This excellent book covers a broad range of topics, including nanomaterials' properties, their synthesis and applications, and market opportunities. I am happy to recommend this book to anyone interested in the scale-up of nanotechnology for commercial production.

Prof. Chennupati Jagadish
Australian National University, Australia

This book serves as the bible of nanomaterials. It covers every possible aspect related to nanomaterials, including their chemical and physical properties, applications, production, enabled greener products, characterization, waste, environment, health and safety, regulation and public engagement. It also covers market opportunities, intellectual property strategy and challenges of adoption and business. It is by far the most comprehensive book I have ever seen.

Dr. Lerwen Liu
Managing Director, NanoGlobe, and Founding Secretary, Asia Nano Forum

Nanotechnology has the potential to revolutionise all aspects of our lives. For this to happen, commercialisation activities have a critical role to play. They bring technology innovation into realisation while creating economic benefits for society. Among many nanotechnology sectors, engineered nanomaterials, especially nanoparticulate materials, are regarded as the leader in commercialisation. At the same time, the nanomaterials sector has attracted much more heated debate than other areas of nanotechnology with regard to safety, ethics and regulation. As such, the nanomaterials sector occupies a unique position in nanotechnology commercialisation.

This book gives an overview of the current trends in and the issues associated with the commercialisation of nanotechnology. It is the first of its kind to exclusively deal with nanomaterials. It brings together nanotechnology experts to provide comprehensive overviews of the critical factors influencing the commercialisation of nanomaterials. By dealing with not only the business aspects but also technological, political and social aspects of nanomaterial commercialisation, the book gives a holistic view on nanomaterial commercialisation and will appeal to a wide range of readers, including business leaders, venture capitalists, technology transfer organisations, regulatory bodies and policy-makers, NGOs, university researchers and graduate/undergraduate students.

Takuya Tsuzuki is associate professor of nanomaterials at the Research School of Engineering, College of Engineering and Computer Science, Australian National University. He received his PhD in condensed matter physics from Kyoto University, Japan. He was chief technology officer of one of the first nanotechnology companies in Australia, where he successfully commercialised the university patents he co-developed. He played a key role in the large-scale production and product development of commercial nanoparticles. His research interests include the synthesis, characterisation and applications of nanoparticles, green nanomaterials for sustainable development, nanometrology, nanosafety and translational nanotechnology.
Nanotechnology Commercialisation
1. Properties of Nanoparticulate Materials 1
Takuya Tsuzuki

1.1 Introduction 2
1.2 Nanoparticulate Materials 4
1.3 Common Characteristics of All Types of Nanoparticulate Materials 5
  1.3.1 High Surface Area 5
  1.3.1.1 Specific surface area 5
  1.3.1.2 Melting point depression 6
  1.3.1.3 Solubility enhancement 7
  1.3.1.4 Reduced sintering temperature 8
  1.3.1.5 Thermodynamically metastable crystal structures 9
  1.3.1.6 Luminescent quenching 11
  1.3.1.7 Surface treatments 12
  1.3.2 Small Light-Scattering Power 13
  1.3.3 Phonon Confinement Effects 14
  1.3.4 Nanoparticle Suspension Systems 15
    1.3.4.1 Distance between particles 15
    1.3.4.2 Particle dispersion 17
    1.3.4.3 Rheology 17
    1.3.4.4 Light scattering 18

1.4 Characteristics of Specific Types of Nanoparticulate Materials 19
  1.4.1 Semiconductor Nanoparticles 20
  1.4.2 Metal Nanoparticles 22
2.4 Nanoparticle Applications in Consumer Products 64
2.5 Summary 67

3. **Production Techniques of Nanoparticles on a Laboratory Scale** 73
   Putla Sudarsanam and Benjaram M. Reddy
   
