

# Functional Organic and Polymeric Materials

Molecular Functionality—Macroscopic Reality

Edited by

**Tim H. Richardson**

Department of Physics and Astronomy, University of Sheffield, Sheffield, UK

JOHN WILEY & SONS, LTD

Chichester · New York · Weinheim · Brisbane · Singapore · Toronto

Copyright © 2000 John Wiley & Sons Ltd.  
Baffins Lane, Chichester,  
West Sussex PO19 1UD, England

National 01243 779777  
International (+44) 1243 779777  
e-mail (for orders and customer service enquiries): [cs-books@wiley.co.uk](mailto:cs-books@wiley.co.uk)  
Visit our Home Page on <http://www.wiley.co.uk>  
or <http://www.wiley.com>

All Rights Reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording, scanning or otherwise, except under the terms of the Copyright Designs and Patents Act 1988 or under the terms of a licence issued by the Copyright Licensing Agency, 90 Tottenham Court Road, London W1P 9HE, UK, without the permission in writing of the Publisher.

*Other Wiley Editorial Offices*

John Wiley & Sons, Inc., 605 Third Avenue,  
New York, NY 10158-0012, USA

WILEY-VCH Verlag GmbH, Pappelallee 3,  
D-69469 Weinheim, Germany

Jacaranda Wiley Ltd, 33 Park Road, Milton,  
Queensland 4064, Australia

John Wiley & Sons (Asia) Pte Ltd, Clementi Loop #02-01,  
Jin Xing Distripark, Singapore 129809

John Wiley & Sons (Canada) Ltd, 22 Worcester Road,  
Rexdale, Ontario M9W 1L1, Canada

***Library of Congress Cataloging-in-Publication Data***

Functional organic and polymeric materials / edited by Tim H.  
Richardson.

p. cm.

Includes bibliographical references.

ISBN 0-471-98724-7 (cloth : alk. paper)

1. Polymers. 2. Organic compounds. 3. Thin films.

4. Monomolecular films. I. Richardson, Tim H.

TA455.P58F85 2000

620.1'92—dc21

99-31707

CIP

***British Library Cataloguing in Publication Data***

A catalogue record for this book is available from the British Library

ISBN 0 471 98724 7

Typeset in 10/12 Times by Thomson Press (India) Ltd., New Delhi

Printed and bound in Great Britain by Antony Rowe, Chippenham, Wilts

This book is printed on acid-free paper responsibly manufactured from sustainable forestry, in which at least two trees are planted for each one used for paper production.

# Functional Organic and Polymeric Materials

# List of Contributors

- |                          |  |
|--------------------------|--|
| <b>A. Campbell</b>       | Department of Physics and Astronomy, Centre for Molecular Materials, University of Sheffield, Hounsfield Road, Sheffield, S3 7RH, UK         |
| <b>D.A. Dunmur</b>       | Department of Chemistry and Liquid Crystal Institute, University of Southampton, Southampton, SO17 1BJ, UK                                   |
| <b>S.D. Evans</b>        | Centre for Self-Organising Molecular Systems, Department of Physics and Astronomy, University of Leeds, Leeds, LS2 9JT, UK                   |
| <b>Louise D. Farrand</b> | Merck Ltd, West Quay Road, Poole, Dorset, BH15 1HX, UK   |
| <b>A.J. Hudson</b>       | Sharp Laboratories of Europe Ltd, Edmund Halley Road, Oxford Science Park, Oxford, OX4 4GA, UK   |
| <b>F. Kajzar</b>         | LETI (CEA – Technologies Avancées), DEIN/SPE, Centre d'Etudes de SACLAY, 91191 Gif sur Yvette Cedex, France                                  |
| <b>D. Lacey</b>          | Liquid Crystals and Advanced Organic Materials Research Group, Department of Chemistry, University of Hull, Hull, HU6 7RX, UK                |
| <b>J.M. Nunzi</b>        | LETI (CEA – Technologies Avancées), DEIN/SPE, Centre d'Etudes de SACLAY, 91191 Gif sur Yvette Cedex, France                                  |
| <b>I.R. Peterson</b>     | Centre for Molecular and Biomolecular Electronics, Coventry University, UK, and NIMA Technology Ltd, The Science Park, Coventry, CV4 7EZ, UK |

