# Carbon Nanotubes

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# Preface

Carbon nanotubes (CNT) discovered in 1991 have been a subject of intensive research for a wide range of applications. These one-dimensional (1D) graphene sheets rolled into a tubular form have been the target of many researchers around the world due to their exceptional electrical and mechanical properties. This book provides a unique insight on the phenomena encountered in the physical electronics when operating with carbon nanotubes. This book also presents the reader with useful information on the fabrication and applications of these outstanding materials in current technology.

In the past decades, carbon nanotubes have undergone massive research from countless researchers around the world. Nevertheless, considering the success of Silicon, it has been difficult to appreciate the potential influence of carbon nanotubes in current technology. The main objective of this book is to give in-depth understanding of the physical electronics and mechanical properties of carbon nanotubes. In other words, this book is intended to provide a profound knowledge of these electrical and mechanical characteristics allowing the reader to further appreciate the potential and applications of carbon nanotubes.

Readers of this book should have a strong background on physical electronics and semiconductor device physics. Philanthropists and readers with strong background in quantum transport physics and semiconductors materials could definitely benefit from the results presented in the chapters of this book. Especially, those with research interests in the areas of nanoparticles and nanotechnology.

This book has been outlined as follows: A review on the literature and increasing research interests in the field of carbon nanotubes. Fabrication techniques followed by an analysis on the physical properties of carbon nanotubes. The device physics of implemented carbon nanotubes applications along with proposed models in an effort to describe their behavior in circuits and interconnects. And ultimately, the book pursues a significant amount of work in applications of carbon nanotubes in sensors, nanoparticles and nanostructures, and biotechnology.

A list of the chapters is given below. It is highly recommended for the reader to go over the following descriptions, as they provide excellent insights on the contents and results of the book's chapters.

*Chapter 1. Carbon Nanotubes - A Scientometric study*

The book starts with an outline on the time dependent and overall number of carbon nanotube's articles written in the past decades. This chapter reveals the still strongly increasing research activity in this field.

*Chapter 2. Chemical Vapour Deposition of CNTs Using Structural Nanoparticle Catalysts*

The role of the catalyst in the selective growth of single walled carbon nanotubes (SWNTs) by chemical vapour deposition (CVD) is studied. In addition, SWNT growth was shown to be possible from ceramic, noble metal, and semiconducting catalysts.

*Chapter 3. Properties of Carbon Nanotubes under External Factors*

The electronic and magnetic carbon nanotube properties under external factors are discussed. Radial deformation and external electric fields are investigated. The combined effects of radial deformation and external electric field are given in terms of band gap modulations and electronic band structure changes, due to the strength of the applied electric field and electric field orientation.

*Chapter 4. Electronic Structure of Fluorinated Carbon Nanotubes*

The study of the electronic structure of fluorinated single-walled (F-SWCNTs) and multiwalled (F-MWCNT) carbon nanotubes is conducted. High-energy resolution X-ray Carbon 1s and Fluor 1s absorption and photoelectron spectra of F-SWCNTs with different fluorine contents (35 and 40%) and F-MWCNTs with fluorine contents (10 to 55%) are measured.

*Chapter 5. Microwave Dielectric Properties of Carbon Nanotube Composites*

The complex permittivity of single-walled carbon nanotubes (SWCNTs), double-walled carbon nanotubes (DWCNTs), and multi-walled carbon nanotubes (MWCNTs) at microwave band is obtained experimentally using the impedance method.

*Chapter 6. Environmental effects on photoluminescence of single-walled carbon nanotubes*

The environmental effects on the optical properties of single-walled carbon nanotubes (SWNTs) are discussed. It is shown that a detail understanding of the environmental effects contributes into making, a spectroscopic technique under a standardized methodology, to evaluate the chirality abundance and the quality of SWNTs.

*Chapter 7. Charge Transport in Carbon Nanotube Films and Fibers*

Electrical and magneto transport properties of various types of carbon nanotubes arrays are reported. It is experimentally shown that the electrical and magneto transport properties of the investigated carbon nanotubes arrays are defined not only by the types of pristine carbon nanotubes (multi- or single-walled carbon nanotubes with different chiralities), but also by the quality of inter-tube coupling between separate nanotubes from which these assemblies consist of.

*Chapter 8. Doped Carbon Nanotube Properties*

The effect of impurities from the atoms of Aluminum (Al), Boron (B), Nitrogen (N) and Phosphorous (P) on models of carbon nanotubes with chiral vectors (10,0) and (6,5), consisting of 200 atoms is reviewed in terms of the performances of their energy-band structure. The magnification of number of atoms of carbon of the doped nanostructure feebly influences its energy distribution, results shows a diminution of the forbidden gap of the nanotube by approximately, 0.1 eV.

