4 Nanomanufacturing and the industrial application of nanotechnologies

4.1 Introduction

1 In the previous chapter, we saw many examples of nanoscience and some current and potential applications of nanotechnologies. Current industrial applications of nanotechnologies are mainly in the characterisation of materials, the production of chemicals and materials, precision manufacturing and ICT. In general, these applications represent incremental rather than truly disruptive advances; however, in the longer term it is likely that many manufacturing processes will be influenced by nanotechnologies, just as they are today by ICT.

2 In this chapter we outline how nanotechnologies are being realised in industry, focusing on the generic methods of nanomaterial manufacture, production rates and applications in some key industry areas. We indicate how nanoscience and nanotechnologies might impact on industry in the longer term, and highlight some of the factors that will affect the commercialisation of nanotechnologies. A detailed consideration of these issues for the UK can be found in the Taylor report (DTI 2002). Our aim, in particular, is to provide an appropriate background for Chapter 5, in which we discuss the health, environmental and safety impacts of nanotechnologies. We have focused disproportionately on the manufacture and use of nanoparticles and nanotubes, because they raise particular concerns, but it should be noted that nanoparticles and nanotubes only account for a small fraction of the predicted global market for nanotechnologies.

4.2 Characterisation

3 The characterisation of materials – the determination of their shape, size, distribution, mechanical and chemical properties – is an important part of the industrial process. It serves two broad purposes: as quality control, and as part of the research and development of new processes, materials and products. Evidence taken during our industry workshop suggested that many areas of industry did not consider nanotechnologies to be new (for example, nanoscale structures have been important to the catalyst industry for over 100 years). However, the industrialists believed that a nanotechnology 'breakthrough' had occurred in the tools used to observe and measure properties and processes at the nanoscale level. Sophisticated tools, such as the STM, AFM and TEM (see Box 3.1), enable surface and interfacial characterisation of materials at the nanoscale, allowing individual atoms to be observed and analysed. This is leading to greater understanding of the relationship between form and material properties, and enabling the control of processes at the nanoscale and the design materials with specific properties. However, the commercialisation of such advanced functional materials requires that they can be made in a predictable, reliable way, and in sufficient quantities. Until that is achieved production will be limited to academia and R&D departments within industry.

4.3 Fabrication techniques

4 There are a wide variety of techniques that are capable of creating nanostructures with various degrees of quality, speed and cost. These manufacturing approaches fall under two categories (first introduced in Chapter 2): 'bottom-up', and 'top-down'. In recent years the limits of each approach, in terms of feature size and quality that can be achieved, have started to converge. A diagram illustrating some of the types of materials and products that these two approaches are used for is shown below in Figure 4.1.

