Nanotechnologies for Future Mobile Devices

Learn how nanotechnologies, mobile communication, and the Internet are related to each other, and explore the potential for nanotechnologies to transform future mobile and Internet communications and the value networks of future electronics manufacturing. Based on a research collaboration between Nokia, Helsinki University of Technology, and the University of Cambridge, here leading researchers and business analysts review the current state-of-the-art and future prospects for:

- Structural materials in mobile devices, including novel multifunctional materials, dirt-repellent, self-healing surface materials, and lightweight structural materials capable of adapting their shape.
- Portable energy storage using supercapacitor-battery hybrids based on new materials including carbon nanohorns and porous electrodes, fuel cell technologies, energy harvesting, and more efficient solar cells.
- Electronics and computing advances reaching beyond IC scaling limits, new computing approaches and architectures, embedded intelligence, and future memory technologies.
- Nanoscale transducers for mechanical, optical, and chemical sensing, nature’s way of sensing and actuation, biomimetics in sensor signal processing, and nanoscale actuation.
- Nanoelectronics, for example based on graphene, to create ultrafast and adaptive electronics for future radio technologies, such as cognitive radio.
- Flat panel displays – how nanotechnologies can be used to achieve greater robustness, improved resolution, brightness and contrast, as well as mechanical flexibility.
- Open innovation in nanotechnology development, future manufacturing, and value networks.
- Commercialization of nanotechnologies.

Tapani Ryhänen is Laboratory Director of Nokia Research Center, heading Nokia’s research laboratories in Cambridge and Lausanne. He is also responsible for Nokia’s research collaboration with the University of Cambridge and the Ecole Polytechnique Fédérale de Lausanne (EPFL), and he is a Visiting Lecturer at the University of Cambridge.

Mikko A. Uusitalo is Principal Member of Research Staff at Nokia Research Center, Helsinki, where he has worked since 2000. He is a Founding Member of the Wireless World Research Forum (WWRF) and EUREKA CELTIC Initiative, and he is a Senior Member of the IEEE.

Olli Ikkala is Academy Professor of the Academy of Finland and Professor of Polymer Physics and Molecular Nanostructures at the Helsinki University of Technology. His current research interest is in developing concepts for functional nanomaterials based on macromolecules, synthetic polymers, and biomacromolecules.

Asta Kärkkäinen is Principal Scientist at Nokia Research Center, Helsinki, where she has worked since 1997. As a Research Manager of the Predictive Engineering Group, she has coordinated research on multidisciplinary design to enable optimal structural, thermal, acoustical, and chemical performance of future Nokia devices.
Nanotechnologies for Future Mobile Devices

