

Introduction to Graphene-Based Nanomaterials

Graphene is one of the most intensively studied materials and has unusual electrical, mechanical, and thermal properties which provide almost unlimited potential applications. This book provides an introduction to the electrical and transport properties of graphene and other two-dimensional nanomaterials, covering *abinitio* to multiscale methods. Updated from the first edition, this book contains added chapters on other two-dimensional materials, spin-related phenomena, and an improved overview of Berry phase effects. Other topics include powerful order-N electronic structure, transport calculations, AC transport, and multiscale transport methodologies. Chapters are complemented with concrete examples and case studies, questions and exercises, detailed appendices, and computational codes. This book is a valuable resource for graduate students and researchers working in physics, or materials science or engineering, who are interested in the field of graphene-and two-dimensional nanomaterials.

Luis E. F. Foa Torres is a condensed matter physicist and Associate Professor of Physics at the University of Chile. Previous positions include Research Scientist at the National Council for Scientific and Technical Research (CONICET) in Argentina, and fellow of the Alexander von Humboldt Foundation in Dresden, Germany. His research is focused on quantum transport, two-dimensional materials, topological insulators, and the physics of driven systems. He was awarded the International Centre for Theoretical Physics (ICTP) Prize in 2018.

Stephan Roche is a Catalan Institution for Research and Advanced Studies (ICREA) Research Professor working at the Catalan Institute of Nanoscience and Nanotechnology (ICN2) and at the Barcelona Institute of Science and Technology (BIST). He leads the Theoretical and Computational Nanoscience group which focuses on the understanding of quantum transport phenomena from the molecular to the mesoscopic scales with particular focus on spin dynamics in topological (and Dirac) matter. In 2009, he was awarded the prestigious Friedrich Wilhelm Bessel Prize from the Alexander von Humboldt Foundation (Germany). He serves as deputy leader of the Spintronics Work Package in the Graphene Flagship consortium.

Jean-Christophe Charlier is Full Professor at the École Polytechnique de Louvain and Senior Researcher at the Institute of Condensed Matter and Nanosciences of the University of Louvain (UCLouvain) in Belgium. His main scientific interests are centered on theoretical condensed matter physics and nanosciences, covering the areas of electronic, structural, and dynamical properties and quantum transport in nanostructures using first-principles theories and computational physics. In 2016, he was awarded the chair of Francqui Research Professor at UCLouvain from the Francqui-Stichting Foundation (Belgium).

Cambridge University Press
978-1-108-47699-7 — Introduction to Graphene-Based Nanomaterials
2nd Edition
Frontmatter
[More Information](#)

Introduction to Graphene-Based Nanomaterials

From Electronic Structure to Quantum Transport

Second Edition

LUIS E. F. FOA TORRES

University of Chile

STEPHAN ROCHE

Barcelona Institute of Science and Technology

JEAN-CHRISTOPHE CHARLIER

University of Louvain



CAMBRIDGE
UNIVERSITY PRESS

Cambridge University Press
978-1-108-47699-7 — Introduction to Graphene-Based Nanomaterials
2nd Edition
Frontmatter
[More Information](#)

CAMBRIDGE UNIVERSITY PRESS

University Printing House, Cambridge CB2 8BS, United Kingdom
One Liberty Plaza, 20th Floor, New York, NY 10006, USA
477 Williamstown Road, Port Melbourne, VIC 3207, Australia
314–321, 3rd Floor, Plot 3, Splendor Forum, Jasola District Centre, New Delhi – 110025, India
79 Anson Road, #06–04/06, Singapore 079906

Cambridge University Press is part of the University of Cambridge.

It furthers the University's mission by disseminating knowledge in the pursuit of education, learning, and research at the highest international levels of excellence.

www.cambridge.org
Information on this title: www.cambridge.org/9781108476997
DOI: 10.1017/9781108664462

© Cambridge University Press 2020

This publication is in copyright. Subject to statutory exception and to the provisions of relevant collective licensing agreements, no reproduction of any part may take place without the written permission of Cambridge University Press.