Figure 4.1 The use of bottom-up and top-down techniques in manufacturing

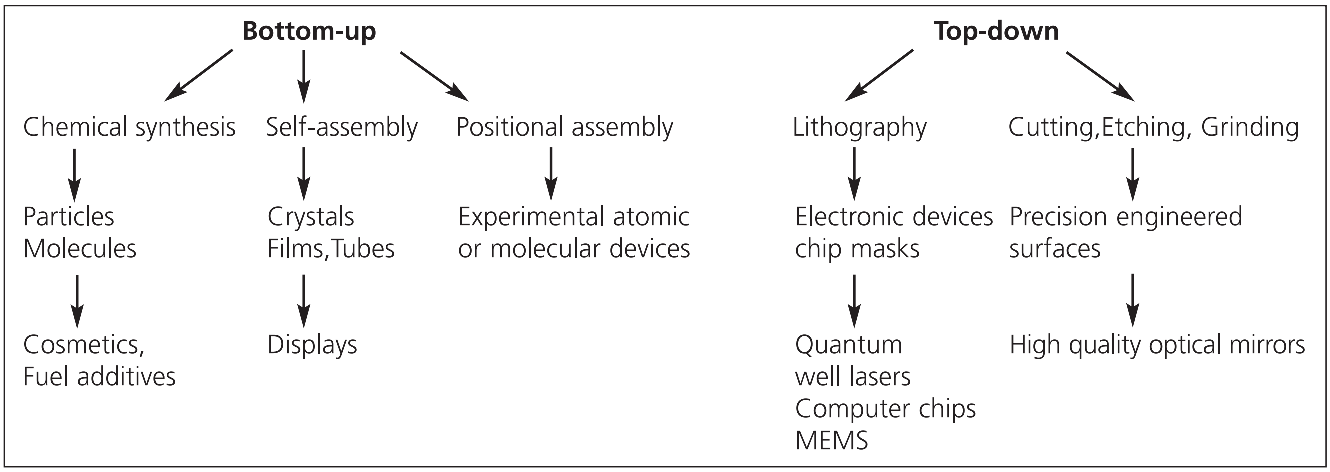
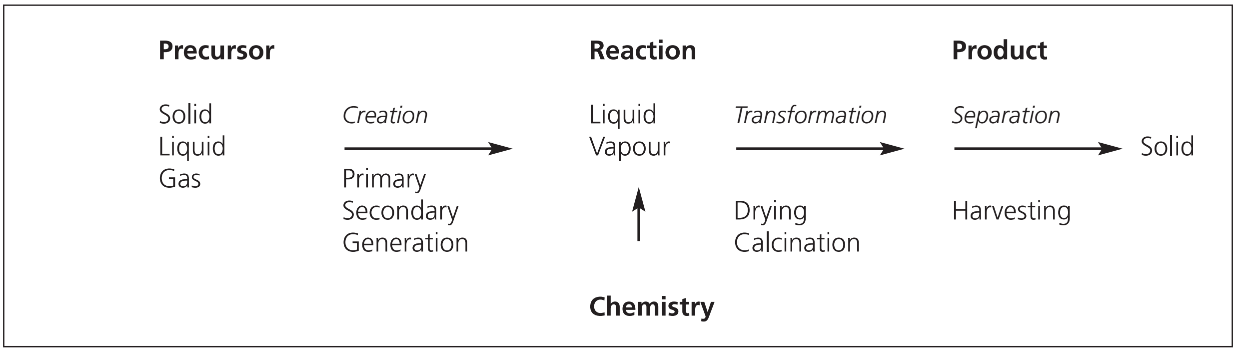


Figure 4.2 The generic processes that are involved in the production of nanoparticles



4.3.1 Bottom-up manufacturing

5 Bottom-up manufacturing involves the building of structures, atom-by-atom or molecule-by-molecule. The wide variety of approaches towards achieving this goal can be split into three categories: chemical synthesis, self-assembly, and positional assembly. As discussed below, positional assembly (with its many practical drawbacks as a manufacturing tool) is the only technique in which single atoms or molecules can be placed deliberately one-by-one. More typically, large numbers of atoms, molecules or particles are used or created by chemical synthesis, and then arranged through naturally occurring processes into a desired structure.

a) Chemical synthesis

6 Chemical synthesis is a method of producing raw materials, such as molecules or particles, which can then be used either directly in products in their bulk disordered form, or as the building blocks of more advanced ordered materials, produced using the techniques outlined in sections (b) and (c) below.

7 A generic process by which nanoparticles may be produced by chemical synthesis is shown in Figure 4.2.

8 The precursor phase is the starting point, and the material can be in any physical state (or multiphase) or spatial arrangement to other components. The first step is the creation of a new phase or state where the nanoparticles either form or can be formed by a chemical step. In other words, the phase change itself could bring about nanoparticle formation (rare but possible) although generally the circumstances are created whereby nanoparticles can be made, for example vaporisation of a precursor mixture. Once in a state where nanoparticles can be made, usually a chemical reaction of some description is performed to generate the desired material. A further phase transformation or even solid-state reaction may be necessary to produce the final product.

9 Potential exposure of the workforce to nanoparticles is likely to be greatest when these materials are processed in a gaseous environment; in such cases worker exposure will need to be monitored closely. However, nanoparticles have a tendency to agglomerate, and are therefore often manufactured from a liquid phase as this enables surface energies to be better controlled, reducing agglomeration. This also reduces the potential exposure level of workers. The expected health impacts of nanoparticles and the implications for regulation in the workplace are discussed in sections 5.3 and 8.3, respectively. Processing and handling ability is very important for nanomaterials: mixing nanoscale particles together before agglomerating and (for example) sintering can generate wholly new complex nanophase materials which could not be made by any other method. Most genuinely nanoscale and nanostructured materials, however, are still at the laboratory scale of synthesis (kilograms per day scale of operation or even less).