Edited by

TAPANI RYHÄNEN
Nokia Research Center, Cambridge

MIKKO A. UUSITALO
Nokia Research Center, Helsinki

OLLI IKKALA
Helsinki University of Technology

ASTA KÄRKKÄINEN
Nokia Research Center, Helsinki
# Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>List of contributors</td>
<td>x</td>
</tr>
<tr>
<td>Preface</td>
<td>xiii</td>
</tr>
<tr>
<td>1  When everything is connected</td>
<td></td>
</tr>
<tr>
<td>1.1 Introduction</td>
<td>1</td>
</tr>
<tr>
<td>1.1.1 Mobile communication and the Internet</td>
<td>1</td>
</tr>
<tr>
<td>1.1.2 Towards merging of physical and digital worlds</td>
<td>3</td>
</tr>
<tr>
<td>1.2 Future devices, lifestyle, and design</td>
<td>4</td>
</tr>
<tr>
<td>1.2.1 Navigation in space and time</td>
<td>4</td>
</tr>
<tr>
<td>1.2.2 Transformable device</td>
<td>5</td>
</tr>
<tr>
<td>1.2.3 Fashion and expression</td>
<td>7</td>
</tr>
<tr>
<td>1.2.4 Lifestyle and the mobile device (global knowledge, local view)</td>
<td>7</td>
</tr>
<tr>
<td>1.3 Trusted personal device becomes a cognitive interface</td>
<td>9</td>
</tr>
<tr>
<td>1.3.1 Assisted living and remote health care for the elderly</td>
<td>9</td>
</tr>
<tr>
<td>1.3.2 Integrated cognitive systems</td>
<td>10</td>
</tr>
<tr>
<td>1.4 Ambient intelligence</td>
<td>11</td>
</tr>
<tr>
<td>1.4.1 Augmented reality</td>
<td>11</td>
</tr>
<tr>
<td>1.4.2 Embedded ambient intelligence</td>
<td>12</td>
</tr>
<tr>
<td>1.5 Technology challenges for humankind</td>
<td>13</td>
</tr>
<tr>
<td>1.5.1 Looking for the global solution</td>
<td>13</td>
</tr>
<tr>
<td>1.5.2 Global population is ageing and polarizing</td>
<td>14</td>
</tr>
<tr>
<td>1.5.3 Environmental challenges need global solutions</td>
<td>16</td>
</tr>
<tr>
<td>1.5.4 Sustainable economies and efficient ways of living</td>
<td>17</td>
</tr>
<tr>
<td>1.6 About this book</td>
<td>18</td>
</tr>
<tr>
<td>References</td>
<td>19</td>
</tr>
<tr>
<td>2  On the possible developments for the structural materials relevant for future mobile devices</td>
<td></td>
</tr>
<tr>
<td>2.1 Introduction</td>
<td>21</td>
</tr>
<tr>
<td>2.2 Nanocomposites by adding nanoscale reinforcements to tune the mechanical properties</td>
<td>22</td>
</tr>
</tbody>
</table>
4.5.2 Computations with dynamical systems and hybrid analog–digital systems 88
4.6 Physical implementation 89
  4.6.1 Recipes for nanocomputing systems 95
4.7 Architectures for nanosystems 96
  4.7.1 Challenges of nanoarchitectures 97
  4.7.2 Examples 99
4.8 Memory technologies for the future 103
  4.8.1 Flash memory 104
  4.8.2 Future options for memory technologies 105
  4.8.3 Comparison of the memory technologies 111
4.9 Comparisons of nanocomputing solutions for mobile devices 111
Acknowledgments 116
References 117

5 Sensing, actuation, and interaction 121
5.1 Introduction 121
  5.1.1 Ubiquitous sensing, actuation, and interaction 121
  5.1.2 The need for sensors and actuators in future mobile devices 123
5.2 Sensing 125
  5.2.1 Creating the sensors of the future 125
  5.2.2 Nature’s way of sensing 127
  5.2.3 Physical nanoscale transducers – nanowires and resonators 131
  5.2.4 Optical sensing 142
  5.2.5 Plasmonics 144
  5.2.6 Electrochemical sensors at the nanoscale 148
5.3 Sensor signal processing 151
  5.3.1 Nanoscale enablers for signal processing 151
  5.3.2 Power amplification and signal coding 152
  5.3.3 Noise enhanced signal processing 153
  5.3.4 Large arrays of nanoscale components 156
  5.3.5 Machine learning in sensor signal processing 157
  5.3.6 Plasmonics in signal processing 158
5.4 Actuation 160
  5.4.1 Principles of actuators in nature and artificial systems 160
  5.4.2 Nanoscale actuation based on electroactive polymers 160
  5.4.3 Mechanical metamaterials 164
5.5 Towards future cognitive solutions 165
References 166

6 Future of Radio and Communication 174
6.1 Introduction 174
  6.2 Some principles of radio communications systems 175
### Contents

<table>
<thead>
<tr>
<th></th>
<th>Seeing beyond the hype: what the Internet teaches us about the development of nanotechnology</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>§ Introduction 250</td>
</tr>
<tr>
<td></td>
<td>§ Perception and performance 250</td>
</tr>
<tr>
<td></td>
<td>§ The development of the Internet 252</td>
</tr>
<tr>
<td></td>
<td>§ Reaching maturity: Nanotech 1.0 253</td>
</tr>
<tr>
<td></td>
<td>§ Towards industrial reinvention 254</td>
</tr>
<tr>
<td></td>
<td>§ Future hype cycles 256</td>
</tr>
<tr>
<td></td>
<td>§ Conclusions 256</td>
</tr>
<tr>
<td></td>
<td>§ References 257</td>
</tr>
</tbody>
</table>

| 10 | Conclusions 258                                                                             |