First edition published 2014
Second edition published 2020

Printed in the United Kingdom by TJ International Ltd, Padstow Cornwall

A catalogue record for this publication is available from the British Library.

ISBN 978-1-108-47699-7 Hardback

Cambridge University Press has no responsibility for the persistence or accuracy of URLs for external or third-party internet websites referred to in this publication and does not guarantee that any content on such websites is, or will remain, accurate or appropriate.

Contents

	<i>Preface to the Second Edition</i>	page xi
	<i>Preface to the First Edition</i>	xiii
1	Introduction to Carbon-Based Nanostructures	1
	1.1 Carbon Structures and Hybridizations	1
	1.2 Carbon Nanostructures	4
	1.3 Guide to the Book	8
	1.4 Further Reading	10
2	Electronic Properties of Carbon-Based Nanostructures	11
	2.1 Introduction	11
	2.2 Electronic Properties of Graphene	12
	2.2.1 <i>Tight-Binding</i> Description of Graphene	12
	2.2.2 Effective Description Close to the Dirac Point and Massless Dirac Fermions	18
	2.2.3 Electronic Properties of Graphene beyond the Linear Approximation	20
	2.3 Electronic Properties of Few-Layer Graphene	24
	2.4 Electronic Properties of Graphene Nanoribbons	29
	2.4.1 Electronic Properties of Armchair Nanoribbons (aGNRs)	33
	2.4.2 Electronic Properties of Zigzag Nanoribbons (zGNRs)	36
	2.5 Electronic Properties of Carbon Nanotubes	40
	2.5.1 Structural Parameters of CNTs	40
	2.5.2 Electronic Structure of CNTs within the Zone-Folding Approximation	41
	2.5.3 Curvature Effects: Beyond the Zone-Folding Model	47
	2.5.4 Small-Diameter Nanotubes: Beyond the <i>Tight-Binding</i> Approach	48
	2.5.5 Nanotubes in Bundles	51
	2.5.6 Multiwall Nanotubes	52
	2.6 Defects and Disorder in Graphene-Based Nanostructures	54
	2.6.1 Structural Point Defects in Graphene	54
	2.6.2 Grain Boundaries and Extended Defects in Graphene	57

vi	Contents	
	2.6.3 Structural Defects at Graphene Edges	62
	2.6.4 Defects in Carbon Nanotubes	63
	2.7 Further Reading and Problems	66
3	The New Family of Two-Dimensional Materials and van der Waals Heterostructures	70
	3.1 Introduction	70
	3.2 Hexagonal Boron Nitride Monolayer	72
	3.3 Two-Dimensional Transition Metal Dichalcogenides	76
	3.4 Other Two-Dimensional Materials	79
	3.4.1 Phosphorene	79
	3.4.2 Borophene	81
	3.4.3 Silicene, Germanene, and Stanene	83
	3.4.4 MXenes	85
	3.5 van der Waals Heterostructures	87
	3.6 Conclusion	90
	3.7 Further Reading	91
4	Quantum Transport: General Concepts	92
	4.1 Introduction	92
	4.1.1 Relevant Time and Length Scales	92
	4.1.2 Coherent versus Sequential Transport	93
	4.2 Landauer–Büttiker Theory	95
	4.2.1 Heuristic Derivation of Landauer’s Formula	98
	4.3 Boltzmann Semiclassical Transport	99
	4.3.1 The Relaxation Time Approximation and the Boltzmann Conductivity	100
	4.4 Kubo Formula for the Electronic Conductivity	102
	4.4.1 Illustrations for Ballistic and Diffusive Regimes	106
	4.4.2 Kubo versus Landauer	109
	4.4.3 Validity Limit of Ohm’s Law in the Quantum Regime	110
	4.4.4 The Kubo Formalism in Real Space	110
	4.4.5 Scaling Theory of Localization	113
	4.5 Quantum Transport beyond the Fully Coherent or Decoherent Limits	117
	4.6 Further Reading and Problems	118
5	Klein Tunneling and Ballistic Transport in Graphene and Related Materials	120
	5.1 The Klein Tunneling Mechanism	120
	5.1.1 Klein Tunneling through Monolayer Graphene with a Single (Impurity) Potential Barrier	121
	5.1.2 Klein Tunneling through Bilayer Graphene with a Single (Impurity) Potential Barrier	126