10 Table 4.1 gives our estimates of current and future production of nanomaterials. Metal oxides, such as titanium dioxide, zinc oxide, silicon dioxide, aluminium oxide, zirconia and iron oxide, are currently the most commercially important nanoparticles. They are available as dry powders or liquid suspensions. The quantities currently used in the skincare market sectors (titanium dioxide etc.) amount to 1,000–2,000 tonnes per annum worldwide, with the nanoscalar component materials worth approximately $10 to $100,000 per tonne. Although the world market for nanoparticles is expected to increase during the next few years, to provide perspective, it is worth noting that the global production rate of all chemicals is around 400 M tonnes per annum (European Commission 2001), and so chemicals in nanoparticulate form account for only a tiny fraction of the total (around 0.01%) currently produced. Nanoscalar inorganic, metallic or semiconductor material often will have multifunctionality, which enables it to be used across many industry sectors. Zinc oxide, for example, will have more commercial use as an optoelectronic material (for displays or advanced solar and photovoltaic cells) where it will be fixed in the final product, than as an ingredient for skincare products, where particles will be free.

Table 4.1 Estimated global production rates for various nanomaterials and devices based on international chemical journals and reviews (2003–2004), and market research (BCC 2001). These rates are intended for guidance only, as validated numbers are commercially confidential.

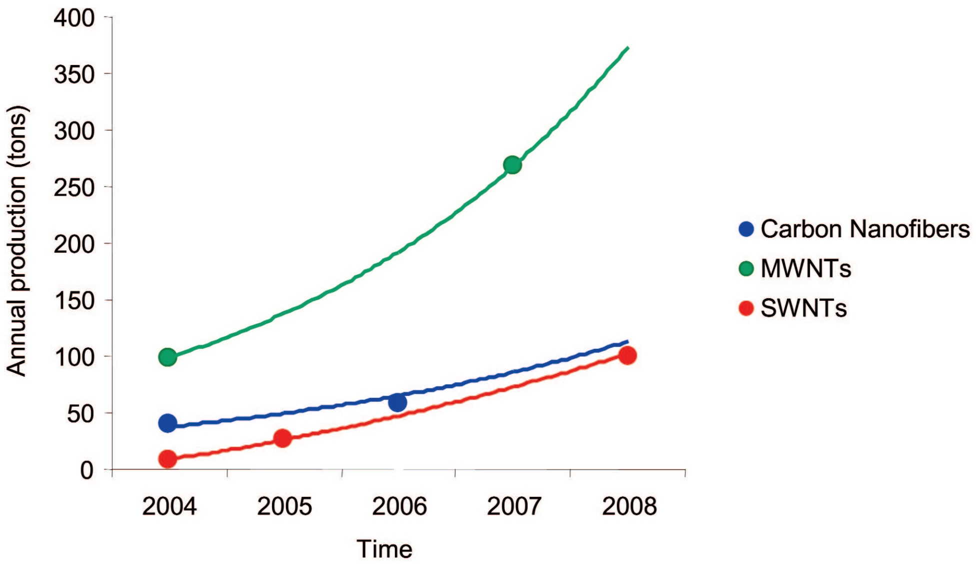
Application	**Material/device**	**Estimated production rates (tonnes/annum)**		
		Present	2005–2010	2011–2020
Structural applications	Ceramics, catalysts, composites, coatings, thin films, powders, metals	10	10^3	10^4–10^5
Skincare products	Metal oxides (titanium dioxide, zinc oxide, iron oxide)	10^3	10^3	10^3 or less
ICT	Single wall nanotubes, nano electronics, opto-electro materials (titanium dioxide, zinc oxide, iron oxide), organic light-emitting diodes (OLEDs)	10	10^2	10^3 or more
Biotechnology	Nanoencapsulates, targeted drug delivery, bio-compatible, quantum dots, composites, biosensors	less than 1	1	10
Instruments, sensors, characterisation	MEMS, NEMS, SPM, dip-pen lithography, direct write tools	10	10^2	10^2–10^3
Environmental	Nanofiltration, membranes	10	10^2	10^3–10^4

b) Self assembly

11 Self assembly is a bottom-up production technique in which atoms or molecules arrange themselves into ordered nanoscale structures by physical or chemical interactions between the units (see Chapter 2). The formation of salt crystals and snowflakes, with their intricate structure, are examples of self-assembly processes. Although self assembly has occurred in nature for thousands of years, the use of self assembly in industry is relatively new. There is an economic and environmental interest in processes through which materials or product components essentially form themselves, creating less waste and using less energy. However, current understanding extends only to the creation of fairly rudimentary systems. Improved understanding of thermodynamic and kinetic processes at the nanoscale, enabled through advances in the characterisation techniques described in section 4.2 and Box 3.1, and improved computer modelling, are expected to aid the development of more complex systems. One potential processing technique involves the use of an external force or field (for example, electric or magnetic) to accelerate the often slow self-assembly process, which is attractive in an industrial context. This is known as directed self assembly.