- M. Petty** School of Engineering and Centre for Molecular Electronics, University of Durham, South Road, Durham, DH1 3LE, UK
- T. Richardson** Department of Physics and Astronomy, Centre for Molecular Materials, University of Sheffield, Hounsfield Road, Sheffield, S3 7RH, UK
- P. Skabara** Division of Chemistry, Sheffield Hallam University, Pond Street, Sheffield, S1 1WB, UK
- M.P. Srinivasan** Department of Chemical and Environmental Engineering, National University of Singapore, 10 Kent Ridge Crescent, Singapore 119260
- M.S. Weaver** Sharp Laboratories of Europe Ltd, Edmund Halley Road, Oxford Science Park, Oxford, OX4 4GA, UK
- L.E. Williams** Centre for Self-Organising Molecular Systems, Department of Physics and Astronomy, University of Leeds, Leeds, LS2 9JT, UK
- P.V. Wright** Department of Engineering Materials, Sir Robert, Hadfield Building, University of Sheffield, Sheffield, S1 3DU, UK
- Y. Zheng** Department of Engineering Materials, Sir Robert, Hadfield Building, University of Sheffield, Sheffield, S1 3DU, UK

# Editor's Acknowledgements

Finding time to write a book chapter is never easy as a research scientist and I am truly grateful for the contributions of the authors. I know that their enthusiasm for their research area, which is carried by their words, remains triumphant even whilst operating in the confused world of third millenium academia. Most of the authors are personal friends as well as research colleagues, so I take this opportunity to thank them for their friendship over the years. The publishers have been very patient with me in the preparation of this book and I thank them for that and for their guidance. My own journey in Molecular Materials has been aided tremendously by my research group at the University of Sheffield and by many colleagues both in the UK and overseas. I am grateful to you all for the friendly working environment you have created. In particular, I would like to thank Gareth Roberts who steered me in the beginning, Fred Combley who kept me on track and Rifat Capan who continues to give me new enthusiasm for this work. Finally I thank my wife and our parents for their support and dedicate this book to my sons, Matthew and Liam, not because of the content, but to show them an example of how people can help each other.

# Contents

<b>List of Contributors</b> . . . . .	<b>xiii</b>
<b>Editors Acknowledgements</b> . . . . .	<b>xv</b>
<b>1. Molecular Functionality—Macroscopic Reality</b> . . . . .	<b>1</b>
<i>Tim H. Richardson</i>	
References . . . . .	5
<b>2. Organic Thin-Film Deposition Techniques</b> . . . . .	<b>7</b>
<i>M. C. Petty</i>	
1 Introduction . . . . .	7
2 Deposition Methods . . . . .	8
2.1 Spin-Coating . . . . .	8
2.2 Physical Vapour Deposition . . . . .	10
2.3 Chemical Vapour Deposition . . . . .	16
2.4 Electrochemical Methods . . . . .	17
2.5 Langmuir–Blodgett Film Deposition . . . . .	18
2.6 Self-Assembly and Related Methods . . . . .	22
2.7 Other Techniques . . . . .	25
3 Towards Nanofabrication . . . . .	26
4 Conclusions . . . . .	29
References . . . . .	29
<b>3. Liquid Crystals as Functional Molecular Materials</b> . . . . .	<b>31</b>
<i>David A. Dunmur and Louise D. Farrand</i>	
1 Introduction . . . . .	31
2 Types of Liquid Crystals . . . . .	33
3 Molecular Properties and Macroscopic Function and Response . . . . .	39
3.1 Phase Behaviour . . . . .	39
3.2 Optical Properties . . . . .	41