*Chapter 9. Fundamental Physical Aspects of Carbon Nanotube Transistors*

Two simulation methodologies are reliable for modeling carbon nanotube field effect transistors (CNT-FETs): The non equilibrium green's function (NEGF) transport equation self-consistently with Poisson's equation and the semi-classical Wentzel-Kramers-Brillouin (WKB) method for calculating the tunneling current through the Schottky barriers (SB) in the SB-CNT-FETs. Using the simulation methods discussed, trade-offs are studied for the different parameters of a particular CNT-FET design.

*Chapter 10. Gate controlled Particle-Wave duality in a single walled carbon nanotube hole-transistor*

After successfully fabricating and demonstrating a multi-functional quantum transistor using the particle nature and wave nature of holes in single-walled carbon nanotubes (SWNTs); a transistor that is able to operate in the wave nature mode as an RTT (resonant tunneling transistor) and in the particle nature mode as an SHT (single hole transistor) is accomplished and described.

*Chapter 11. Numerical Modeling of the I-V Characteristics of Carbon Nanotube Field Effect Transistors*

A numerically based model for the carbon nanotube potential and current transport of carbon nanotube field effect transistors (CNT-FETs) is presented. The tight binding model approximation for the electronic band structure of a carbon nanotube is used to find the carrier concentration. Poisson's equation is solved inside a CNT-FET and used to characterize the charge transport, resulting in the I-V characteristics. Results provide designers with useful mathematical relations describing the properties in conductivity of carbon nanotubes and their response in circuit applications.

*Chapter 12. Compact Modeling of Carbon Nanotube Transistor and Interconnects*

A detailed procedure for developing compact models for carbon nanotube transistors and interconnects is presented. The developed model does not use any iteration-based calculations; therefore, it is scalable with process and design parameters while keeping a high accuracy.

*Chapter 13. Measurement of High-Frequency Characteristics of CNTFETs and Equivalent Circuit Model Analysis*

A method for accurately measuring and modeling the high-frequency characteristics of CNTFETs is described. In addition, a high-density multiple-channel CNTFET structure with focus on accurately measuring the S-parameters is developed. Consequently, a cut-off frequency (fT) of 10.3 GHz and a maximum oscillation frequency (fmax) of 3.5 GHz are achieved.

*Chapter 14. Carbon Nanotubes Interconnects for Nanoelectronics Circuits*

The use of carbon nanotubes as possible innovative materials to fabricate high-speed interconnects at various hierarchical levels of the future nanoelectronics technology is studied. The electromagnetic model presented is used to describe the electrical propagation along the carbon nanotube interconnects and it is derived from a semi-classical solution of Boltzmann's transport equation.

*Chapter 15. Interconnect Challenges and Carbon Nanotube as Interconnect in Nano VLSI Circuits*

The study of the interconnect challenges and the behaviour of carbon nanotubes (CNTs) as interconnects in VLSI circuits is presented. In this chapter, the two main structures of

carbon nanotubes, including carbon nanotube bundles and multi-walled carbon nanotubes (MWCNTs) are reviewed. Results show extremely good performance using parallel singlewalled carbon nanotubes (SWCNTs) in a bundle and using the parallel shells of MWCNTs.

*Chapter 16. Affinity of CNT for metal - Its importance to application: Molecular dynamics approach*

A molecular dynamics (MD) simulation approach for carbon nanotubes (CNT) analysis is explained. A simulation is conducted for carbon nanotubes using physical vapour deposition (PVD) and using coating; the simulations presented show good agreement with the experimental results from the fabricated CNTs.

*Chapter 17. Carbon nanotube field emitters*

The field emission from carbon nanotube field emitters in a diode configuration between a flat anode and a cathode is theoretically investigated. It is concluded that carbon nanotubes are excellent field emitters and have good potential in the field emission display market.

*Chapter 18. Sensing mechanisms of carbon nanotube based NH3 gas detectors*

Sensing mechanisms using carbon nanotube (CNT) based NH3 detection are studied. Selective Si3N4 passivation clearly shows that the Schottky barrier (SB) modulation at the CNT/metal contacts dominates the sensing performance at room temperature, and the sensor exhibits high sensitivity and good tuning ability under the appropriate gate voltages.

*Chapter 19. Gas sensors based on decorated carbon nanotubes*

It is shown that the study of gas sensors based on short multi-walled carbon nanotubes (MWCNTs), in a chemical resistor configuration (where nanotubes can be heated considerably by current), reveals two main effects. These effects occur under the exposure to simple low-pressure gases like Ar, N2 and O2, and show significantly different results for supported (over SiO2) and suspended nanotubes.