12 As we saw in section 3.2.3, CNTs are generating interest within industry because of their remarkable properties. Potential applications include composites, conductive plastics, sensors, batteries and fuel cells. CNTs can be grown by several techniques, such as the laser ablation of metal-doped graphite targets, carbon arc discharge, and the pyrolysis of hydrocarbons over metal catalysts. However, because of a lack of understanding of the growth mechanism, the selective and uniform production of CNTs with specific dimensions and physical properties has yet to be achieved (as, indeed, has an industrial process for separation of the spaghetti-like bundles that are

Figure 4.3 Estimated future global production of nanotubes (Cientifica 2004)



currently produced). This is an area of intense research. Current production capacity for CNTs is estimated to be around 100 tonnes per annum (Cientifica 2004); the actual production output remains commercially confidential, but is expected to be lower. Most of the capacity is estimated to be multi-walled tubes, with single-wall tubes accounting for about 9 tonnes of capacity. Estimated future global production of nanotubes is outlined in Figure 4.3.

c) Positional assembly

13 The final bottom-up technique is positional assembly, whereby atoms, molecules or clusters are deliberately manipulated and positioned one-by-one (see Chapter 2). Techniques such as SPM for work on surfaces, or optical tweezers in free space, are used for this. Positional assembly is extremely laborious and is currently not suitable as an atomic-scale industrial process. As described in Chapters 2 and 3, the utility and strength of SPM in industry lie in their ability to characterise and measure surfaces with atomic-level precision, rather than as fabrication tools.

14 The fact that (albeit very rudimentary) structures can be fabricated atom-by-atom has lead to speculation that tiny nanoscale machines could be made which could be used in parallel to manufacture materials atom-by-atom. The idea is to fabricate one or a few machines (or assemblers) that would first make copies of themselves, and then go on to make materials in parallel, in principle solving the problem of slow production speed. This speculation has led some individuals to voice fears of uncontrollable self-replication, known as 'grey goo', which are discussed in Annex D. Such concerns currently belong in the realm of science fiction. We have seen no evidence of the possibility of such nanoscale machines in the peer-reviewed literature, or interest in their development from the mainstream scientific community or industry. Indeed, the originator of concerns over grey goo, Eric Drexler, has since retracted his position (Phoenix and Drexler 2004).

4.3.2 Top-down manufacturing

15 Top-down manufacturing involves starting with a larger piece of material and etching, milling or machining a nanostructure from it by removing material (as, for example, in circuits on microchips). This can be done by using techniques such as precision engineering and lithography, and has been developed and refined by the semiconductor industry over the past 30 years. Top-down methods offer reliability and device complexity, although they are generally higher in energy usage, and produce more waste than bottom-up methods. The production of computer chips, for example, is not yet possible through bottom-up methods; however, techniques using bottom-up (or hybrid top-down/bottom-up) methods are under exploration (see sections 3.4.4 and 4.3.3).

a) Precision engineering

16 In general, ultra-precision engineering and manufacture underpin much of the micro-electronics industry in everything from the production of the flat low-damage semiconductor wafers used as substrates for computer chips, to the mechanical stages used to position the wafers, to the manufacture of the precision optics used to print the patterns on the wafers. In addition, the techniques of ultra-precision engineering are used in a variety of consumer products such as computer hard disks, CD and DVD players.

