INTRODUCTION

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You see things; and you say "Why?" But I dream things that never were; and I say "Why not?"
George Bernard Shaw

Of the volumes planned for this series of books from the Royal Society and Imperial College Press, this is the only one that is devoted to "engineering" rather than "science". The distinction between these broad disciplines is often blurred: scientists searching for the answer to their question "Why?" often need to develop technology to make progress, in effect becoming engineers. Similarly, engineers wanting to exploit science to answer their question "How?", or possibly "Why not?", often find they must understand better the underlying fundamental science and so, perhaps temporarily, become scientists.

The blurring between these disciplines occurs probably none more so than in the emerging field(s) of nanoscience and nanotechnology. Using the definitions established by the recent Royal Society/Royal Academy of Engineering wide-ranging report on nanotechnology,[a] nanoscience is the study of phenomena and manipulation of materials at atomic, molecular and macromolecular scales, where properties differ significantly from those

[a] *Nanoscience and Nanotechnologies: Opportunities and Uncertainties*, published on 29 July 2004 by the Royal Society and the Royal Academy of Engineering (see http://www.nanotec.org.uk/).

ADVANCES IN NANOENGINEERING: ELECTRONICS, MATERIALS AND ASSEMBLY

at a larger scale. Nanotechnologies are the design, characterization, production and application of structures, devices and systems by controlling shape and size at the nanometer scale. As such, the experimental and theoretical work of chemists, physicists, electronic and mechanical engineers, material scientists, biochemists, molecular biologists, *inter alia*, can all contribute to this cross-disciplinary field, making it, in my (perhaps biased) opinion, one of the most exciting and challenging research activities to pursue.

Broadly speaking, nanoscience and nanotechnology are concerned with materials that have at least one dimension less than 100 nm, or one-tenth of a micron. To put this into context, a carbon Buckminsterfullerene molecule ("Bucky Ball"), which comprises 60 carbon atoms arranged into a spherical soccer-ball-shaped structure, has a diameter of 1 nm — this is about 200 billion times smaller than the diameter of a real soccer ball, which itself is about 200 billion times smaller than the diameter of the earth. A nanostructure can be categorized as zero-, one-, or two-dimensional according to whether its features are confined to the nanometer scale (nanoscale) in three, two, or one dimensions, respectively. The fullerene molecule, for example, can be regarded to be zero-dimensional owing to its size being on the nanoscale in all three dimensions. Other zero-dimensional nanostructures include metal and semiconductor particles that are a few nanometers in diameter, and are sometimes called "quantum dots". A one-dimensional nanostructure (a "quantum wire") is confined in two dimensions, and extended in the third. Carbon nanotubes, for example, which can be visualized as rolled up sheets of graphene, can be regarded as quantum wires, as indeed can many molecules and biomolecules, particularly if they are polymeric. Finally, there are two-dimensional nanostructures, which are confined on the nanoscale in one dimension but are extended in the plane, and can manifest as coatings or thin films, or electron layers buried inside semiconductor devices, for example.

A further broad categorization is often made according to how the nanostructure is fabricated. The "top-down" approach, as the name implies, involves defining the nanostructure out of a larger macroscopic material perhaps by chemical etching, milling, or electrostatic confinement, *inter alia*, and crudely speaking, has predominantly lay in the remit of the physical and material scientist, or the electronic and mechanical engineer. The "bottom-up" approach, on the other hand, fashions the desired nanostructure from smaller, constituent parts, perhaps by chemical synthesis, and has its provenance in the laboratories of the chemist or biochemist, for example. These characterizations emphasize how nanotechnology is a convergence of a vast range of disparate science and technology, and is inherently a multidisciplinary field.

However, the focus of nanoscience and technology is not with materials that are simply small; the properties of the structure or material must be different from those exhibited in the bulk. There are two main reasons that this can be the case. Electrons, the fundamental particle central to most of the physical and chemical properties of materials, and in particular their electronic and optical characteristics, have a size. This size is related to their wavelength, a consequence of the wave–particle duality inherent in the quantum mechanics that governs electron behaviour, and this wavelength can be on the nanoscale. If the dimension of a material approaches the electron wavelength in one or more dimensions, quantum mechanical characteristics of the electrons that are not manifest in the bulk material can start to contribute to or even dominate the physical properties of the material. This allows fundamental quantum mechanical properties to be accessed for their study and potentially for their exploitation.

The second main reason that the properties of nanoscale materials can be different from those exhibited in the bulk is associated with their increased relative surface area. By reducing the diameter of a quantum dot from 30 to 3 nm, the number of atoms on its surface increases from 5% to 50%.[b] Therefore, for a given mass of material, nanoparticles will have a greater surface area compared to larger particles, and hence will be much more reactive, as chemical reactivity, catalytic activity, and growth reactions occur at a material's surface. Similarly, the high grain boundary area in materials comprising nanoscale crystalline grains can instill enhanced mechanical properties.