*Chapter 20. Suspended Carbon Nanotubes: Applications in Physical Sensors and Actuators*

An overview of the applications of suspended or freestanding carbon nanotubes (CNTs) as sensors and actuators is provided. A scheme for using 5-10 mm long, diffusively contacted single-walled carbon nanotubes (SWNTs) as thermal conductivity-based pressure sensors is presented. The actuator applications of suspended CNTs are also presented. The use of direct current plasma-enhanced chemical vapour deposition (dc PECVD) for forming isolated vertically oriented tubes with manufacturability techniques, where such tubes have applications in three-dimensional (3D) electronics is also provided.

*Chapter 21. Study of Carbon NanoTube Field Effect Transistors for NEMS*

Given the chemical and physical structure, low mass, and exceptional stiffness of carbon nanotubes (CNTs); CNTs are presented as ideal candidates for nanoelectromechanical systems (NEMS). It is shown that even with pessimistic assumptions, CNT-FET nanoelectronics can achieve significantly greater performance than Silicon technology.

*Chapter 22. Solid phase (micro) extraction tools based on carbon nanotubes and related*

Nanostructures Carbon nanoparticles (nanotubes, fullerenes, and nanocones) have been proved to positively contribute to the development of analytical methods further enhancing the

properties of carbon nanotubes. It is shown that the present research on carbon nanoparticles is also capable of reducing the negative aspect related to the aggregation tendency of the carbon nanotubes.

*Chapter 23. Broadband Terahertz Source based on Photomixing in Laser-Assisted Field Emission*

with Clusters of Carbon Nanotubes It is demonstrated that photo mixing in laser-assisted field emission shows considerable promises as the means to generate microwave or THz radiation with an extremely large tuneable bandwidth. The purpose of this chapter is to obtain fundamental research and understanding of the process of quantum tunneling for applications in the THz range.

*Chapter 24. Liquid crystal dispersions of carbon nanotubes: dielectric, electro-optical and structural peculiarities*

A class of unique composites with fascinating electrical, optical, electro-optical, nonlinear optical, and structural properties is presented after the combination of carbon nanotubes and liquid crystals (LCs). Carbon nanotubes (CNTs) shunt double electric layers in the LC cells and in this way; they change essentially a spatial distribution of the electric field applied in these cells.

*Chapter 25. Functionalization of carbon nanotubes with luminescent silicon nanocrystals upon nanosecond laser processing in liquid media*

Scalable and low cost approaches introducing the silicon nanocrystals (Si-ncs) within carbon nanotubes (CNTs) and lipid nanotubes (LNTs) are discussed. It is shown that after opening the CNT ends and freeze-draying the LNTs; it is possible to introduce Si-ncs inside the emptied cavity of both type of nanotubes.

*Chapter 26. Microstructured Optical Fibers filled with Carbon Nanotubes: Photonic Bandgap Modification and Sensing Applications*

Research activities devoted to the integration of microstructured optical fibers (MOFs) with single-walled carbon nanotubes (SWCNTs) in order to develop new in-fiber active and passive optoelectronic devices are reviewed. On the basis of the retrieved results, a novel opto-chemical sensor for VOCs (Volatile Organic Compounds) detection is developed and its sensing capability is proved by the exposure to VOC traces in a proper test chamber.

*Chapter 27. Carbon Nanotubes as a New Solid Phase Extraction Sorbent for Analysis of Environmental Pollutants*

Several comparative studies present results that show carbon nanotubes (CNTs) to be more effective than other commonly used adsorbents such as the Carbon 18 bonded silica, activated Carbon, or macro porous resins. It is reported that CNTs may be re-used more than 100 times before the need for a proper cleaning and reconditioning.

*Chapter 28. Hydrogen storage by carbon materials*

An overview of the experimental work on systems dealing with storing hydrogenin is provided. The experimental work together with an outline of the theoretical studies that have been under taken to estimate the practical limits of the amount of hydrogen that can be stored per unit weight are also presented.

*Chapter 29. Carbon Nanotube Supercapacitors*

Carbon nanotubes (CNTs) are explored as a new type of electrode materials for supercapacitors. Due to their unique properties and large surface area, both randomly entangled and highly aligned CNTs are investigated for high capacitance and high rate composites applications.

*Chapter 30. Carbon Nanotube Membrane Solar Sails A Challenge for Extremely Fast Space Flight*

A better understanding and appreciation of the recent technological advancements in the sail material through a proper development of carbon nanotube membranes is presented. This allows the design of a solar sail featuring a cruising speed on the order of thousands the speed of light. This shows a speed much higher than the speed attainable by any other propulsion method.