17 Ultra-precision machine tools can now achieve very high performance in terms of both the accuracy with which form can be defined (up to 1 part in 10^7, or better than 100 nm over distances of tens of centimetres) and the surface finishes that can be achieved (0.5–1 nm root mean square surface roughness), although these are currently on simple shape surfaces and with low output levels. This capability, which is bringing benefits in several areas (see (b) below), has been achieved through a combination of advances. These include: the use of advanced materials for cutting tools, based on diamond or cubic boron nitride; very stiff, precise machine tool structures; new linear and rotary bearing designs employing fluid films; and sensors for size control combined with numerical control and advanced servo-drive technologies. Very precise process and temperature control is needed to achieve this performance (the latter being of the order of ±0.01 °C).

b) Lithography

18 As discussed in section 3.4, manufacturing in the ICT sector predominantly involves lithographic processes that pattern a semiconductor wafer in a sequence of fabrication steps. Lithography involves the patterning of a surface through exposure to light, ions or electrons, and then subsequent etching and/or deposition of material on to that surface to produce the desired device. The ability to pattern features in the nanometre range is fundamental to the success of the IT industry and the ITRS roadmap. The main lithographic tools can be conveniently separated into methods that use a focused beam of electrons or ions to write patterns, and those that rely on the projection of light through a mask to define a pattern over a complete semiconductor wafer. Electron- and ion-based methods are both capable of making sub-10 nm structures (with electron beam lithography having the greatest routine resolution), but they are too slow to be used directly in production. Optical lithography is used for production of semiconductor devices. Although it does not have the resolution of the beam-based techniques, it provides rapid throughput and cost-effective manufacture. Electron beam lithography is primarily used to fabricate the masks used for optical lithography, and ion beam techniques are mostly used to repair masks and for specialist device applications.

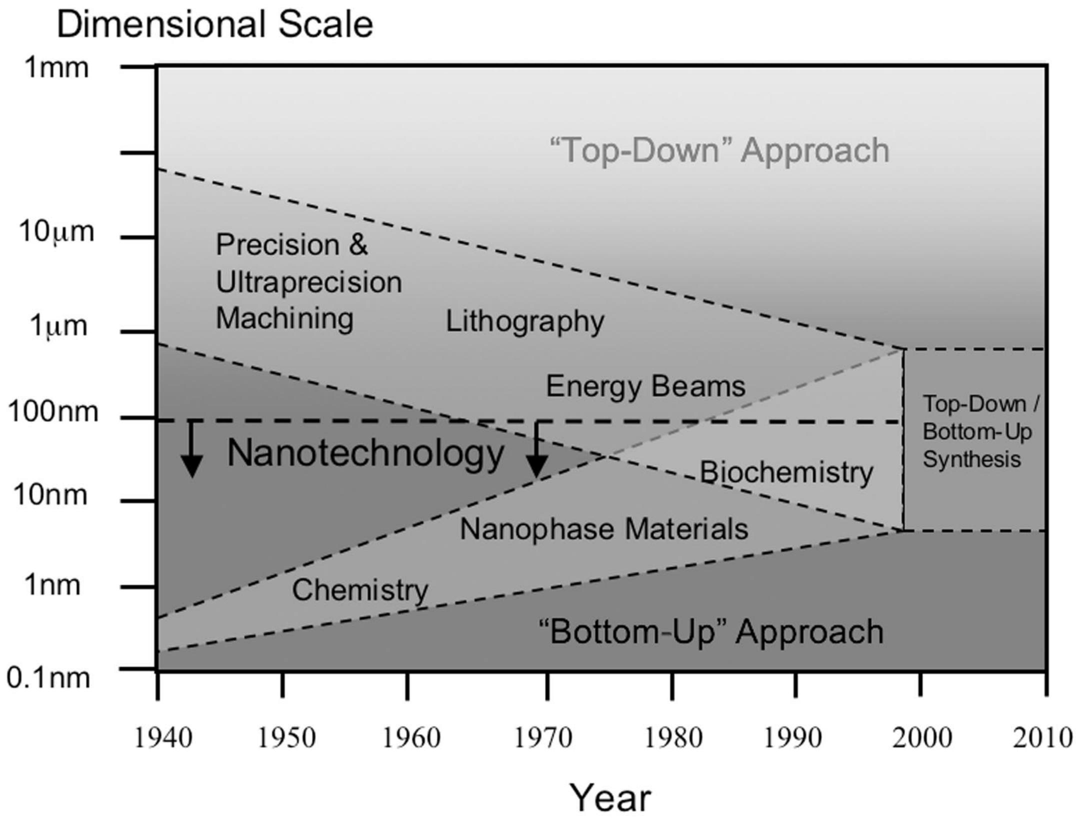
19 The requirement for ever-shrinking device structures has placed enormous technical demands on optical lithographic process, as the nanostructures have length scales similar to or less than the wavelength of the illuminating light (ultraviolet). Despite these difficulties, the ITRS roadmap implicitly expects optical lithography to keep track of future device dimensions until 2016 when the target critical device dimension reaches 22nm.