It is probably becoming clear that the field of nanotechnology is vast, and this book can only hope to give a taste of the immense activity currently taking place. A significant part of this book is devoted to the fundamental nanotechnology building blocks — the nanostructures themselves. In Chapter 1, Humberto and Mauricio Terrones describe carbon-based nanostructures and, in particular, carbon nanotubes and carbon fullerenes. The authors review the fabrication and properties of these fascinating structures, and discuss their emerging and potential applications. Moving from the organic to the inorganic world, Caterina Ducati discusses the growth of nanowires made of inorganic materials such as silicon, ruthenium oxide, and nickel sulphide by a number of physical and chemical processes in

[b] *Ibid.*

Chapter 2. And in Chapter 3, material scientists Jon Molina-Aldareguia and Stephen Lloyd describe multi-layered inorganic materials, which have a range of potential applications including hard coatings and data storage systems. In his fascinating chapter (Chapter 4), Simon Hall draws on nature for inspiration and techniques to fabricate inorganic nanowires, and illustrates how fruitful the adoption or exploitation of processes, techniques or systems from traditionally distinct disciplines can be. In particular, we see how chitosan, a derivative of chitin (one of the main components in the cell walls of fungi and insect exoskeletons), can be used to template the fabrication of high-temperature superconductor wires.

Equally important to the fabrication of nanostructures is the development of techniques to assemble them onto surfaces, or into appropriate geometries or circuits, or to interface them with the outside world. This is particularly necessary for the exploitation of nanotechnology to produce useful applications, since no matter how fascinating the physical, chemical, or biological properties are of any given nanostructure, it is likely that they will need to be organized into some kind of functional device to employ their properties. In particular, there is a need for directed assembly tools, in which the nanostructures can self-assemble or be programmed to self-assemble into their desired final configuration. In Chapter 5, Philip Gale discusses progress in the field of supermolecular chemistry, concentrating on how molecular subunits can be designed to assemble into larger chemical complexes, which allows one to engineer new molecular knots and chains, and even nanoscale molecular machines, that could not be made previously. Probably the best known self-assembling molecular system is DNA (deoxyribonucleic acid), which in its physiological state comprises two polymeric molecules of complementary chemical structure entwined around one another — the famous double-helix structure. If the individual strands are not chemically complementary, they remain separate and the double helix does not form. This has led a number of researchers to propose that DNA, and other (biological) systems with analogous lock-and-key recognition properties, could form the basis of a nanostructure assembly procedure. In Chapter 6, Christoph Wälti reviews this field and describes a number of experiments designed to exploit DNA to this end, including the selective attachment of molecules to surfaces at a nanometer-scale resolution, the manipulation of surface-tethered molecules by electric fields, and the fabrication of branched DNA constructs.

Chapter 6 approaches nanotechnology from the broad perspective of developing molecular-scale electronic devices — the natural evolution of the progressive miniaturization of semiconductor electronics over the past 50 years. This is a theme shared with the chapters that immediately follow. In Chapter 7, Jason Davis continues the discussion of the integration of biological molecules into electronic circuitry, and describes a range of experiments on metallo-proteins, proteins containing transition metals, including studies of their electrical conduction properties. In Chapter 8, John Cunningham returns the discussion to the top-down methodology and reviews a number of nanoscale electronic devices formed by electrostatic confinement, including devices that control individual electrons or operate by the action of individual electrons. Rolf Crook continues with this theme in Chapter 9 describing an innovative technique to pattern electronic nanostructures in an erasable fashion, providing a flexible approach for investigating and optimizing such devices. Moving sideways from nanoelectronic systems to nanomagnetic systems, Robert Hicken's chapter (Chapter 10) is concerned with the development of nanomagnetic materials and how they can be exploited for future data storage applications. Indeed, the ongoing parallel miniaturization of the electronic and magnetic components integral to consumer products such as personal computers is one example of how relevant this technology is to everyday life; nanotechnology is not just an esoteric research field that might find application in the future, it is in use, all around us, now.

The analysis and characterization of nanostructures is a crucial part of their fabrication, assembly, and understanding, and all of the preceding chapters describe the techniques employed to study and assess the specific systems under discussion. The last two chapters of this book, however, particularly concentrate on sophisticated analytical techniques. In Chapter 11, David Richards discusses new scanning-probe technology developed to address the nanoscale optically, while in Chapter 12, Mark Osborne describes fluorescent techniques to investigate single molecules and how they interact with their immediate environment.

The authors of these chapters are young researchers, many of whom hold or have recently held prestigious Royal Society University Research Fellowships or Advanced Research Fellowships from the UK's Engineering and Physical Sciences Research Council (EPSRC). They are working at the cutting edge of their fields, and these articles describing their research and setting it into a wider context provide an excellent overview of these topics and demonstrate the infectious enthusiasm of young people passionate about what they do best — asking the questions "Why?" and "Why not?"

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Giles Davies studied at Bristol University where he graduated with first class honors in Chemical Physics in 1987, and obtained his PhD in 1991 from the Cavendish Laboratory, University of Cambridge, in Semiconductor Physics. He spent three years as an Australian Research Council Postdoctoral Fellow at the University of New South Wales, Sydney, before returning to the Cavendish Laboratory as a Royal Society University Research Fellow in 1995. He took up the Chair of Electronic and Photonic Engineering at the University of Leeds in 2002, becoming Director of the Institute of Microwaves and Photonics in 2005, and has built up large research teams studying high-frequency (terahertz) electronics and photonics, semiconductor device growth and processing, and bio-nanotechnology. He is especially interested in cross-disciplinary research and, in particular, the combination of biological processes with micro- and nanoelectronics. He is an associate editor of the *Philosophical Transactions of the Royal Society A.*