

# Carbon Nanotube And Graphene Device Physics

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Nanotechnology *H.-S. Philip Wong Kazuyoshi Tanaka A. Martinez Stelbin Peter Figerez Debaprasad Das Bhanu Pratap Singh B.A. Baker Mahmood Aliofkhazraei Philip Scard Wei Fan Filipe Vargas Ferreira Kazuhiko Matsumoto John E. Proctor James E. Morris Boris Dzyubenko Konstantinos I. Tserpes Boris Dzyubenko Eduardo A. Castro Yarub Al-Douri*

the first introductory textbook to explain the properties and performance of practical nanotube devices and related applications

carbon nanotubes and graphene is a timely second edition of the original science and technology of carbon nanotubes updated to include expanded coverage of the preparation purification structural characterization and common application areas of single and multi walled cnt structures this work compares contrasts and where appropriate unitizes cnt to graphene this much expanded second edition reference supports knowledge discovery production of impactful carbon research encourages transition between research fields and aids the formation of emergent applications new chapters encompass recent developments in the theoretical treatments of electronic and vibrational structures and magnetic optical and electrical solid state properties providing a vital base to research current and potential applications of both materials including the prospect for large scale synthesis of graphene biological structures and flexible electronics are also critically discussed updated discussion of properties structure and morphology of biological and flexible electronic applications aids fundamental knowledge discovery innovative parallel focus on nanotubes and graphene enables you to learn from the successes and failures of respectively mature and emergent partner research disciplines high quality figures and tables on physical and mathematical applications expertly summarize key information essential if you need quick critically relevant data

fiber laser technology is attracting a great deal of attention due to its numerous applications in fields as diverse as micromachining biology and medical sciences or telecommunications and its potential as a substitute for solid state lasers in industrial and technological applications fiber lasers are also exciting from the scientific point of view as they are an excellent platform to further study and understand nonlinear optical phenomena in this chapter we review the impact of nano materials such as graphene and carbon nanotubes in advancing fiber laser technology both graphene and carbon nanotubes present a highly nonlinear optical response with a high third order susceptibility and saturable absorption here we discuss how these properties can be used to achieve pulse operation using a technique known as mode locking and how these two materials compare to other mode locking mechanisms in terms of their ability to achieve pulse operation the stability of the mode locked lasers and their long term reliability

this title covers the fundamentals of carbon nanomaterials in a logical and clear manner to make concepts accessible to researchers from different disciplines it summarizes in a comprehensive manner recent technological and scientific accomplishments in the area of carbon nanomaterials and their application in lithium ion batteries the book also addresses all the components anodes cathodes and electrolytes of lithium ion battery and discusses the technology of lithium ion batteries that can safely operate at high temperature

an alternative to copper based interconnect technology with an increase in demand for more circuit components on a single chip there is a growing need for nanoelectronic devices and their interconnects a physical connecting medium made of thin metal films between several electrical nodes in a semiconducting chip that transmit signals from one point to another without any distortion carbon nanotube and graphene nanoribbon interconnects explores two new important carbon nanomaterials carbon nanotube cnt and graphene nanoribbon gnr and compares them with that of copper based interconnects these nanomaterials show almost 1 000 times more current carrying capacity and significantly higher mean free path than copper due to their remarkable properties cnt and gnr could soon replace traditional copper interconnects dedicated to proving their benefits this book covers the basic theory of cnt and gnr and provides a comprehensive analysis of the cnt and gnr based vlsi interconnects at nanometric dimensions explore the potential applications of cnt and graphene for vlsi circuits the book starts off with a brief introduction of carbon nanomaterials discusses the latest research and details the modeling and analysis of cnt and gnr interconnects it also describes the electrical thermal and mechanical properties and structural behavior of these materials in addition it chronicles the progression of these fundamental properties explores possible engineering applications and growth technologies and considers applications for cnt and gnr apart from their use in vlsi circuits comprising eight chapters this text covers the basics of carbon nanotube and graphene nanoribbon discusses the growth and characterization of carbon nanotube and graphene nanoribbon presents the modeling of cnt and gnr as future vlsi interconnects examines the applicability of cnt and gnr in terms of several analysis works addresses the timing and frequency response of the cnt and gnr interconnects explores the signal integrity analysis for cnt and gnr interconnects models and analyzes the applicability of cnt and gnr as power interconnects considers the future scope of cnt and gnr beneficial to vlsi designers working in this area carbon nanotube and graphene nanoribbon interconnects provides a complete understanding of carbon based materials and interconnect technology and equips the reader with sufficient knowledge about the future scope of research and development for this emerging topic