5.2	Ballistic Transport in Carbon Nanotubes and Graphene	128
5.2.1	Ballistic Motion and Conductance Quantization	129
5.2.2	Mode Decomposition in Real Space	130
5.2.3	Fabry–Pérot Conductance Oscillations	134
5.2.4	Contact Effects: SWNT-Based Heterojunctions and the Role of Contacts between Metals and Carbon-Based Devices	137
5.3	Ballistic Motion through a Graphene Constriction: The 2D Limit and the Minimum Conductivity	142
5.4	Further Reading and Problems	143
6	Quantum Transport in Disordered Graphene-Based Materials	145
6.1	Elastic Mean Free Path	145
6.1.1	Temperature Dependence of the Mean Free Path	148
6.1.2	Inelastic Mean Free Path in the High-Bias Regime	150
6.1.3	Quantum Interference Effects and Localization Phenomena in Disordered Graphene-Based Materials	152
6.1.4	Edge Disorder and Transport Gaps in Graphene Nanoribbons	154
6.2	Transport Properties in Disordered Two-Dimensional Graphene	156
6.2.1	Two-Dimensional Disordered Graphene: Experimental and Theoretical Overview	156
6.2.2	Metallic versus Insulating State and Minimum Conductivity	160
6.2.3	Boltzmann Transport in Two-Dimensional Graphene	161
6.2.4	Kubo Transport: Graphene with Anderson Disorder	168
6.2.5	Kubo Transport: Graphene with Gaussian Impurities	170
6.2.6	Weak Localization Phenomena in Disordered Graphene	175
6.2.7	Strong Localization in Disordered Graphene	183
6.3	Graphene with Monovacancies	185
6.3.1	Electronic Structure of Graphene with Monovacancies	187
6.3.2	Transport Features of Graphene with Monovacancies	189
6.4	Polycrystalline Graphene	194
6.4.1	Motivation and Structural Models	194
6.4.2	Electronic Properties of Polycrystalline Graphene	198
6.4.3	Mean Free Path, Conductivity and Charge Mobility	199
6.5	Graphene Quantum Dots	202
6.5.1	Generalities on Coulomb Blockade	203
6.5.2	Confining Charges in Graphene Devices	205
6.6	Further Reading and Problems	208
7	Quantum Hall Effects in Graphene	210
7.1	Berry Phase	210
7.2	Graphene's Berry Phase and Its Observation in ARPES Experiments	213

7.3	Anomalous Velocity and Valley Hall Effect	214
7.4	The Peierls Substitution	216
7.5	Aharonov–Bohm Gap Opening and Orbital Degeneracy Splitting in Carbon Nanotubes	217
7.6	Landau Levels in Graphene	222
7.7	Quantum Hall Effect in Graphene	225
7.7.1	Experimental Observation of Hall Quantization in Graphene	226
7.7.2	Remarks for the Numerical Investigation of the Hall Response	227
7.7.3	The Mystery of the Zero-Energy Landau Level Splitting	228
7.7.4	Universal Longitudinal Conductivity at the Dirac Point	229
7.8	The Haldane Model	232
7.9	Further Reading and Problems	235
8	Spin-Related Phenomena	237
8.1	Introduction	237
8.2	Spin–Orbit Coupling in Graphene	239
8.2.1	Derivation from the Dirac Equation	240
8.2.2	Theoretical Estimation of the SOC Terms Magnitude	245
8.3	Spin Transport Measurements and Spin Lifetime	246
8.4	Spin Dynamics and Relaxation Mechanisms	248
8.4.1	Dyakonov–Perel Mechanism	250
8.4.2	Elliot–Yafet Mechanism for Graphene	253
8.4.3	Spin–Pseudospin Entanglement and Spin Relaxation	255
8.5	Manipulating Spin by Proximity Effects	259
8.5.1	Manipulating Spin Using 2D Magnetic Substrates	260
8.5.2	Magnetic Proximity Effects in Vertical Spin Devices	260
8.5.3	Weak Antilocalization in Graphene/TMD Heterostructures	262
8.5.4	Spin Transport Anisotropy	263
8.6	Spin Hall Effect	269
8.6.1	Introductory Picture and Basics	269
8.6.2	Enhanced SHE in Graphene?	271
8.7	Spin Transport Formalism and Computational Methodologies	274
8.8	Further Reading	277
9	Quantum Transport beyond DC	278
9.1	Introduction: Why AC Fields?	278
9.2	Adiabatic Approximation	279
9.3	Floquet Theory	280
9.3.1	Average Current and Density of States	281
9.3.2	Homogeneous Driving and the Tien–Gordon Model	283
9.3.3	Time-Evolution Operator	284