   3.1 Introduction 74
   3.2 Precipitation Methods 77
   3.3 Deposition-Precipitation (DP) Techniques 81
   3.4 Sol-Gel Methods 85
       3.4.1 Aqueous Sol-Gel Method 86
       3.4.2 Non-Aqueous (or Non-Hydrolytic) Sol-Gel Method 88
   3.5 Microemulsion Techniques 92
       3.5.1 Oil-in-Water (O/W) Microemulsion Method 92
       3.5.2 Water-in-Oil (W/O) Microemulsion Method 94
       3.5.3 Water-in-scCO₂ (W/scCO₂) Microemulsion Method 97
   3.6 Hydrothermal and Solvothermal Methods 98
       3.6.1 Hydrothermal Method 98
       3.6.2 Solvothermal Method 102
   3.7 Microwave-Assisted Techniques 104
   3.8 Polyol Methods 107
   3.9 Liquid Feed Flame Spray Pyrolysis (LF-FSP) Methods 110
   3.10 Template-Directed Synthetic Techniques 113
   3.11 Mechanochemical Processing 116
   3.12 Ionic Liquid-Assisted Methods 118
   3.13 Conclusions 120

4. **Commercial-Scale Production of Nanoparticles** 139
   Takuya Tsuzuki
   
   4.1 Introduction 139
   4.2 Methods Used in the Commercial-Scale Production of Nanoparticles 140
4.2.1 Challenges in Production Scale-Up 140
4.2.2 Inorganic Nanoparticles 142
   4.2.2.1 Mechanical grinding/milling (top-down) 143
   4.2.2.2 Vapour phase technique (bottom-up) 143
   4.2.2.3 Liquid-phase technique (bottom-up) 144
   4.2.2.4 Solid-phase technique; mechanochemical processing (bottom-up) 145
   4.2.2.5 Which methods and why? 146
4.2.3 Carbon-Based Nanoparticles 148
   4.2.3.1 Carbon nanotubes 148
   4.2.3.2 Fullerenes 152
   4.2.3.3 Diamond nanoparticles 153
4.3 Effects of Production Methods on the Properties of Commercial Nanoparticles 154
   4.3.1 ZnO 155
   4.3.2 CeO₂ 161
4.4 Summary 164

5. The Commercialisation of Nanotechnology: The Five Critical Success Factors to a Nanotech-Enabled Whole Product 171

Craig Belcher, Richard Marshall, Grant Edwards, and Darren Martin

5.1 Introduction 172
   5.1.1 The Valley of Death 173
5.2 Nanotechnology Commercialisation Critical Success Factors 176
   5.2.1 Product Orientation (and Not Technology Admiration) 176
      5.2.1.1 The need for focus on the single most commercially viable and attainable application 176
5.2.1.2 The need to start with an exhaustive list of potential base markets and applications 180

5.2.2 Continuous Market Interaction and Selection of a Beachhead Application 184

5.2.3 Application of Spiral Product Development Methodology 187

5.2.4 Attraction and Retention of Commercialisation Partners 191

5.2.5 Mitigation of Nanotechnology-Specific Technology Risks 198

5.2.5.1 Manufacturing methods and scale-up 198

5.2.5.2 Quality control and specification tolerance of nanotechnology in the whole product 199

5.2.5.3 Occupational and environmental health and safety 199

5.3 Conclusions 200

6. Overcoming Nanotechnology Commercialisation Challenges: Case Studies of Nanotechnology Ventures 205

Elicia Maine

6.1 Introduction 205

6.2 Case Studies 206

6.2.1 Hyperion Catalysis 207

6.2.2 NanoGram/NeoPhotonics Corp. 211

6.2.3 Degussa Advanced Nanomaterials (AdNano) 217

6.3 Analysis of Case Study Commercialisation Challenges 223

6.4 Approaches to Nanotech Commercialisation Critical Success Factors 227

6.4.1 Product Orientation (and Not Technology Admiration) 227
6.4.2 Continuous Market Interaction and Selection of a Beachhead Application
6.4.3 Application of Spiral Product Development Methodology
6.4.4 Attraction and Maintenance of Commercialisation Partners
6.4.5 Mitigation of Nanotechnology-Specific Technology Risks
6.4.6 Licensing vs. Manufacturing Decision