3.3	Electrical Properties	42
3.4	Elastic Properties	47
3.5	Viscosities	49
3.6	Chiral Properties	51
4	Macrostructures for External Function and Response	54
4.1	Surface-Stabilized Thin Films	54
4.2	Networks, Polymers, Elastomers and Gels	59
4.3	Micro-Encapsulation	61
4.4	Biostructures, Vesicles and Membranes	63
5	Applications of Liquid Crystals: Recent Developments	64
5.1	Viewing-Angle Improvement	66
5.2	Brightness Enhancement	67
5.3	Reflective Displays	68
5.4	Faster Displays	69
6	Conclusions	70
	References	71
<b>4.</b>	<b>Thermotropic Side-Chain Liquid Crystalline Polymers</b>	<b>75</b>
	<i>David Lacey</i>	
1	Liquid Crystals	75
1.1	Calamitic versus Discotic	76
1.2	The Mesophases	77
2	Side-Chain Liquid Crystalline Polymers	81
2.1	The Polymer Backbone	83
2.2	The Flexible Spacer Group	91
2.3	Mesogenic Side Group	95
3	Liquid Crystalline Elastomers	99
3.1	Structure of Liquid Crystalline Elastomers	99
3.2	Mechanical Field Effect	99
3.3	Mono-Domain Liquid Crystalline Elastomers	101
4	Fast-Switching Anisotropic Networks	104
5	Final Remarks	105
	References	106
<b>5.</b>	<b>Langmuir Monolayers</b>	<b>109</b>
	<i>I.R. Peterson</i>	
1	Introduction	109
2	Molecular Interactions	110
3	Amphiphiles	113
4	Self-Assembly	118
5	Order and Symmetry	120
6	Mesophases	123
7	Hexatics	126



8	Isotherms	128
9	Conceptual Development	133
10	Phase Diagrams	134
11	Textures	139
12	Equivalent States	143
13	Perspectives	145
	References	146
<b>6.</b>	<b>The Formation of Organized Molecular Assemblies via Spontaneous Adsorption: Monolayers to Multilayers</b>	<b>149</b>
	<i>S.D. Evans and L.M. Williams</i>	
1	Self-Assembled Monolayers	149
1.1	Self-Assembled Monolayer Formation	150
1.2	Structure and Conformational Order within Alkanethiol Self-Assembled Monolayers on Gold	152
1.3	Interior Functionality	155
1.4	Surface Functionalization	156
2	Multifunctional Self-Assembled Monolayers	158
3	Photoisomerizable Monolayers	159
4	Supported Lipid Bilayers	161
5	Patterned Monolayers	163
5.1	Microcontact Printing ( $\mu$ CP)	164
5.2	Photolithography	164
5.3	Proximal Probe and Other Serial Techniques	166
6	Fluid–Surface Interactions	166
7	Self-Assembled Monolayers on Non-Planar Surfaces	168
8	Self-Assembly Routes to Multilayer Formation	168
8.1	Methodologies for Multilayer Growth	169
9	Conclusions	175
	References	176
<b>7.</b>	<b>Langmuir–Blodgett Films: From Deposition to Application</b>	<b>181</b>
	<i>Tim H. Richardson</i>	
1	Introduction	181
2	Fabrication of Langmuir–Blodgett Films	182
2.1	Langmuir Monolayer Formation	182
2.2	Langmuir Film Transfer	185
3	Characterization of Langmuir–Blodgett Films	188
4	Applied Physics of Functional Langmuir–Blodgett Films	193
4.1	Ionic Conductivity through Langmuir–Blodgett Films	193
4.2	Pyroelectricity	195

4.3 Gas Sensing . . . . .	195
5 Summary . . . . .	198
References . . . . .	199
<b>8. Conduction in Conjugated Molecular Materials . . . . .</b>	<b>201</b>
<i>A.J. Campbell</i>	
1 Introduction . . . . .	201
2 Physical Structure of Molecular Solids . . . . .	203
3 Electronic Structure of Molecular Solids and the Nature of the Charge Carriers . . . . .	204
4 Charge Transport . . . . .	210
5 Carrier Densities . . . . .	214
6 Contacts . . . . .	215
7 Injection-Limited Current Flow . . . . .	220
8 Bulk-Dominated Conduction . . . . .	224
References . . . . .	231
<b>9. Conductivity and Structural Organization of Macromolecular Polyether Alkali Metal Salt Complexes . . . . .</b>	<b>233</b>
<i>Peter V. Wright and Yungui Zheng</i>	
1 Introduction . . . . .	233
2 Ionic Conductivity of PEO-Based Complexes with Inorganic Alkali Metal Salts . . . . .	234
3 The Structure of Organized Phases of PEO-Alkali Salt Complexes . . . . .	236
4 Thermal Properties and Morphology of PEO-Alkali Salt Complexes . . . . .	238
5 Thermodynamic Stabilities of PEO-Alkali Salt Complexes . . . . .	241
6 Complexes with Salts of Aromatic and Heterocyclic Anions . . . . .	243
7 Mixed Electronic-Ionic Conductivity . . . . .	248
8 New Directions in Polymer Electrolytes . . . . .	249
9 Some Elementary Considerations of Ion Mobility in Polymer Systems . . . . .	250
10 Towards Practical Low-Dimensional Systems with Supramolecular Organization . . . . .	253
11 The Structure of the Low-Dimensional Amphiphilic Complexes . . . . .	254
12 Ionic Conductivity of Low-Dimensional Complexes . . . . .	262
13 Further Developments in Low-Dimensional Polymer Electrolytes . . . . .	268
Acknowledgements . . . . .	269
References . . . . .	270