20 Techniques developed in the microelectronics industry have also enabled the miniaturisation of small mechanical moving devices (MEMS), which in turn have lead to research into NEMS. MEMS technology seeks to exploit and extend the capabilities that have been provided by silicon integrated circuit manufacturing from one of making chips for electronic signal processing to the provision of on-chip sensing and/or actuation through the use of moving mechanical parts. Some MEMS technologies are starting to attain maturity in manufacture (for example, MEMS accelerometers are used widely in air-bag sensors). However, there are currently difficulties in the reproducible large-scale manufacture of more complex MEMS systems. Although not strictly a 'nanotechnology' as defined in this report, MEMS, NEMS and the technologies used to make them are used extensively in techniques that can access and exploit the nanoscale (such as SPMs or lab-on-a-chip and biosensing). The reducing dimensional tolerances (less than 100 nm) being provided by modern lithographic patterning techniques are now enabling the production of structures of such small dimensions that they are becoming a legitimate part of nanotechnologies in their own right.

4.3.3 Convergence of top-down and bottom-up techniques

21 The relationship between top-down and bottom-up manufacturing is illustrated in Figure 4.4. The 'top-down' section is an updated version of the diagram produced by Norio Taniguchi, which showed the development in the accuracy of artefact definition from the early 20th century to 1974, extrapolated to the end of the century. The 'bottom up' section illustrates how bottom-up processes have evolved to control ever-larger structures through advances in chemical processing. Now the dimensions that can be controlled by either approach are of a similar order, and this is leading to exciting new hybrid methods of manufacture.

Figure 4.4 The convergence of top-down and bottom-up production techniques (Whatmore 2001)



4.4 Visions for the future

4.4.1 Precision Engineering

22 There are strong drivers to reduce tolerances in engineering, including miniaturisation, improved wear and reliability characteristics, automated assembly and greater interchangeability, reduced waste and requirement for re-work. As the trend towards miniaturisation continues, research and the industrial application of energy beam processing methods will increase, driven in particular by the electronics and computer industries. Techniques such as electron beam lithography (EBL), focused ion beam (FIB), reactive ion etching (RIE) and femtosecond pulsed laser ablation are becoming more accurate and cheaper to apply in a production context. Some examples of future applications of high-precision engineering are given below.

- ICT: the machines used to fabricate chips depend fundamentally upon the use of ultra-high precision techniques for their manufacture and nanometrology techniques for their operation. The manufacture of larger-diameter semiconductor wafers with improved flatness and reduced sub-surface damage should lead to improved device yields and reduced costs.

- Optics: innovative ductile-mode grinding processes, together with electrolytic in-process dressing (ELID), should result in the elimination of polishing in the production of high-quality optical devices. This is likely to be of particular importance in the production of the optics for extra-large astronomical telescopes such as the proposed 50 m and 100 m systems (Euro50 and OWL), which will consist of many individually figured segments (Shore et al 2003).

- Transport: precision-machined parts should be more reliable, because of reduced wear, requiring fewer replacement parts and less energy consumption. For example, the ability to produce surfaces with controlled textures through finishing to 10 nm average roughness followed by laser surface treatment is expected to lead to improved power transmission trains with losses through slip reduced by up to 50%. Precision manufacturing is predicted to lead to weight reductions in airframe wings and to improve the performance of internal combustion chambers.

- Medical: it is hoped that the use of ultra-precision machining techniques to produce improved surface finishes on prosthetic implants should lead to lower wear and better reliability.

23 It is hoped that advances in precision engineering will enable the reduction of environmental impacts by, for example, reducing the use of lubricants. However, for any particular product, the whole life cycle needs to be taken into account before it can be established

whether there is a net environmental benefit. This is discussed further in section 4.5.

4.4.2 The chemicals industry

24 The long-term goal within the chemicals industry is to use nanoscale 'building blocks' to assemble organised nanostructures, that can in turn be manufactured into commercially useful products. From an understanding of the chemistry and physics of nanoscale materials, and top-down/bottom-up modelling and measurement, industry will concentrate on processes that use manufacturing at the nanoscale in a way that preserves the desired effect and function as nanoscale components are combined into macroscale materials and products. This will involve the development of technologies based on self-assembling materials, or more probably on directed-assembly methods, which allow for some form of massively parallel production, along with modelling and measuring tools. The vision is the manufacture of reproducible, accurate and designable nanomaterials.