this book comprehensively reviews recent and emerging applications of carbon nanotubes and graphene materials in a wide range of sectors

detailed applications include structural materials ballistic materials energy storage and conversion batteries supercapacitors smart sensors environmental protection nanoelectronics optoelectronic and photovoltaics thermoelectric and conducting wires it further covers human and structural health monitoring and thermal management applications key selling features exclusively takes an application oriented approach to cover emerging areas in carbon nanotubes and graphene covers fundamental and applied knowledge related to carbon nanomaterials includes advanced applications like human and structural health monitoring smart sensors ballistic protection and so forth discusses novel applications such as thermoelectrics along with environmental protection related application explores aspects of energy storage generation and conversion including batteries supercapacitors and photovoltaics this book is aimed at graduate students and researchers in electrical nanomaterials chemistry and other related areas

carbon nanotubes have been explored in light harvesting and photovoltaic devices because of their unique optoelectronic properties this chapter provides a brief description of the optoelectronic properties of carbon nanotubes particularly single wall carbon nanotubes swcnts and their implication in various solar cell applications including donor acceptor solar cells polymer solar cells and dye sensitized solar cells where carbon nanotubes are utilized as photoactive materials carbon nanotube based electrodes in photovoltaic devices are also introduced carbon nanotube based light harvesting devices are reviewed in terms of fabrication and material processing as well as performance finally advanced emerging methods and the future outlook for carbon nanotube based solar cells are discussed

composites and nanocomposites are used in cases where long durability and strength of components are required i e where high stress levels erosion processes and multiphase environments are present including the parts under collision and impact the parts under rotating motion and erosion like excavation drills in oil and gas wells the first volume of this book aims to provide a guide for fabrication of new nanocomposites mainly based on carbon nanotubes and graphene the main topics of this volume are application of nano powders for formation of metal matrix of composites conjugated polymer nanocomposites biopolymer nanocomposites dental nanocomposites graphene based nanocomposites for electrochemical energy storage polymer filler composites for optical diffuse reflectors synthesis and applications of ldh based nanocomposites rubber cnt nanocomposites nanocomposite fibers with carbon nanotubes fabrications of graphene based nanocomposites for electrochemical sensing of drug molecules recent advances in graphene metal oxide based nanocomposites

this volume is devoted to mostly to nanotubes unique synthetic nanoscale quantum systems whose physical properties are often singular i e

record setting nanotubes can be formed from a myriad of atomic or molecular species the only requirement apparently being that the host material or wall fabric be configurable as a layered or sheet like structure nanotubes with  $sp^2$  bonded atoms such as carbon or boron together with nitrogen are the champions of extreme mechanical strength electrical response either highly conducting or highly insulating and thermal conductance carbon nanotubes can be easily produced by a variety of synthesis techniques and for this reason they are the most studied nanotubes both experimentally and theoretically boron nitride nanotubes are much more difficult to produce and only limited experimental characterization data exist indeed for boron nitride nanotubes theory is well ahead of experiment for these reasons this volume deals largely with carbon nanotubes conceptually the building block for a carbon nanotube is a single sheet of graphite called graphene recently it has become possible to experimentally isolate such single sheets either on a substrate or suspended this capability has in turn fueled many new theoretical and experimental studies of graphene itself it is therefore fitting that this volume contains also a chapter devoted to graphene comprehension overview highlights in the field