<b>10. Organic Photochromism: Spiro Compounds as Functional Molecules</b>	<b>273</b>
<i>M.P. Srinivasan</i>	
1 Introduction	273
2 Photochromism	274
3 Structure and Behaviour of Spiro Compounds	275
4 Photochromism in Molecular Engineering	277
5 Organization in Spiro Photochromes	278
6 Orientation in Spiro Photochromes	281
7 Effect of the Environment	284
8 Adsorbed and Complexed Photochromes	286
9 Applications	287
10 Conclusions	290
Acknowledgements	290
References	291
<b>11. Organic Second-Order Non-Linear Optical Materials</b>	<b>295</b>
<i>P. Skabara</i>	
1 Introduction	295
2 Fundamentals of Non-Linear Optics	296
2.1 Basic Principles	296
2.2 Consideration of Non-Linearity at the Microscopic and Macroscopic Levels	297
2.3 Devices	298
2.4 Pockels Effect	299
2.5 Second-Harmonic Generation	299
2.6 Frequency Dependence of the First Molecular Hyperpolarizability	300
2.7 Techniques for Measuring Second-Order Non-Linear Optical Activity	301
2.8 Requirements for Second-Order Non-Linear Optical Activity	303
2.9 Strategies for Improving Second-Order Non-Linear Optical Activity	305
2.10 Recent Advances in the Design of New Materials for Non-Linear Optics	309
3 Conclusions	323
References	324
<b>12. Third-Order Effects and Applications</b>	<b>327</b>
<i>F. Kajzar and J.M. Nunzi</i>	
1 Introduction	327
2 Classification of Third-Order Processes	329

2.1	Conventions . . . . .	329
2.2	Resonant Conditions for Third-Order Non-Linearities . . . . .	330
3	Four-Wave Mixing Processes . . . . .	337
3.1	Non-Linear Refractive Index . . . . .	337
3.2	Two-Photon Absorption . . . . .	341
4	Experimental Techniques . . . . .	343
4.1	Single-Beam Experiments . . . . .	343
4.2	Pump-Probe Experiments . . . . .	347
4.3	Four-Wave Mixing Experiments . . . . .	351
5	Materials . . . . .	351
5.1	Conjugated Polymers . . . . .	351
5.2	Functionalized Polymers . . . . .	352
5.3	Importance of Order . . . . .	352
6	Applications . . . . .	355
6.1	Guided-Wave Mode . . . . .	355
6.2	Free-Wave Mode . . . . .	356
7	Conclusions . . . . .	359
	References . . . . .	360
<b>13.</b>	<b>Organic Electroluminescence . . . . .</b>	<b>365</b>
	<i>A.J. Hudson and M.S. Weaver</i>	
1	Introduction . . . . .	365
2	Historical Perspective . . . . .	366
3	Device Issues . . . . .	368
3.1	Anode . . . . .	369
3.2	Organic Materials . . . . .	369
3.3	Cathode . . . . .	370
3.4	Device Operation . . . . .	370
3.5	Device Fabrication . . . . .	371
4	Charge-Transport Materials . . . . .	374
4.1	Improved Hole-Transport Materials . . . . .	374
4.2	Improved Electron-Transport Materials . . . . .	375
4.3	Efficient Electron Transport in Polymer Devices . . . . .	376
5	Emitter Materials . . . . .	376
5.1	Structural Modification . . . . .	377
5.2	Doping . . . . .	379
5.3	Pure Emission . . . . .	380
6	Improved Efficiency and Lifetimes . . . . .	381
6.1	Improved Efficiency through Doping . . . . .	382
6.2	Improved Efficiency with Triplet Emission . . . . .	383
7	Display Devices . . . . .	385
7.1	Passive Addressing Schemes . . . . .	385
7.2	Active Addressing Schemes . . . . .	385

