the use of metallic nanoparticles or purification procedures; they possess high aspect ratio, surface to volume ratio have good electrical conductivity and biocompatibility. Due to the thin film layer of nanos. This thesis is divided into **6 chapters** as follows:

The progresses made in the field of Carbon Nanomaterials are discussed in **Chapter 1.** This chapter provides a literature review of different carbon based nanoallatrope. The first section explains the different methods for the production, synthesis and Raman characteristics of CNMs. Raman spectroscopy gives an in depth look at the bonding between Carbon atoms in CNMs thus providing the best information about the various CNM properties. The second section will describe the development of CNMs in Photovoltaic, Electronics, Batteries, Fuel Cells and Biomedical related applications. The third section focuses on CNM suitability in Lab-on-Chip and Organ-on-Chip devices, this chapter also discusses the progress that has been made in developments in Multi Organs-on-Chip and how they have been improved and better integrated in drug testing, pathogen detection and their implication in personalized medicine.

In studying nanometer size phenomenon, advanced instruments have to be employed for the fabrication and characterization of Carbon Nanomaterials and Nanoparticles. These instruments will be discussed in **Chapter 2**. This chapter is split into multiple sections that will discuss the fabrication, functionalization and characterization of CNWs through Surface Wave Microwave Plasma Enhanced Chemical Vapor Deposition system (SWMWPECVD), The morphological and topological characterization of the materials were performed with Scanning Electron Microscope (SEM), Transmission Electron Microscope (TEM) and Atomic Force Microscope (AFM). Physiochemical characterization was performed using X-ray Photoelectron Spectroscopy (XPS), Auger Electron Spectroscopy (AES), Raman Spectroscopy, Fourier Transform Infrared Spectroscopy (FTIR) and

Sessile Drop Contact Angle technique. Electrochemical characterization was performed using Cyclic voltammetry (CV) and Electrochemical Impedance Spectroscopy (EIS).

The incorporation of human endothelial cells on functionalized Carbon Nanowalls scaffolding is discussed in **Chapter 3.** This chapter highlights how the cell dendrites were attached to the petal like CNW due to high surface roughness. The chapter describes method used for fabrication and Nitrogen functionalization of CNW using Plasma Enhanced Chemical Vapor Deposition. This chapter studies the effects of nitrogen on the structure of CNWs and how Nitrogen concentration changes the contact angle and surface wettability of CNW. The chapter also demonstrates that adhesion of endothelial cells is much stronger on functionalized CNWs than normal cover slips used in cell culture studies. This section also discusses the fact that certain major angiogenic markers have found to be additionally expressed on the CNW-N_2 substrates. This phenomenon has not been reported so far.

The use of Glucose Oxidase enzyme to develop a glucose sensor using CNW is detailed in **Chapter 4,** the fabrication of bioelectrodes are discussed. Glucose Oxidase has a very high specificity for commonly found sugars in the bloodstream that indicate the onset of Diabetes Mellitus. These enzymes have been utilized in developing glucose sensors. Previously CNT and Graphene have been used for electrochemically measuring glucose concentration however due to the limitations in the reproducibility of CNT and Graphene in different fabrication procedures are used. Due to these factors, CNW has been utilized in immobilization of Glucose Oxidase from *Aspergillus Niger* for the sensing of Glucose molecules in a buffer solution using Cyclic Voltammetry. Thus, CNW present a more reproducible and quicker method of using carbon-based nanomaterials in amperometric glucose sensors with high controllability. This proof of concept can then be applied in the fabrication of other biomolecule sensing platforms.

CNW in fabricating electrodes were investigated and are discussed in **Chapter 5**. This chapter examines thin film electrodes that have been developed using CNW and Poly (3,4-ethylenedioxythiophene):polystyrene sulfonate (PEDOT:PSS) mixture. The Current-Voltage characteristics are then studied to understand the electrical properties of the film. This chapter considers the methods of fabrication, deposition and characterization of the fabricated thin film electrodes. The future application for these electrodes is also theorized.

The results of the preceding chapters are summarized in **Chapter 6**; important results that were obtained from the different applications of CNW are showcased in this chapter. Future improvements in procedures and techniques to successfully apply CNW for the fabrication of nanostructured electrode have been examined. CNWs have unique properties such as high surface area, film uniformity, and tunable and electrical properties. Due to these properties they are good candidates for use in cell scaffolding, electrodes and to trap biomolecules and nanoparticles and the future extensions of the previously mentioned projects are theorized. The use of CNWs in fabricating cell scaffolding and sensors highlights a unique opportunity to incorporate these features into microfluidic devices, Lab-on-chip and Organ-on-chip devices. Since CNWs can be formed as a uniform film they can be employed in the miniaturization of circuits to fabricate screen printed sensors and electronics.