9.4	Overview of AC Transport in Carbon-Based Devices	284
9.5	AC Transport and Laser-Induced Effects on the Electronic Properties of Graphene	286
9.6	Further Reading and Problems	290
10	<i>Ab Initio</i> and Multiscale Quantum Transport in Graphene-Based Materials	293
10.1	Introduction	293
10.2	Chemically Doped Nanotubes	294
10.2.1	Tight-Binding Hamiltonian of the Pristine Carbon Nanotube	294
10.2.2	Boron-Doped Metallic Carbon Nanotubes	294
10.2.3	Nitrogen-Doped Metallic Carbon Nanotubes	297
10.3	Two-Dimensional Disordered Graphene with Adatoms Defects	304
10.3.1	Monatomic Oxygen Defects	304
10.3.2	Atomic Hydrogen Defects	307
10.3.3	Scattering Times	310
10.4	Structural Point Defects Embedded in Graphene	310
10.5	<i>Ab Initio</i> Quantum Transport in 1D Carbon Nanostructures	313
10.5.1	Introduction	313
10.5.2	Carbon Nanotubes	314
10.5.3	Defective Carbon Nanotubes	316
10.5.4	Doped Carbon Nanotubes	321
10.5.5	Functionalized Carbon Nanotubes	323
10.5.6	Carbon Nanotubes Decorated with Metal Clusters	330
10.5.7	Graphene Nanoribbons	331
10.5.8	Graphene Nanoribbons with Point Defects	332
10.5.9	Graphene Nanoribbons with Edge Reconstruction	334
10.5.10	Graphene Nanoribbons with Edge Disorder	335
10.5.11	Doped Graphene Nanoribbons	342
10.5.12	GNR-Based Networks	347
10.6	Conclusion	352
10.7	Further Reading	353
Appendix A	Electronic Structure Calculations: The Density Functional Theory (DFT)	354
A.1	Introduction	354
A.2	Overview of the Approximations	354
A.2.1	The Schrödinger Equation	354
A.2.2	The Born–Oppenheimer Approximation	355
A.2.3	The Hartree Approximation	356
A.2.4	The Hartree–Fock Approximation	357
A.3	Density Functional Theory	358
A.3.1	The Thomas–Fermi Model	358

x	Contents	
	A.3.2	The Hohenberg–Kohn Theorem 359
	A.3.3	The Kohn–Sham Equations 360
	A.3.4	The Exchange–Correlation Functionals 362
	A.4	Practical Calculations 364
	A.4.1	Crystal Lattice and Reciprocal Space 364
	A.4.2	The Plane Wave Representation 365
	A.4.3	k-Point Grids and Band Structures 366
	A.4.4	The Pseudopotential Approximation 367
	A.4.5	Available DFT Codes 370
	Appendix B	Electronic Structure Calculations: The Many-Body Perturbation Theory (MBPT) 373
	B.1	Introduction 373
	B.2	Many-Body Perturbation Theory (MBPT) 374
	B.2.1	Hedin’s Equations 374
	B.2.2	<i>GW</i> Approximation 375
	B.3	Practical Implementation of G_0W_0 376
	B.3.1	Perturbative Approach 376
	B.3.2	Plasmon Pole 377
	Appendix C	Green’s Functions and <i>Ab Initio</i> Quantum Transport in the Landauer–Büttiker Formalism 379
	C.1	Phase-Coherent Quantum Transport and the Green’s Function Formalism 379
	C.2	Self-Energy Corrections and Recursive Green’s Functions Techniques 387
	C.3	Dyson’s Equation and an Application to Treatment of Disordered Systems 389
	C.4	Computing Transport Properties within <i>Ab Initio</i> Simulations 393
	Appendix D	Recursion Methods for Computing the Density of States (DOS) and Wavepacket Dynamics 401
	D.1	Lanczos Method for the Density of States 401
	D.1.1	Termination of the Continued Fraction 404
	D.2	Wavepacket Propagation Method 405
	D.3	Lanczos Method for Computing Off-Diagonal Green’s Functions 411
	<i>References</i>	413
	<i>Index</i>	457