electronic devices in which the electrons are confined to fewer than three spatial dimensions are an important tool for physics research and future developments in computing technology recently discovered carbon nanotubes 1991 and graphene 2004 are intrinsically low dimensional materials with remarkable electronic properties combined with semiconductor technologies they might be used to fabricate smaller devices with more complex functionality this thesis addresses two routes towards this goal the detection of charge transport through quantum dots using a *gaas* point contact is a potential tool for quantum computation this project aimed to fabricate and measure hybrid devices with carbon nanotube quantum dots on top of *gaas* point contacts dispersion and *afm* manipulations of nanotubes on *gaas* were studied revealing comparatively weak binding transport measurements indicated that *gaas* induces disorder in nanotubes creating multiple tunnel barriers preliminary attempts were made at *cvd* growth and ink jet printing of nanotubes directly onto *gaas* although only one atom thick graphene is macroscopic in area and must be patterned to confine conduction room temperature transistor behaviour requires graphene ribbons only a few nanometres wide this work fabricated such structures using a charged *afm* tip achieving reliable cutting even on single layer graphene and feature sizes as small as 5 nm the cutting mechanism was found to be chemical oxidation of carbon by a polarised water layer with an activation energy determined by the energy of dissociation of water at the graphene surface the critical variables were the voltage difference between the tip and graphene and the atmospheric humidity an unstable solid oxide intermediate was also observed thermal annealing revealed the presence of a layer of water beneath flakes finally *efm* measurements were made of graphene at 20 mk enabling

estimates of the local carrier density and revealing spatial variations in the electronic structure on a scale consistent with electron and hole puddles

this book describes various carbon nanomaterials and their unique properties and offers a detailed introduction to graphene carbon nanotube cnt hybrids it demonstrates strategies for the hybridization of cnts with graphene which fully utilize the synergistic effect between graphene and cnts it also presents a wide range of applications of graphene cnt hybrids as novel materials for energy storage and environmental remediation further it discusses the preparation structures and properties of graphene cnt hybrids providing interesting examples of three types of graphene cnt hybrids with different nanostructures this book is of interest to a wide readership in various fields of materials science and engineering

this book compiles all current information on the different types of functionalization of carbon nanotubes cnts and graphene both covalent and non covalent the book starts with a general overview of the synthesis characterization and application of functionalized cnts and graphene special attention is dedicated to the characterization of functionalized materials a topic rarely addressed on the literature the authors provide a comparison between the functionalization of these two types of carbon materials

this book focuses on carbon nanotubes and graphene as representatives of nano carbon materials and describes the growth of new technology and applications of new devices as new devices and as new materials nano carbon materials are expected to be world pioneers that could not have been realized with conventional semiconductor materials and as those that extend the limits of conventional semiconductor performance this book introduces the latest achievements of nano carbon devices processes and technology growth it is anticipated that these studies will also be pioneers in the development of future research of nano carbon devices and materials this book consists of 18 chapters chapters 1 to 8 describe new device applications and new growth methods of graphene and chapters 9 to 18 those of carbon nanotubes it is expected that by increasing the advantages and overcoming the weak points of nanocarbon materials a new world that cannot be achieved with conventional materials will be greatly expanded we strongly hope this book contributes to its development

carbon nanotubes and graphene have been the subject of intense scientific research since their relatively recent discoveries this book introduces the reader to the science behind these rapidly developing fields and covers both the fundamentals and latest advances uniquely

this book covers the topics in a pedagogical manner suitable for undergraduate students the book also uses the simple systems of nanotubes and graphene as models to teach concepts such as molecular orbital theory tight binding theory and the laue treatment of diffraction suitable for undergraduate students with a working knowledge of basic quantum mechanics and for postgraduate researchers commencing their studies into the field this book will equip the reader to critically evaluate the physical properties and potential for applications of graphene and carbon nanotubes