CONTENTS	xi
7.3 Full-Colour Displays . . . . .	387
8 Future Developments . . . . .	388
9 Summary . . . . .	390
References . . . . .	390
<b>Index . . . . .</b>	<b>395</b>

# Molecular Functionality— Macroscopic Reality

TIM H. RICHARDSON

Department of Physics and Astronomy, University of Sheffield, UK

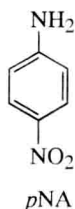
A Formula One racing car mechanic expends a great deal of time and energy tinkering with the innards of the engine and the peripheral components which are housed around it, such as the suspension system. Highly sophisticated machinery is used to modify and test the resulting performance of the vehicle, with large amounts of data being constantly fed back to the team of technicians to provide valuable information that will determine yet further modifications to the car when it next makes a pit stop. In principle, this process not only ensures that the best possible performance is achieved from the car during a particular race, but when elongated over a time period of years, it also provides the opportunity for huge technological advances to be made in combustion-engine-based transport.

This unlikely introduction to a book concerned with *organic materials* highlights several of the key themes that characterize this field. Like much of all materials work, organic materials research is iterative in nature. It involves making adjustments to the material of interest before an evaluation of its properties is made. The resulting characterization data enable researchers to determine which further modifications (composition, purity, shape, polarity, electron density distribution, polymer chain length, etc.) are necessary in order to achieve the sought after performance. Often slight modifications can have dramatic effects on properties, such as in the doping of silicon in order to modify its electronic conductivity, or in the doping of iron to produce steels of different hardness or elasticity. In these two examples, the macroscopic properties of the materials (e.g. electronic conductivity and Young's modulus) are governed most critically by the packing of the many billions of atoms contained within them. In the case of silicon, for example, the band structure

formation brought about by the packing of atoms is a complex process which is only easily predicted with the use of sophisticated computer simulation and modelling software. It is simply not possible to draw a diagram representing a silicon atom and then use it to successfully predict the physical properties of the *material* formed when many such atoms are assembled. The strong interatomic forces that govern atomic packing in crystals are all powerful determinants for their physical properties [1].

Generally speaking, and indeed there are notable exceptions, organic molecules often interact loosely via relatively weak van der Waals forces and dipole–dipole forces. Their properties are more closely described by the specific arrangement of atoms within each molecule rather than how the molecules themselves are packed. This is not to say that molecular packing is unimportant—far from it. This remark simply highlights one of the most important opportunities that we have been given, i.e. that with organic materials we have the opportunity to attempt to predict the macroscopic properties of a material based on the atomic arrangements within a discrete molecule or very small assemblies of molecules. An illustrative example of this is found on inspection of the molecule in Figure 1, i.e. *p*-nitroaniline (*p*NA)

This molecule has been studied by several researchers interested in second-order nonlinear optical effects (see Chapter 11) [2]. The benzene ring acts as a rich source of electrons which are delocalized, that is they are not confined to oscillate around individual atomic nuclei but rather they can be polarized as an electron cloud which extends over the entire region of the benzene ring. The nitro- and amino-groups are examples of chemical groups that are capable of withdrawing or donating electron density into such a ring structure, thus producing this polarized electron distribution. The resulting polar molecule can be polarized further by the application of an electric field. However, the ease of charge flow is asymmetric—the electron density can flow more easily in the direction towards the nitro-group than it can in the opposite direction. Hence the resulting polarization of the molecule is asymmetric. Fourier analysis shows that an alternating electric field, driven at a frequency  $\omega$ , imposed on our discrete molecule, will result in the broadcast of electric field components at new frequencies in additions to  $\omega$ . The second-harmonic frequency,  $2\omega$ , is particularly useful for extending the range of available laser wavelengths towards the ultraviolet [3]. More importantly, the required molecular asymmetry (which



**Figure 1** *p*-Nitroaniline: an example of a second-order nonlinear optical material

is not the only criterion which must be satisfied in order to obtain useful optical second-harmonic generation) can be easily understood by using simple chemical drawings. In other words, this is an example of a macroscopic property which, provided other symmetry considerations are overcome, can be predicted by consideration of the behaviour of the discrete individual molecules. This is just one example of many that have evolved over the last three decades throughout which the growth in organic materials research has continued to increase significantly. The principal aim of this present book is to provide many other examples of organic systems whose design begins with the consideration of the properties of their discrete molecules.