Preface to the Second Edition

We are delighted to give a second birth to this book on the presentation of electronic and transport properties of graphene-related materials five years after its first edition. Over these years, research in the area of graphene and two-dimensional materials has evolved. The changes are well reflected by the name of the 2017 Solvay Workshop dedicated to this field: *From physics of graphene to graphene for physics*. Indeed today, rather than studying graphene's properties, we are using it mostly as a platform for unveiling new physics. Furthermore, with each newly discovered two-dimensional material a similar path emerges, from studying their properties to using them as a brave new playground for exciting physics. At the same time, we are witnessing a very interesting return to three-dimensional systems, this time based on the stacking of two-dimensional structures which allows for more tailor-made properties.

In this new edition we decided to expand different aspects that were either missing or too succinct in the previous edition. This includes, the new family of two-dimensional materials Berry phases and quantum Hall effects, and spintronics. We have reduced a few chapters that did not age very well to make space for this more exciting new material. As with the first edition we keep being committed to offering problems and solutions through our website, besides those provided in the book.

Please do not hesitate to contact us if you have questions or comments. In this sense, when choosing whom to contact it might be useful to keep in mind the distribution of our contributions to the book, which take advantage of our complementary expertise: Jean-Christophe wrote of the parts dealing with *ab initio* and new two-dimensional materials (Chapters 1, 3, 10, Appendices A and B, and parts of Chapter 2 and Appendix C), Stephan was in charge of spintronics, disorder effects, and transport (Chapters 6, 8, Appendix D, and parts of Chapters 2, 4, 5, and 7), Luis took care of the transport, quantum Hall effects, and AC transport parts (Chapters 4, 7, and 9 and parts of Chapters 2, 5, and Appendix C).

We would like to thank again our colleagues and coworkers for their help and inspiring our work. Besides those already acknowledged in our first preface, here we would like to also thank those newcomers to our family: Matías Berdakin, David Beljonne, Felix Casanova, Aurélie Champagne, José Chesta, Samuel Dechamps, José Hugo García, Rocío González, Benoît Hackens, Hafid Khalfoun, Víctor Manuel Martínez Álvarez, Joaquín Medina, Viet-Hung Nguyen, Álvaro Núñez, Esteban Rodríguez, Pierre Seneor, Christoph Stampfer, Benoît Van Troeye, and Marc Vila.

We thank our home institutions for supporting our research, as well as the Alexander von Humboldt Foundation (SR and LEFFT), the Abdus Salam International Centre for Theoretical Physics (LEFFT), and the Francqui-Stichting Foundation of Belgium (JCC). Finally, we are indebted to our respective wives (Sandra Rieger, Encarni Carrasco Perea, and Mireille Toth-Budai) and our children (Hector and Gabriel Roche, and Ilona, Elise, and Mathilde Charlier) for their warm enthusiasm and continuous support during all these years of time-consuming work.

We hope that you find this second edition to be a useful companion for starting in this field and perhaps even for your day-to-day research.

And we wish you an exciting journey in Flatland and beyond!

Preface to the First Edition

Once deemed impossible to exist in nature, graphene, *the first truly two-dimensional nanomaterial ever discovered*, has rocketed to stardom since being first isolated in 2004 by Nobel Laureates Konstantin Novoselov and Andre K. Geim of the University of Manchester. Graphene is a single layer of carbon atoms arranged in a flat honeycomb lattice. Researchers in high energy physics, condensed matter physics, chemistry, biology, and engineering, together with funding agencies and companies from diverse industrial sectors, have all been captivated by graphene and related carbon-based materials such as carbon nanotubes and graphene nanoribbons, owing to their fascinating physical properties, potential applications, and market perspectives.

