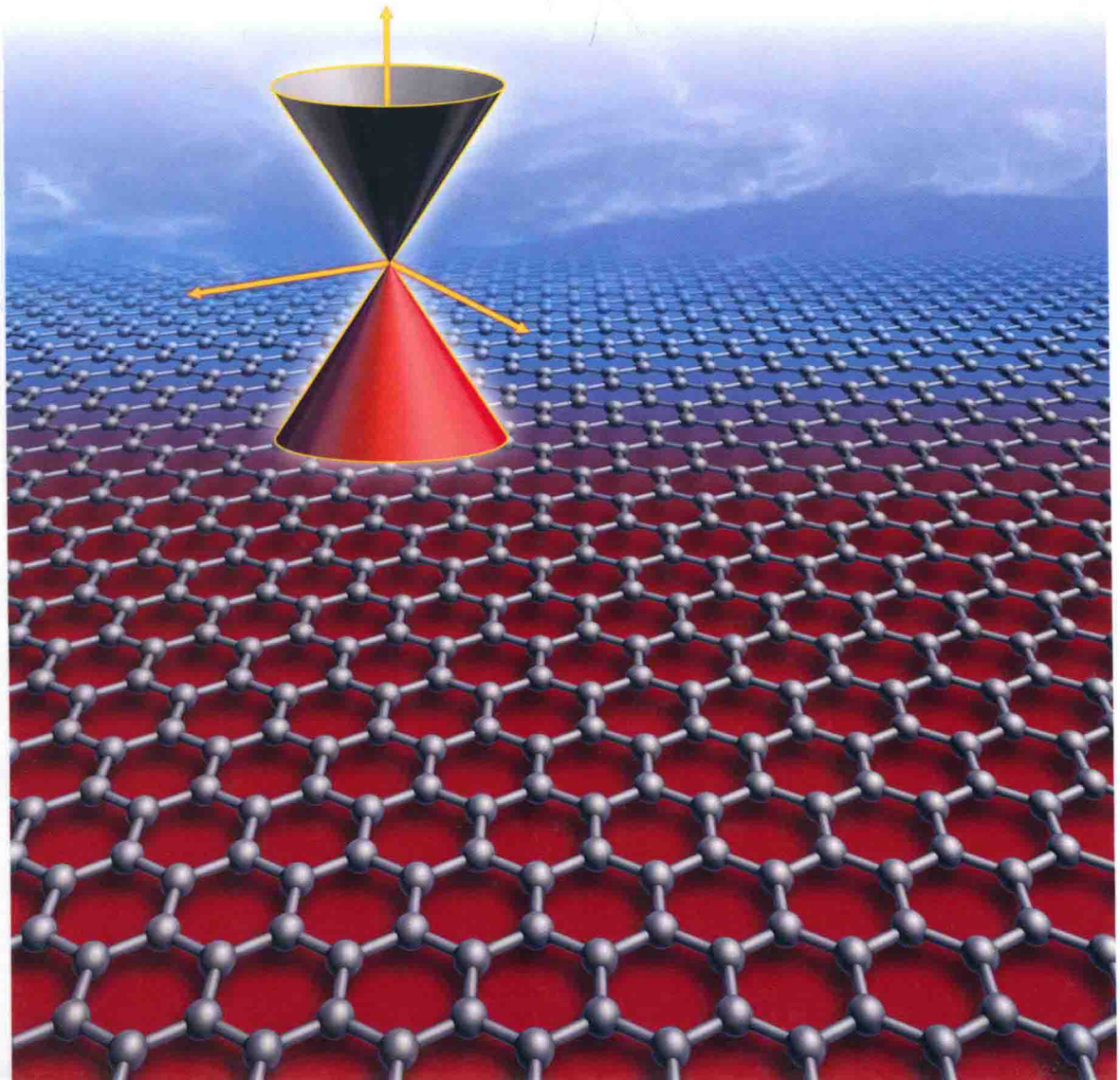
Edited by C. N. R. Rao and A. K. Sood

WILEY-VCH

Graphene

Synthesis, Properties, and Phenomena



Edited by C. N. R. Rao and A. K. Sood

Graphene

Synthesis, Properties, and Phenomena

WILEY-VCH

WILEY-VCH Verlag GmbH & Co. KGaA

The Editors

Prof. Dr. C. N. R. Rao
Chemistry of Materials Unit
Jawaharlal Nehru Centre
Jakkur P.O.
Bangalore 560 064
India

Prof. Dr. A. K. Sood
Indian Institute of Science
Department of Physics
Bangalore 560 012
India

Library of Congress Card No.: applied for

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library.