graphene carbon nanotubes and nanostructures techniques and applications offers a comprehensive review of groundbreaking research in nanofabrication technology and explores myriad applications that this technology has enabled the book examines the historical evolution and emerging trends of nanofabrication and supplies an analytical understanding of some of the most important underlying nanofabrication technologies with an emphasis on graphene carbon nanotubes cnts and nanowires featuring contributions by experts from academia and industry around the world this book presents cutting edge nanofabrication research in a wide range of areas topics include cnt electrodynamics and signal propagation models electronic structure calculations of a graphene hexagonal boron nitride interface to aid the understanding of experimental devices based on these heterostructures how a laser field would modify the electronic structure and transport response of graphene to generate bandgaps the fabrication of transparent cnt electrodes for organic light emitting diodes direct graphene growth on dielectric substrates and potential applications in electronic and spintronic devices cnts as a promising candidate for next generation interconnect conductors cmos cnt integration approaches including the promising localized heating cnt synthesis method cnts in electrochemical and optical biosensors the synthesis of diamondoids by pulsed laser ablation plasmas generated in supercritical fluids and possible applications the use of dna nanostructures in lithography cmos compatible silicon nanowire biosensors the use of titanium oxide b nanowires to detect explosive vapors the properties of protective layers on silver nanoparticles for ink jet printing nanostructured thin film production using microreactors a one stop reference for professionals researchers and graduate students working in nanofabrication this book will also be useful for investors who want an overview of the current nanofabrication landscape

rare gas adsorption was studied on suspended individual single walled carbon nanotubes and graphene the devices were fabricated as field effect transistors adsorption on graphene was studied through two terminal conductance on nanotube devices adsorption was studied through conductance while the coverage density of the adsorbates was determined from the mechanical resonance frequency shifts the adsorbed

atoms modified the conductance of the nanotube field effect transistors in part through charge transfer from the adsorbates to the nanotube by tracking the shifts of conductance as a function of gate voltage  $g/g_{\text{vg}}$  and comparing these shifts with the periodicity of the coulomb blockade oscillations we quantified the charge transfer to the nanotubes with high accuracy for all studied gases he ar kr xe n<sub>2</sub> co and o<sub>2</sub> the charge transfer had a similar magnitude and was rather small on the order of  $10^{-5}$  to  $10^{-3}$  electrons per adsorbed atom the nanotube devices displayed two classes of adsorption behavior on some devices the monolayers exhibited first order phase transitions analogous to those that occur in adsorbed monolayers on graphite on other devices phase transitions within the adsorbed monolayers were absent we present evidence that a highly uniform layer of contaminants deposits on the surface of suspended nanotube devices either upon cooldown in the cryostat or at room temperature from air these contaminants modify the adsorption behavior preventing the adsorbed monolayers from exhibiting the first order phase transitions expected to occur on a clean surface a similar type of contamination leading to virtually identical effects occurs on suspended graphene in the low coverage regions of isotherms on nanotubes we observe henry's law behavior demonstrating a high uniformity of the surface and allowing us to accurately determine the single particle binding energy to this surface the determined binding energies were 776  $\pm$  10 k for ar and 997  $\pm$  37 k for kr in the second part of the dissertation we present the first measurements of adsorption on a pristine graphene surface exposed through aggressive electric current annealing on graphene the rare gas adsorbates form monolayers with phases analogous to those on graphite but with phase transitions occurring at slightly higher pressures due to a reduction of binding energy the condensations of monolayers with phases not commensurate with the graphene lattice resulted in a slight shift of the charge neutrality point of monolayer graphene corresponding to a change of carrier concentration on the order of  $10^{-9}$  e/cm<sup>2</sup> adsorption of n<sub>2</sub> and co which formed a  $\sqrt{3} \times \sqrt{3}$  commensurate solid monolayer produced a dramatic reduction of the two terminal conductance of graphene by as much as a factor of three this effect is possibly connected with the opening of a band gap expected to occur in such structures we observe hysteretic behavior in the adsorbed  $\sqrt{3} \times \sqrt{3}$  commensurate monolayers on freestanding graphene which is likely due to the interaction of two adsorbed monolayers on opposite surfaces of the graphene sheet