But what makes graphene so interesting? Basically, graphene has redefined the limits of what a material can do: it boasts record thermal conductivity and the highest current density at room temperature ever measured (a million times that of copper!); it is the strongest material known (a hundred times stronger than steel!) yet is highly mechanically flexible; it is the least permeable material known (not even helium atoms can pass through it!); the best transparent conductive film; the thinnest material known; and the list goes on.

A sheet of graphene can be quickly obtained by exfoliating graphite (the material that the tip of your pencil is made of) using sticky tape. Graphene can readily be observed and characterized using standard laboratory methods, and can be mass-produced either by chemical vapor deposition (CVD) or by epitaxy on silicon carbide substrates. Driven by these intriguing properties, graphene research is blossoming at an unprecedented pace and marks the point of convergence of many fields. However, given this rapid development, there is a scarcity of tutorial material to explain the basics of graphene while describing the state of the art in the field. Such materials are needed to consolidate the graphene research community and foster further progress.

The dearth of up-to-date textbooks on the electronic and transport properties of graphene is especially dramatic: the last major work of reference in this area – written by Riichiro Saito, Gene Dresselhaus, and Mildred Dresselhaus – was published in 1998. Seeking to answer the prayers of many colleagues who have had to struggle in a nascent field characterized by a huge body of research papers but very little introductory material, we decided to write this book. It is the fruit of our collective research experience, dating from the early days of research on graphene and related materials, up through the past decade, when each of us developed different computational tools and

theoretical approaches to understanding the complex electronic and transport properties in realistic models of these materials.

We have written *Introduction to Graphene-Based Nanomaterials: From Electronic Structure to Quantum Transport* for everyone doing (or wishing to do) research on the electronic structure and transport properties of graphene-related systems. Assuming basic knowledge of solid-state physics, this book offers a detailed introduction to some of the most useful methods for simulating these properties. Furthermore, we have made additional resources (computational codes, a forum, etc.) available to our readers at cambridge.org/foatorres, and at the book website (introductiontographene.org), where additional exercises as well as corrections to the book text (which will surely appear) will be posted.

Graphene and related materials pertain to a larger family that encompasses all kinds of two-dimensional materials, from boron nitride lattices, to transition-metal dichalcogenides (MoS_2 , WS_2), to the silicon analogue of graphene, silicene, a recently discovered zero-gap semiconductor. Researchers are beginning to explore the third dimension by shuffling two-dimensional materials and by fabricating three-dimensional heterostructures (BN/graphene, BN/ MoS_2 /graphene, etc.) with unprecedented properties.

Interestingly, low-energy excitations in two-dimensional graphene (and in one-dimensional metallic carbon nanotubes), known as massless Dirac fermions, also develop at the surface of topological insulators (such as Bi_2Se_3 , Bi_2Te_3 , etc.), which are bulk insulators. Topological insulators thus share commonalities with graphene, such as Berry's phase-driven quantum phenomena (Klein tunneling, weak antilocalization, etc.), and exhibit other features such as spin-momentum locking that offer different and ground-breaking perspectives for spintronics. Therefore, we believe that our presentation of the fundamentals of electronic and transport properties in graphene and related materials should prove useful to a growing community of scientists, as they touch on advanced concepts in condensed matter physics, materials science, and nanoscience and nanotechnology.

The book starts with an introduction to the electronic structures and basic concepts in transport in low-dimensional materials, and then proceeds to describe the specific transport phenomena unique to graphene-related materials. Transport concepts are then presented through simple disorder models, which in some cases enable comparison with analytical treatments. Additionally, the development of multiscale quantum transport methodologies (either within the Landauer–Büttiker or Kubo–Greenwood formalisms) is introduced in a straightforward way, showing the various options for tackling defects and impurities in graphene materials with more structural and chemical complexity: from combined *ab initio* with tight-binding models to transport calculations fully based on first principles. To facilitate reading, the essential technical aspects concerning the formalism of Green functions, as well as transport implementation and order- N transport schemes are described in dedicated appendices.