Although it is true to say that the predictability of the macroscopic properties of organic systems is usually greater than with inorganic materials, the exact behaviour obviously depends somewhat upon how individual molecules are assembled together in the *material*. A number of techniques exist which allow researchers, in effect, to cheat nature. If we take a solution of an organic material in a test tube and allow the solvent to evaporate slowly, we might expect to form small crystallites of solute in which the molecules are arranged in a completely 'natural' packing arrangement. This packing arrangement will depend on several parameters, including molecular shape, and dipole and charge distribution, among others. However, the molecular packing can often be modified considerably via the use of deposition techniques which effectively introduce new forces to be experienced by the molecules. The self-assembly technique is the simplest of these processes, involving the provision of additional 'binding sites' on a substrate, on to which solute molecules can attach in preference to their natural packing sites [4]. The Langmuir–Blodgett deposition method also provides a way in which the orientation of molecules can be modified by using a highly polar liquid, usually water [5]. These techniques and others are overviewed in Chapter 2 of this book, which intends to provide a survey of the available methods and to guide researchers in selecting the most suitable technique for their particular application. Those particularly wishing to focus on either self-assembly or Langmuir–Blodgett techniques will find other, more specialist chapters elsewhere in this book.

If we were asked how organic materials had made the strongest impact on our lives, we could give several different answers depending on the context of the question. From a medical point of view, we would probably describe the startling advances made in pharmaceuticals which have increased average life expectancy in the developed world to well beyond the age of seventy. Wearing our 'engineering hats', we would argue that engineering plastics have revolutionized virtually all everyday objects that we encounter, from skyscrapers to CD players. Focusing on electronics, we would almost certainly describe the liquid crystal devices which can be found in almost all objects containing an electronic display. Chapter 3 and 4 in this book are devoted to describing how a range of useful macroscopic properties can be achieved by



following a relatively small number of design rules. The story of the unravelling of these design criteria is told for both low-molar-mass and polymeric liquid crystal materials.

Chapters 5, 6, and 7 describe what have become known as 'layer-by-layer' techniques in which single monolayer sheets of organic molecules are deposited (either by chemisorption or physisorption) on to solid substrates. Chapter 5 describes the self-assembly from solution process in which highly organized and ordered functional molecular assemblies can be built up with on specialized equipment, while Chapter 6 details the physics of floating monolayers at an air-water interface. This is followed in Chapter 7 by an account of how such floating monolayers can be transferred on to solid supports to form useful functional materials, covering a wide range of applied physics fields. By the end of Chapter 7, it is hoped that the reader will begin to understand the major attraction of organic materials as a research field and has now sensed the fascination held by many wishing to exploit academically and commercially the concept of *molecular functionality-macroscopic reality*.

The second part of the book focuses on a detailed description of some of the most interesting electrical and optical properties of organic materials. The emphasis remains tightly focused on the processes of conduction through molecular materials, including conjugated polymers (Chapter 8) and polyether-based polymers (Chapter 9). These chapters are followed by accounts of second- and third-order non-linear optics (Chapters 10 and 11, respectively). The data storage industry has been dominated for the last thirty years by magnetic storage systems. More recently, optical storage has risen to prominence in the form of either ablative or photochromic approaches. The latter technique is reviewed (Chapter 12) in order to show how the optical properties of coloured organic materials can be made use of at the macroscopic level for memory applications. Nowhere more than in the field of light-emitting devices have organic materials made themselves the centre of attention. The last eight years in particular has seen an enormous growth area in light-emitting plastics, with the UK boasting a world lead in the area of luminescent polymers [6]. Chapter 11 describes the evolution of a wide range of low-molar-mass and polymeric organic materials and shows how macroscopic materials properties now match or surpass those of their inorganic counterparts.

There are many other topics which could have been included in a book of this nature, namely organic magnets, piezoelectric polymers, organic adhesives, gas and chemical sensors, biosensors, structural assessment techniques such as X-ray and neutron reflectometry, scanning tunnelling microscopies and molecular and biocomputing to name just a few. Restrictions on space, however, have unfortunately closed this book on such topics for now.

It is hoped that, in reading this book, those who are considering organic materials research will be strongly encouraged to pursue this field. It is an area that is characterized by a strong interdisciplinary and multidisciplinary culture,