6.5 Conclusion

7. Intellectual Property and Nanomaterials: Trend and Strategy

Daisuke Kanama

7.1 Introduction

7.2 Background: Patent Application Trends within Each Strategic Priority Area in Japan

7.3 Trend in Patent Applications in the Area of Nanotechnology

7.3.1 Classification

7.3.2 Trends in Nanotechnology Patents in the Four Largest Patent Organisations

7.3.3 Trends in Nanotechnology Patent Application According to the Applicant’s Nationality

7.3.4 Number of Nanotechnology Patent Applications by Corporations, Universities and Public Research Organisations

7.3.5 International Comparison of Nanotechnology-Related Patents in Nine Designated Technology Areas

7.4 Examples of Applied Nanotechnology: Carbon Nanotube Technology

7.4.1 Growth in the Patent Applications Related to CNT

7.4.2 Level of the Maturity of CNT Technology from the Perspective of Patent Trends
7.4.3 Trends in Patent Application Related to CNT, Based on the Type of Technological Fields 258

7.5 Conclusion: Intellectual Property Strategy in the Field of Nanotechnology 258
7.5.1 IP Strategy at the Stage of Basic Research 258
7.5.2 IP Strategy at the Stage of Application Development 261
7.5.3 Connecting Basic Research and Application Development 262

7.6 Notes 263
7.6.1 Note 1 263
7.6.2 Note 2 263

8. Government Regulation of Nanotechnologies 265

Diana M. Bowman and Joel D'Silva

8.1 Introduction 266
8.2 The World of Regulation: Unpacking Different Regulatory Models 267
8.2.1 State-Based Regulation 268
8.2.2 Civil-Based Regulation 269
8.2.3 Co-Regulation 270
8.3 Current Regulatory Frameworks and Their Effectiveness for Nanotechnologies 271
8.4 Multi-Lateral and Multi-Party Initiatives 276
8.5 Conclusion: Acknowledging the Elephant in the Room 278

9. Metrology, Standards and Measurements Concerning Engineered Nanoparticles 287

Åsa Jämting and John Miles

9.1 Metrology: The Science of Measurement 288
9.2 Standards 289
9.2.1 Physical Standards 289
9.2.2 Documentary Standards 290
9.2.3 Reference Materials 295
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.2.4 Nanoparticle Metrology</td>
<td>297</td>
</tr>
<tr>
<td>9.2.4.1 Nanoparticle properties</td>
<td>297</td>
</tr>
<tr>
<td>9.2.4.2 Nanoparticle size measurements</td>
<td>299</td>
</tr>
<tr>
<td>9.2.5 Sampling and Dispersion</td>
<td>300</td>
</tr>
<tr>
<td>9.3 Measurement Techniques for Nanoparticle Characterisation</td>
<td>301</td>
</tr>
<tr>
<td>9.4 Selected Nanoparticle Size Measurement Techniques: Benefits and Limitations</td>
<td>302</td>
</tr>
<tr>
<td>9.4.1 Dynamic Light Scattering</td>
<td>302</td>
</tr>
<tr>
<td>9.4.1.1 Principles</td>
<td>302</td>
</tr>
<tr>
<td>9.4.1.2 Advantages</td>
<td>303</td>
</tr>
<tr>
<td>9.4.1.3 Limitations</td>
<td>304</td>
</tr>
<tr>
<td>9.4.1.4 Instrument performance verification</td>
<td>304</td>
</tr>
<tr>
<td>9.4.2 Laser Diffraction</td>
<td>304</td>
</tr>
<tr>
<td>9.4.2.1 Principles</td>
<td>304</td>
</tr>
<tr>
<td>9.4.2.2 Advantages</td>
<td>305</td>
</tr>
<tr>
<td>9.4.2.3 Limitations</td>
<td>306</td>
</tr>
<tr>
<td>9.4.2.4 Instrument performance verification</td>
<td>306</td>
</tr>
<tr>
<td>9.4.3 Small Angle X-Ray Scattering</td>
<td>306</td>
</tr>
<tr>
<td>9.4.3.1 Principles</td>
<td>306</td>
</tr>
<tr>
<td>9.4.3.2 Advantages</td>
<td>306</td>
</tr>
<tr>
<td>9.4.3.3 Limitations</td>
<td>307</td>
</tr>
<tr>
<td>9.4.3.4 Instrument performance verification</td>
<td>307</td>
</tr>
<tr>
<td>9.4.4 Transmission Electron Microscopy</td>
<td>307</td>
</tr>
<tr>
<td>9.4.4.1 Principles</td>
<td>307</td>
</tr>
<tr>
<td>9.4.4.2 Advantages</td>
<td>308</td>
</tr>
<tr>
<td>9.4.4.3 Limitations</td>
<td>308</td>
</tr>
<tr>
<td>9.4.4.4 Instrument performance verification</td>
<td>309</td>
</tr>
<tr>
<td>9.4.5 Scanning Electron Microscopy</td>
<td>309</td>
</tr>
<tr>
<td>9.4.5.1 Principles</td>
<td>309</td>
</tr>
<tr>
<td>9.4.5.2 Advantages</td>
<td>310</td>
</tr>
<tr>
<td>9.4.5.3 Limitations</td>
<td>310</td>
</tr>
</tbody>
</table>
9.4.5.4 Instrument performance verification 311
9.4.6 Atomic Force Microscopy 311
  9.4.6.1 Principles 311
  9.4.6.2 Advantages 312
  9.4.6.3 Limitations 312
  9.4.6.4 Instrument performance verification 314
9.4.7 Particle-Tracking Analysis 314
  9.4.7.1 Principles 314
  9.4.7.2 Advantages 316
  9.4.7.3 Disadvantages 316
  9.4.7.4 Instrument performance verification 316
9.4.8 Differential Centrifugal Sedimentation 317
  9.4.8.1 Principles 317
  9.4.8.2 Advantages 318
  9.4.8.3 Disadvantages 319
  9.4.8.4 Instrument performance verification 319
9.4.9 Field Flow Fractionation 320
  9.4.9.1 Principles 320
  9.4.9.2 Advantages 322
  9.4.9.3 Disadvantages 322
  9.4.9.4 Instrument performance verification 322
9.5 Summary 323