This book encompasses years of scientific research, research that has enabled us to establish certain foundations in the field, a work made possible by the efforts of

collaborators, including many postdoctoral and doctoral students. We are particularly indebted to Jean-Joseph Adjizian, Hakim Amara, Rémi Avriller, Blanca Biel, Andrés Botello-Méndez, Victoria Bracamonte, Hernán Calvo, Jessica Campos-Delgado, Damien Connétable, Alessandro Cresti, Eduardo Cruz-Silva, Aron Cummings, Virginia Dal Lago, Xavier Declerck, Simon Dubois, Nicolas-Guillermo Ferrer Sanchez, Lucas Ingaramo, Gabriela Lacconi, Sylvain Latil, Nicolas Leconte, Aurélien Lherbier, Alejandro Lopez-Bezanilla, Thibaud Louvet, Yann-Michel Niquet, Daijiro Nozaki, César Núñez, Hanako Okuno, Frank Ortmann, Andreï Palnichenko, Pablo Pérez-Piskunow, Juan Pablo Ramos, Claudia Rocha, Xavier Rocquefelte, Luis Rosales, Haldun Sevincli, Eric Suárez Morell, Florent Tournus, François Triozon, Silvia Urreta, Gregory Van Lier, Dinh Van Tuan, François Varchon, Wu Li, Zeila Zanolli, and Bing Zheng.

We would also like to express our sincere gratitude to the following inspiring individuals with whom we have worked over the past decade: Pulickel Ajayan, Tsuneya Ando, Marcelo Apel, Adrian Bachtold, Carlos Balseiro, Florian Banhart, Robert Baptist, Christophe Bichara, Xavier Blase, Roberto Car, Antonio Castro-Neto, Mairbek Chshiev, Gianaurelio Cuniberti, Silvano De Franceschi, Hongjie Dai, Alessandro De Vita, Millie and Gene Dresselhaus, François Ducastelle, Reinhold Egger, Peter Eklund, Morinobu Endo, Walter Escoffier, Chris Ewels, Andrea Ferrari, Albert Fert, Takeo Fujiwara, Xavier Gonze, Andrea Latgé, Caio Lewenkopf, Annick Loiseau, Jose-Maria Gómez Rodriguez, Nicole Grobert, Paco Guinea, Luc Henrard, Eduardo Hernández, Jean-Paul Issi, Ado Jorio, Philip Kim, Jani Kotakoski, Vladimir Kravtsov, Philippe Lambin, Sergio Makler, Ernesto Medina, Vincent Meunier, Natalio Mingo, Costas Mouloupoulos, Joel Moser, Yann-Michel Niquet, Kentaro Nomura, Kostya Novoselov, Pablo Ordejón, Pedro Orellana, Mónica Pacheco, Michael Payne, Horacio Pastawski, Marcos Pimenta, Bertrand Raquet, Gian-Marco Rignanese, Angel Rubio, Riichiro Saito, Bobby Sumpter, Mauricio and Humberto Terrones, Gonzalo Usaj, and Sergio Valenzuela.

We thank our home institutions for supporting our research, as well as the Alexander von Humboldt Foundation (SR and LEFFT) and the Abdus Salam International Centre for Theoretical Physics (LEFFT). Finally, we are indebted to our respective wives (Sandra Rieger, Encarni Carrasco Perea, and Mireille Toth-Budai) and our children (Hector and Gabriel Roche, and Ilona, Elise, and Mathilde Charlier) for their warm enthusiasm and continuous support during all these years of time-consuming work.

We hope that you find this book to be a useful companion for starting in this field and perhaps even for your day-to-day research. We recommend that you start by reading Chapter 1 and then follow the advice in *Guide to the book* (Section 1.3).

And we wish you an exciting journey in Flatland! . . .

Cambridge University Press
978-1-108-47699-7 — Introduction to Graphene-Based Nanomaterials
2nd Edition
Frontmatter
[More Information](#)