Bibliographic information published by the Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available on the Internet at <http://dnb.d-nb.de>.

Print ISBN: 978-3-527-33258-8
ePDF ISBN: 978-3-527-65115-3
ePub ISBN: 978-3-527-65114-6
mobi ISBN: 978-3-527-65113-9
oBook ISBN: 978-3-527-65112-2

Cover Design Formgeber, Eppelheim
Typesetting Laserwords Private Limited, Chennai, India
Printing and Binding Markono Print Media Pte Ltd, Singapore

Edited by
C. N. R. Rao and A. K. Sood

Graphene

Related Titles

Martin, N., Nierengarten, J.-F. (eds.)

Supramolecular Chemistry of Fullerenes and Carbon Nanotubes

2012
ISBN: 978-3-527-32789-8

Jorio, A., Dresselhaus, M. S., Saito, R., Dresselhaus, G.

Raman Spectroscopy in Graphene Related Systems

2011
ISBN: 978-3-527-40811-5

Kumar, C. S. S. R. (ed.)

Carbon Nanomaterials
Series: Nanomaterials for the Life Sciences (Volume 9)

2011
ISBN: 978-3-527-32169-8

Saito, Y. (ed.)

Carbon Nanotube and Related Field Emitters
Fundamentals and Applications

2010
ISBN: 978-3-527-32734-8

Krüger, A.

Carbon Materials and Nanotechnology

2010
ISBN: 978-3-527-31803-2

Guldi, D. M., Martín, N. (eds.)

Carbon Nanotubes and Related Structures
Synthesis, Characterization, Functionalization, and Applications

2010
ISBN: 978-3-527-32406-4

Preface

Graphene is a fascinating subject of recent origin, its first isolation being made possible through micromechanical cleavage of a graphite crystal. Since its discovery, graphene has caused great sensation because of its unusual electronic properties, and scientists from all over the world have been working on the varied facets of graphene. Thus, there has been much effort to synthesize both single-layer and few-layer graphenes by a number of methods. A variety of properties and phenomena have been investigated, and many of the studies have been directed toward understanding the physical and chemical properties of graphene. Raman spectroscopy has been particularly useful in unraveling various aspects of graphene. A graphene field-effect transistor, a basic building block of nanodevices, is a single-element laboratory to study electron–phonon interactions using Raman scattering. The low-frequency electrical noise or the flicker noise in graphene devices defines the figure of merit of a device and has contrasting behavior for single- and bilayer-graphene devices. Magnetic properties have been of equal interest with the indication that graphene may be ferromagnetic at room temperature, exhibiting magnetoresistance. Graphene nanoribbons have attracted attention because of their unique electronic structure and properties. Graphene also provides a playground for exploring many quantum field related phenomena such as Klein tunneling, antilocalization, zitterbewegung, vacuum collapse by Lorenz boost and so on. Suspended graphene devices have been used to study nanoscale electromechanics and quantum Hall effect.

A variety of applications of graphene have come to the fore. Its use in supercapacitors and batteries has been explored. Other properties of graphene, which are noteworthy, are those that enable its use in nanoelectronics, field emission and catalysis. Biological aspects of graphene have been investigated by a number of workers, with emphasis on its toxicity and its possible use for drug delivery.

In this book, we have tried to cover many of the salient aspects of graphene, which are of current interest. Although the book mostly deals with graphene, we have included some material on graphene-like inorganic layered materials. It is possible, however, that some topics have been left out owing to constraints on the size of the book and possible errors in judgement. We trust that the

book will be useful to students, teachers, and practitioners, and serves as an introduction to those who want to take part in the exciting developments of this subject.

