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H. S. Philip Wong and Deji Akinwande
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Carbon Nanotube and Graphene Device Physics

Explaining the properties and performance of practical nanotube devices and related applications, this is the first introductory textbook on the subject. All the fundamental concepts are introduced, so that readers without an advanced scientific background can follow all the major ideas and results. Additional topics covered include nanotube transistors and interconnects, and the basic physics of graphene. Problem sets at the end of every chapter allow readers to test their knowledge of the material covered and gain a greater understanding of the analytical skillsets developed in the text. This is an ideal textbook for senior undergraduate and graduate students taking courses in semiconductor device physics and nanoelectronics. It is also a perfect self-study guide for professional device engineers and researchers.

H.-S. Philip Wong is a Professor of Electrical Engineering at Stanford University, where he has worked since 2004. Prior to joining Stanford University, he spent 16 years at IBM T. J. Watson Research Center, Yorktown Heights, New York, where he held various positions from Research Staff Member to Senior Manager. He is a Fellow of the IEEE and his current research covers a broad range of topics, including carbon nanotubes, semiconductor nanowires, self-assembly, exploratory logic devices, nano-electromechanical devices, and novel memory devices.

Deji Akinwande is an Assistant Professor at the University of Texas, Austin, which he joined after receiving his Ph.D. from Stanford University in 2009. Prior to beginning his Ph.D., he was a circuit designer at Agilent Technologies, XtremeSpectrum/Freescale, and Motorola. He has published widely on carbon nanomaterials.

"An excellent and timely volume on the physics and applications of carbon nanotubes. A must read for students and researchers in this hot field."

Yuan Taur, UCSD

"This is the textbook that I have been aspiring to see for a long time. With excellent timing, the authors provide one that covers device physics of carbon nanotubes in a coherent, systematic way. The content is perfectly designed and formulated such that both students with little knowledge and researchers with hands-on experience in the field would find it extremely valuable. I would highly recommend this book to anyone who is interested in 'post-silicon' electronics."

Bin Yu, State University of New York, Albany

"I strongly recommend this text book to students, engineers and researchers who wish to build up their knowledge on carbon nanotube fundamentals and applications. They will extend their learning from materials technology and solid state physics to their applications in the fields of nanoelectronics and micro- nanosystems. The readers, interested by graphene and carbon nanotubes based devices, have the possibility to train themselves on the hottest topics and challenges which will pave the future of nanotechnology."

Simon Deleonibus, IEEE Fellow, CEA-LETI Chief Scientist and Research Director, MINATEC, Grenoble, France.

"This book is an excellent overview of carbon-based electronics, and in particular it provides the reader with an up-to-date and crisp description of the physical and electrical phenomena of carbon nanotubes, as well as a perspective on new applications enabled by this nanotechnology.

Both experts and students will enjoy reading this book, as it brings up to focus the important details of carbon solid-state physics to understand the ground rules of carbon transistors and the related nanoelectronic circuits. Moreover, from a global point of view, carbon electronics is a key nanotechnology supporting the continuous development of the information age in computing, sensing and networking."

Giovanni De Micheli, EPFL

"Excellent book covering all aspects of carbon nanotube devices from basic quantum physics in solids over material and device physics to applications including interconnects, field effect transistors and sensors. First complete book in an exciting new nanoelectronics field with great potential, intended for undergraduate and graduate students, researchers in the field and professional engineers, enabling them to get an insight in the field or to broaden their competence."

Cor Claeys, IMEC, Leuven, Belgium

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H.-S. PHILIP WONG
Stanford University

DEJI AKINWANDE
University of Texas, Austin

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Preface

Carbon nanotubes have come a long way since their modern rediscovery in 1991. This time period has afforded a great many scholars across the globe to conduct a vast amount of research investigating their fundamental properties and ensuing applications. Finally, after two decades, the knowledge and understanding obtained, once only accessible to select scholars, is now sufficiently widespread and accepted that the time is ripe for a textbook on this matter. This textbook develops the basic solid-state and device physics of carbon nanotubes and to a lesser extent graphene. The lesser coverage of graphene is simply due to its relative infancy, with a good deal of the device physics still in its formative stage.

The technical discourse starts with the solid-state physics of graphene, subsequently warping into the solid-state physics of nanotubes, which serves as the foundation of the device physics of metallic and semiconducting nanotubes. An elementary and limited introduction to the device physics of graphene nanoribbons and graphene are also developed. This textbook is suitable for senior undergraduates and graduate students with prior exposure to semiconductor devices. Students with a background in solid-state physics will find this book dovetails with their physics background and extends their knowledge into a new material that can potentially have an enormous impact in society. Scholars in the fields of materials, devices, and circuits and researchers exploring ideas and applications of nanoscience and nanotechnology will also find the book appealing as a reference or to learn something new about an old soul (carbon). Research into potential applications of carbon nanotubes has been progressing at a rapid pace. We have refrained from cataloging the continual progress in applications because it is simply impossible to keep up with the developments. Instead, we focus on the fundamental physics and principles so the reader can easily utilize them for the application at hand. Scattered throughout the book are many references that offer further coverage on the technical matters for the interested reader. However, owing to the restricted space there are many outstanding references that are not cited in this book. The avid reader will find much educational pleasure in perusing the technical literature from time to time, as this is a rapidly advancing field of research.

Our "carbon journey" started when one of us was at the IBM T.J. Watson Research Center in Yorktown Heights, New York. Richard Martel (now at Université de Montréal) and Phaedon Avouris were generous with sharing their knowledge; and the management – John Warlaumont and Tom Theis – fostered a nurturing intellectual environment within the confines of an industrial research laboratory. The kernel of this book started from sections of a graduate-level course at Stanford University, first taught in the Fall of 2005. We thank the students who asked the pertinent questions and offered suggestions for improvements. We also want to take this opportunity to thank all our reviewers that devoted their valuable time in improving the final product. We incorporated most of your feedback and apologize that the limited time prevented some feedback from coming through. Thanks to Tayo Akinwande (MIT), Phaedon Avouris (IBM), Zhihong Chen (IBM, Purdue), Azad Naeemi (Georgia Tech), Eric Pop (UIUC), Emmanuel Tutuc (University of Texas), Yin Yuen (Stanford), and Jerry Zhang (Stanford). Your efforts are sincerely appreciated. Now that the textbook is published, we continue to welcome any and all feedback. Errors and omissions of all sorts will no doubt be brought to light despite our best intentions to produce an error-free textbook. As such, we anticipate errata will be made available at Cambridge University Press website and updated as the case warrants. An online resource for instructors is also available at the website: www.cambridge.org/wong.

It has been a great pleasure writing this textbook on the device physics of carbon materials. For us, this book was a labor of love, and the adventure involved in developing the content along a unifying theme was a great enriching experience and sufficient reward in and of itself. We hope that all readers will similarly find great enrichment and understanding as they explore the pages of this book. Finally, we would like to thank our families – the Akinwande clan, Cecilia Mui, Amelia Wong, and Emily Wong – for their support and understanding.

Cheers
Deji Akinwande
Austin, Texas

H.-S. Philip Wong
Stanford, California

September 2010