a large part of the research currently being conducted in the fields of materials science and engineering mechanics is devoted to carbon nanotubes and their applications in this process modeling is a very attractive investigation tool due to the difficulties in manufacturing and testing of nanomaterials continuum modeling offers significant advantages over atomistic modeling furthermore the lack of accuracy in continuum methods can be overtaken by incorporating input data either from experiments or atomistic methods this book reviews the recent

progress in continuum modeling of carbon nanotubes and their composites the advantages and disadvantages of continuum methods over atomistic methods are comprehensively discussed numerical models mainly based on the finite element method as well as analytical models are presented in a comparative way starting from the simulation of isolated pristine and defected nanotubes and proceeding to nanotube based composites the ability of continuum methods to bridge different scales is emphasized recommendations for future research are given by focusing on what still continuum methods have to learn from the nano scale the scope of the book is to provide current knowledge aiming to support researchers entering the scientific area of carbon nanotubes to choose the appropriate modeling tool for accomplishing their study and place their efforts to further improve continuum methods

rare gas adsorption was studied on suspended individual single walled carbon nanotubes and graphene the devices were fabricated as field effect transistors adsorption of  $N_2$  and CO which formed a  $\sqrt{3} \times \sqrt{3}$  commensurate solid monolayer produced a dramatic reduction of the two terminal conductance of graphene by as much as a factor of three this effect is possibly connected with the opening of a band gap expected to occur in such structures

this volume demonstrates the unique place in nanotechnology and nanoscience that carbon nanomaterials occupy owing to their exceptional chemical mechanical thermal and electrical properties carbon nanomaterials have diverse applications in super strong composite materials smart sensors energy storage and conversion super capacitors and more focusing on materials rather than mechanics this volume discusses the key roles of materials science and engineering in the development of composite materials the result of research by many highly qualified experts in the field of experimental and theoretical research on graphene and its derivatives the volume describes experimental methods for obtaining and characterizing samples of chemically modified graphene it reviews the potential application areas and modifications of graphene based composite materials and interprets the interesting physical effects discovered for the first time for graphene materials under consideration this book covers the innovative methodologies and strategies adopted in carbon materials research area including synthesis characterization and functionalization of carbon nanotubes and graphene surface modification of graphene carbon based nanostructured materials the use of carbon nanomaterials for energy applications development of carbon nanotubes reinforced metal matrix composites and non metallic composites and their myriad potential end use applications key challenges to the successful and widespread implementation of carbon nanotubes reinforced metal matrix composites and non metallic composites methods for quantification and improved control of

carbon nanotubes distributions recent research and design trends for carbon nanomaterials based sensors for a variety of applications advances and potential applications in environmental monitoring and healthcare the book will be useful for postgraduate students and researchers as well as for experts in industrial sectors it will also appeal to those involved in materials science and nanotechnology

a comprehensive look combining experimental and theoretical approaches to graphene nanotubes and quantum dots based nanotechnology evaluation and development are including a review of key applications graphene nanotubes and quantum dots based nanotechnology review the fundamentals processing methods and applications of this key materials system the topics addressed are comprehensive including synthesis preparation both physical and chemical properties both accepted and novel processing methods modeling and simulation the book provides fundamental information on key properties that impact performance such as crystal structure and particle size followed by different methods to analyze measure and evaluate graphene nanotubes and quantum dots based nanotechnology and particles finally important applications are covered including different applications of biomedical energy electronics etc graphene nanotubes and quantum dots based nanotechnology is appropriate for those working in the disciplines of nanotechnology materials science chemistry physics biology and medicine provides a comprehensive overview of key topics both on the experimental side and the theoretical discusses important properties that impact graphene nanotubes and quantum dots performance processing methods both novel and accepted and important applications reviews the most relevant applications such as biomedical energy electronics and materials ones

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