Index 262
List of contributors

Gehan Amaratunga
University of Cambridge

Risto Kaunisto
Nokia Research Center

Piers Andrew
Nokia Research Center

Jani Kivioja
Nokia Research Center

Marc Bailey
Nokia Research Center

Pekka Koponen
Spinverse Ltd

Alan Colli
Nokia Research Center

Asta Kärkkäinen
Nokia Research Center

Tom Crawley
Spinverse Ltd

Finbarr Livesey
University of Cambridge

Vladimir Ermolov
Nokia Research Center

William Milne
University of Cambridge

Andrew Flewitt
University of Cambridge

Tim Minshall
University of Cambridge

Christian Gamrat
CEA-LIST

Letizia Mortara
University of Cambridge

Markku Heino
Nokia Research Center

Johann Napp
University of Cambridge

Olli Ikkala
Helsinki University of Technology

Pirjo Pasanen
Nokia Research Center

Laura Juvonen
Spinverse Ltd

Aarno Pärssinen
Nokia Research Center
<table>
<thead>
<tr>
<th>Name</th>
<th>Institution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Markku Rouvala</td>
<td>Nokia Research Center</td>
</tr>
<tr>
<td>Tapani Ryhänen</td>
<td>Nokia Research Center</td>
</tr>
<tr>
<td>Yongjiang Shi</td>
<td>University of Cambridge</td>
</tr>
<tr>
<td>Mikko A. Uusitalo</td>
<td>Nokia Research Center</td>
</tr>
<tr>
<td>Di Wei</td>
<td>Nokia Research Center</td>
</tr>
<tr>
<td>Yufeng Zhang</td>
<td>University of Cambridge</td>
</tr>
</tbody>
</table>
Preface

Human culture is simultaneously extending its capabilities to master the physical world at its molecular scale and to connect people, businesses, information, and things globally, locally, and pervasively in real time. Nanotechnologies, mobile communication, and the Internet have had a disruptive impact on our economies and everyday lives. Nanotechnologies enable us to use physical, chemical, and biological processes to create new functional materials, nanoscale components, and systems. This book explains how these technologies are related to each other, how nanotechnologies can be used to extend the use of mobile communication and the Internet, and how nanotechnologies may transform future manufacturing and value networks.

At the beginning of 2007, the University of Cambridge, Helsinki University of Technology, and Nokia Research Center established a collaboration in nanotechnology research according to open innovation principles. The target has been to develop concrete, tangible technologies for future mobile devices and also to explore nanotechnologies in order to understand their impact in the bigger picture. The collaboration is based on joint research teams and joint decision making. We believe that this is the proper way to build a solid foundation for future mobile communication technologies. The book is based on the visions of researchers from both academia and industry.

During the summer of 2007 a team of researchers and industrial designers from the University of Cambridge and Nokia created a new mobile device concept called Morph. The Morph concept was launched alongside the “Design and The Elastic Mind” exhibition at the Museum of Modern Art (MOMA) in New York, has been featured in several other exhibitions, won a prestigious red dot design concept award, and has had considerable publicity – especially in the Internet. To date, the concept has been viewed over three million times on YouTube. The story of Morph illustrates how nanotechnologies are linked to our everyday artifacts and our everyday lives. In our messages we have always emphasized realism and the responsible introduction of these new technologies to future products. We need to understand thoroughly both the opportunities and risks.

The public interest in the Morph concept may be related to the concreteness of everyday nanotechnology applications illustrating tangible, appealing consumer benefit and value. If the story of Morph was directed to a wider audience, this book is targeted at researchers and people creating future technology and business strategies in both industry and academia. However, we still emphasize the two issues, concreteness and consumer value. Our target has not been to write a comprehensive textbook or a review of nanotechnologies for future mobile devices but through selected examples to illustrate...
the impact on key mobile device technologies, manufacturing, value networks, innovation models, and ultimately on human societies. Our approach is also critical: sometimes the impact of a new technology is not straightforward and needs to be evaluated against competing technologies that may already be commercially available.

This is a vision statement of academic and industrial researchers working together in the spirit of open innovation. We hope that our book helps to promote stronger links between people working in different fields creating future concepts of mobile communication, Internet services, and nanotechnologies.