10. Safety of Engineered Nanomaterials and OH&S Issues for Commercial-Scale Production 331

Paul F. A. Wright and Neale R. C. Jackson

10.1 Introduction 331
10.2 Overview of Nanotoxicology 332
  10.2.1 Toxic Potential of Nanoparticles 333
  10.2.2 Toxicokinetic Characteristics of Nanoparticles 335
10.2.2.1 Absorption 33
10.2.2.2 Distribution 33
10.2.2.3 Metabolism 33
10.2.2.4 Excretion 33

10.2.3 Mechanisms of Nanoparticle Toxicity in Biological Systems 33
10.2.3.1 Particle uptake pathways in cells 33
10.2.3.2 Protein corona effects 33

10.2.4 Summary of Nanoparticle Bioactivity 34
10.2.4.1 Nanoparticle size, and surface area, charge and chemistry effects 34
10.2.4.2 Nanoparticle shape and form effects 34
10.2.4.3 Nanoparticle effects on target cells 34
10.2.4.4 Contaminant effects 34
10.2.4.5 Neurotoxicity potential of nanoparticles 34
10.2.4.6 Immunotoxic potential of nanoparticles 34

10.2.5 Potential Biomarkers of NP Exposure 34

10.2.6 Toxicology of Specific Inorganic Engineered Nanomaterials 34
10.2.6.1 Nano titanium dioxide 34
10.2.6.2 Nano cerium dioxide 34
10.2.6.3 Nano zinc oxide 34
10.2.6.4 Nano gold 34
10.2.6.5 Nano silver 34
10.2.6.6 Nano silica 34
10.2.6.7 Quantum dots 34

10.2.7 Latest Initiatives in Nanosafety Research 34

10.3 Overview of Occupational Health and Safety Issues and Workplace Controls 34
10.3.1 Occupational Health and Safety Issues Relating to Engineered Nanomaterials 34
## 10.3.2 Nanomaterial Health Risk Assessment