*Chapter 31. Carbon Nanotube-Nanoparticle Hybrid Structures*

The electrostatic force directed assembly (ESFDA) technique is used to efficiently coat randomly dispersed and vertically-aligned carbon nanotubes (CNTs) with various aerosol nanoparticles (NPs). The final NP size distribution and areal density can be controlled through flow residence time/electric field or assembly time, respectively. For verticallyaligned CNTs, the electric field distribution near the CNT surface is computed using a simple model for the CNT as a cylinder with a hemispherical cap. It is shown that the field enhancement factor increases from the root to the tip of the CNT for the two cases studied.

*Chapter 32. SWC of AI/CNT Two Phase Systems*

Micro-nanosystem research on preparing materials and using shock wave compaction (SWC) for future developments is presented. Al-MWCNT (Aluminum multi-walled carbon nanotube) aggregate 2-phase composites of 2 and 5% volume fraction are fabricated and presented using a single tube shockwave consolidation process.

*Chapter 33. Superconductivity in carbon nanotubes*

Superconductivity is reported at 12 K in arrays of multi-walled carbon nanotube (MWNTs) and Boron-doped single-walled carbon nanotube (SWNTs) at 19 K. The possibility of quantum spin entangler and quantum bit utilizing a hybrid system of carbon nanotubes (CNTs)/superconductor is presented. This allows the feasibility of CNTs as onedimensional (1D) superconductors and the understanding of 1D electron correlation for quantum devices.

*Chapter 34. Nucleic acid interaction and interfaces with single-walled carbon nanotubes*

An experimental and theoretical study of the DNA-interface coupling is performed to achieve better understanding of the properties of carbon nanotubes based biosystems, as well as the study of the novel phenomena caused by the interaction of carbon nanotubes with biomolecules.

*Chapter 35. DNA-Wrapped CNTs From Synthesis to Application*

It is shown that working with the chemical functionality of carbon nanotubes (CNTs) is the most efficient method to increase their solubility. DNA-CNT hybrids can take advantage of the unique properties of CNTs and the outstanding recognition properties of DNA. The non-covalent interaction between CNTs and DNA wrapping facilitates separations applications and allows the functionality of CNTs without altering their unique properties.

*Chapter 36. The Unlikely Surfactant: DNA as a Ligand for Single-Walled Carbon Nanotubes*

Oligonucleotide-SWCNTs (single-walled carbon nanotubes) complexes are discussed. Results show an emphasis on the fact that DNA has surfactant properties that make it useful for solubilizing carbon nanotubes. It is shown that after sonication and separation processes, a stable, largely mono-disperse suspension can be obtained, such as density gradient ultracentrifugation.

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I would like to thank the authors of the chapters of this book for their excellent contributions in their areas of expertise and for the efforts place in the publication of their work. I am certainly sure that the material published in this book will be of great help and genuinely appreciated by students, professors, and researchers all around the world.

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# Contents

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# Carbon Nanotubes – A scientometric study

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## 1. Introduction

In contrast to our previous study (Barth & Marx, 2008) dealing with a currently decreasing research field (high-temperature superconductors) we analyzed here a topic which has raised a strongly increasing interest among researchers: research activities around carbon nanotubes (CNTs or NTs). Carbon nanotubes (often named only nanotubes) are graphite sheets rolled up into cylinders with diameters of the order of a few nanometers and up to some millimeters in length with at least one end capped with a hemisphere of the fullerene structure. There are two main types of nanotubes: the single-walled nanotubes (SWCNTs or SWNTs) and the multi-walled nanotubes (MWCNTs or MWNTs), in particular the double-walled nanotubes (DWCNTs or DWNTs). MWCNTs consist of a single sheet of graphite rolled in around itself (like a rolled up newspaper) or consist of multiple layers of graphite arranged in concentric cylinders (like a Russian Doll).

Nanotubes exhibit some remarkable properties: They feature extraordinary strength, show efficient conductivity of heat, and unique electrical properties (metallic conductivity and semiconductivity). These properties make them potentially useful in a wide range of applications like in materials science, electronics, and nanotechnology. The one-atom thick single graphite layers building up the nanotube cylinders are named graphene, the newest member of this structural family. This species was presumed not to exist in the free state before it was discovered in the year 2004.

The large number of articles with respect to nanotubes has brought about that scientists being active in this research field have increasingly problems to overview their discipline. On the other hand, modern information systems offer databases and analysis tools providing remedy. However, due to lack of access and experience, many scientists do not take advantage of them. In this analysis we demonstrate the potential of such tools with respect to different kinds of meta-information. The data presented here are not expected to reveal surprising insights for experts working in this research field. However, they provide a quantification of (1) the productivity of the active players and (2) of the impact of their works. Moreover, the data could also be interesting for scientists working in neighboring research fields.