June 2012

C.N.R. Rao
A.K. Sood

List of Contributors

Ganapathy Baskaran
The Institute of Mathematical Sciences
C.I.T. Campus
Chennai 600 113
Tamil Nadu
India

and

Perimeter Institute for Theoretical Physics
31 Caroline Street North
Waterloo
Ontario
Canada N2L 2Y5

Santanu Bhattacharya
Indian Institute of Science
Department of Organic Chemistry
Bangalore 560 012
Tala Marg
Karnataka
India

and

The Chemical Biology Unit
Jawaharlal Nehru Centre for Advanced Scientific Research
Bangalore 560 064
Jakkur
Karnataka
India

Biswanath Chakraborty
Indian Institute of Science
Department of Physics
Bangalore 560012
Karnataka
India

Mandar M. Deshmukh
Tata Institute of Fundamental Research
Department of Condensed Matter Physics and Materials Science
Homi Bhabha Road
Mumbai 400005
India

M. Samy El-Shall
Virginia Commonwealth University
Department of Chemistry
Richmond
VA 23284-2006
USA

and

King Abdualziz University
Department of Chemistry
Jeddah 21589
Kingdom of Saudi Arabia

Toshiaki Enoki
Tokyo Institute of Technology
Department of Chemistry
Ookayama
Meguro-ku
Tokyo 152-8551
Japan

Arindam Ghosh
Indian Institute of Science
Department of Physics
C.V. Raman Avenue
Bangalore 560012
Karnataka
India

Srijit Goswami
Indian Institute of Science
Department of Physics
C.V. Raman Avenue
Bangalore 560012
Karnataka
India

Vidya Kochat
Indian Institute of Science
Department of Physics
C.V. Raman Avenue
Bangalore 560012
Karnataka
India

Manzoor Koyakutty
Amrita Vishwa Vidyapeetham
University
Amrita Centre for Nanosciences
and Molecular Medicine
Elamakkara
Kochi 682041
Kerala
India

Urmimala Maitra
Jawaharlal Nehru Centre for
Advanced Scientific Research
International Centre for Materials
Science
Chemistry and Physics of
Materials Unit, and CSIR Centre
of Excellence in Chemistry
Jakkur P.O.
Bangalore 560 064
Karnataka
India

H. S. S. Ramakrishna Matte
Jawaharlal Nehru Centre for
Advanced Scientific Research
International Centre for Materials
Science
Chemistry and Physics of
Materials Unit, and CSIR Centre
of Excellence in Chemistry
Jakkur P.O.
Bangalore 560 064
Karnataka
India

Shantikumar Nair
Amrita Vishwa Vidyapeetham
University
Amrita Centre for Nanosciences
and Molecular Medicine
Elamakkara
Kochi 682041
Kerala
India

Atindra Nath Pal
Indian Institute of Science
Department of Physics
C.V. Raman Avenue
Bangalore 560012
Karnataka
India

Ganganahalli Kotturappa Ramesha
Indian Institute of Science
Department of Inorganic and Physical Chemistry
Bangalore 560 012
Karnataka
India

C. N. R. Rao
Jawaharlal Nehru Centre for Advanced Scientific Research
International Centre for Materials Science
Chemistry and Physics of Materials Unit, and CSIR Centre of Excellence in Chemistry
Jakkur P.O.
Bangalore 560 064
Karnataka
India

Suman K. Samanta
Indian Institute of Science
Department of Organic Chemistry
Bangalore 560 012
Tala Marg
Karnataka
India

Srinivasan Sampath
Indian Institute of Science
Department of Inorganic and Physical Chemistry
Bangalore 560 012
Karnataka
India

Biplab Sanyal
Uppsala University
Department of Physics and Astronomy
Box-516
75120 Uppsala
Sweden

Sharmila N. Shirodkar
Theoretical Sciences Unit
Jawaharlal Nehru Centre for Advanced Scientific Research
Srirampura Cross
Jakkur P.O.
Bangalore 560 064
Karnataka
India

Vibhor Singh
Tata Institute of Fundamental Research
Department of Condensed Matter Physics and Materials Science
Homi Bhabha Road
Mumbai 400005
India

A. K. Sood
Indian Institute of Science
Department of Physics
Bangalore 560012
Karnataka
India

Abhilash Sasidharan
Amrita Vishwa Vidyapeetham
University
Amrita Centre for Nanosciences
and Molecular Medicine
Elamakkara
Kochi 682041
Kerala
India

Umesh V. Waghmare
Theoretical Sciences Unit
Jawaharlal Nehru Centre for
Advanced Scientific Research
Srirampura Cross
Jakkur P.O.
Bangalore 560 064
Karnataka
India

Contents