10.3.3 Hierarchy of Workplace Controls for Handling Nanomaterials

10.3.3.1 Elimination controls

10.3.3.2 Substitution and modification controls

10.3.3.3 Enclosure controls

10.3.3.4 Extraction controls

10.3.3.5 Administrative controls

10.3.3.6 Personal protective equipment

10.3.4 Risk Management and Control Banding


*Jeremy Allan*

11.1 Introduction

11.2 Conceptualising Nanowaste

11.2.1 Nanowaste Streams

11.3 Measuring Nanowaste

11.3.1 Indicators and Parameters

11.3.2 Monitoring and Reporting

11.4 Managing Nanowaste

11.4.1 Corporate Nanowaste Management Policy

11.4.2 Disclosure and Transparency

11.4.3 Contract Nanowaste Management Services

11.5 Nanowaste Risk Management

11.5.1 Legal and Regulatory Drivers

11.5.2 Risk Assessment Techniques

11.5.3 Common Exposure Scenarios

11.5.4 Corporate Social Responsibility

11.5.5 Extended Producer Responsibility

11.6 Nanowaste Handling

11.6.1 Routine Nanowaste Handling

11.6.2 Contingency Response
11.6.3 Nanowaste Containment, Storage and Treatment

11.7 Future Directions

12. Public Engagement

Craig Cormick

12.1 Introduction
12.2 Nanotechnology in Society
12.3 So What Does Good Engagement Look Like?
12.4 Obstacles to Good Engagement
12.5 A Short History of Public Engagement
12.6 Deficit 2.0
12.7 Understanding NGOs and Affected Publics
12.8 Public Attitude Research
12.9 Engaging the Unengaged
12.10 Public Perception Barriers to Good Engagement
12.11 Examples of Engagement
12.12 Public Engagement Models for the Future
12.13 Online Communities and Online Community Engagement
12.14 Areas for More Work
12.15 So What Does It All Mean?

Index
Preface

Nanotechnology has the potential to revolutionise all aspects of our lives. For this to happen, commercialisation activities have a critical role to play. They bring technology innovation into realisation whilst creating economic benefits for society. The past 30 years have seen significant progress in nanotechnology. As a result, many innovative and practical applications of nanotechnology have been explored. This book aims to give an overview of the current trends in and the issues associated with the commercialisation of nanotechnology.

Nanotechnology encompasses many disciplines of science and engineering, including nanomaterials, nanomedicine, nano/micro-electromechanical systems, nanofabrication and nano-instrumentation. This book is unique in that it focuses on the nanomaterial sector. Engineered nanomaterials, especially nanoparticulate materials, are regarded as the leader in nanotechnology commercialisation. This is owing to the wide range of their unique properties, relative ease of fabrication, significant market opportunities and a short product development timeframe. In addition, the nanomaterial sector has attracted much more heated debate than any other areas of nanotechnology with regard to safety, regulation, standardisation and ethics. As such, the nanomaterials sector occupies a unique position in nanotechnology commercialisation.

Another unique aspect of this book is that it fills the existing gap between academic research and commercial production of nanomaterials. As shown in Fig. 1, nanotechnology commercialisation is the culmination of a broad spectrum of collective activities, from laboratory-scale investigations through production scale-up, to the non-technological issues surrounding commercialisation. Understanding the continuum of the spectrum is critical not only for the product development but also for regulatory and risk management purposes. Many stakeholders, including consumers, government officials, corporate managers and university researchers, are involved
in the process of nanomaterial commercialisation. The interaction between the stakeholders from different segments of the spectrum is essential for it to be successful. Hence, instead of focusing solely on the business side of nanotechnology commercialisation, a special effort has been made to capture and review each segment of the commercialisation spectrum. The chapters in this book are placed in the order roughly aligned with the spectrum.

Figure 1  Spectrum of nanotechnology commercialisation activity.

The applications of nanomaterials in biomedical/medicinal areas are largely excluded. Nanotechnology commercialisation in the medical field has unique characteristics in terms of business models, funding sources, regulatory issues and other aspects of commercialisation. Hence, these topics should be covered in a separate review volume. Also excluded are the aspects of organic polymeric nanoparticles. Although polymer nanoparticles have been widely used in paint and plastic industries and will have many important medical applications, they have technological, as well as safety and regulatory issues different from those for inorganic nanomaterials and hence deserve a separate volume of their own. Nonetheless, some aspects of carbon-related nanomaterials such as carbon nanotubes and nano-diamonds are covered in this volume.

This book is the collective achievement of many passionate and dedicated individuals. First of all, I would like to express my sincere gratitude to the chapter authors, who provided wonderful contributions despite their extremely busy schedules. Their presence in this book as renowned experts in their field was
critical to the project. I would also like to thank Mr. Stanford Chong, director of Pan Stanford Publishing, for making the publication possible. Finally, I am deeply grateful to my wife, Savitri, who has been a constant source of help and encouragement throughout the project.

Takuya Tsuzuki
Canberra, Australia
2013