25 The time-scale for the commercial exploitation of these types of highly organised structures or quantum materials is approximately 2020 and beyond, for use in the biotechnology and IT sectors. These materials will be extremely valuable, in excess of $1,000,000 per tonne, with the production rates of the order of 10–10,000 tonnes a year. The price is expected to remain relatively high because, though the effect of the nanomaterial will be to add value to consumer products, it will only form a tiny fraction of the final product as sold.

26 The desired functionality is created through exploiting structure – property relationships. Measurement, modelling and simulation are essential for the characterisation and subsequent control of property and functional performance and therefore the production of desirable materials. The development of measurement tools for use at the nanoscale will move from laboratory-based characterisation to in-line and on-line methods of monitoring and controlling accuracy at the 6-sigma level (99.9997% accurate) in terms of reproducible structure, texture and surface properties. The use of computer simulation based on advanced structure – property – process predictor codes will become the key technology for manufacture-by-design, where the characteristics of the material are effectively 'dialled up' through morphology, texture, structure and reactivity based on the interaction of materials across molecular- and nano-length scales. The structure or form of the material then dictates the processing options for economic, reliable and reproducible operation. The combination of measurement, modelling and manufacturing technologies will be the basis for intelligent material systems. It is also hoped that it will be possible to produce materials with less waste.

27 The synthesis and control of micro- and nano-scale structures may yield unprecedented control of meso- and macro-scale properties in functional materials for use in applications of direct relevance to industry. It has been predicted (Chemical Industry 2003) that over the course of the century, many of the needs of commerce and society may be satisfied through a materials revolution involving synthesis and smart fabrication. Because of some of the barriers outlined in section 4.6 it is difficult to predict when these developments might occur, but we provide some estimated timeframes in Box 4.1.

Box 4.1 Estimated timeframes for developments in nanomanufacturing

Short term (next 5 years): opportunities will arrive through the exploitation of equipment capable of imaging, analysing and fabricating simple materials and devices at the nanoscale.

Medium term (5–15 years): nanoscience and technology will give rise to nanomanufacture-by-design, using self-assembly and directed assembly methodologies to create a sustainable knowledge-based industry capable of addressing simple bio–info–nano material needs.

Longer term: it is hoped that the idea of nanomanufacturing will encompass genuine 'green' concepts of zero waste and little or no solvent use incorporating life cycle (sometimes referred to as 'cradle to grave') concepts of responsible products coupling biology with inorganic materials.

4.4.3 The information and communication technology industry

28 Although the future of device fabrication is still centred around the lithographic processes described in section 4.3.2, there are other techniques that are increasingly being applied both to on-roadmap developments and to alternative approaches to device materials. Soft lithography techniques where a flexible master is used to stamp out patterns on a range of surfaces have been available for several years. The accuracy demands imposed by the silicon-based industry have, until now, prohibited the use of soft lithographies as the elastic nature of the stamp can cause small, but still unacceptable, physical distortions across a wafer surface. However, for small-area device fabrication and for applications where spatial tolerances are less restrictive, they offer a real alternative to conventional methods, although the fabrication of the master still requires optical or electron beam methods. Soft lithographies can be used for plastic electronics, as can alternative ink-jet based methods which use essentially the same technology as desk-top printers. Although plastic electronics are not truly in the nano-range in terms of critical dimensions, a relatively simple

manufacturing technique that can deal with wet chemistries will enable cheap electronic and photonic devices. Such developments, combined with advances in directed self-assembly, may bring the semiconductor, materials and chemical industries closer together, in order to create novel alternative methods for chip production as the end of the roadmap approaches.

4.5 Resource management and environmental issues

29 It has been claimed that several nanotechnology-based applications and processes will bring environmental benefits, for example through fewer resources required in manufacture or improved energy efficiency in use. It is important to substantiate such claims by checking that there are indeed net benefits over the life of the material or product.

30 The potential benefits of nanotechnologies should be assessed in terms of life cycle assessment (LCA) (sometimes referred to as 'cradle-to-grave' analysis). LCA is the systematic analysis of the resource usages (for example, energy, water, raw materials) and emissions over the complete supply chain from the 'cradle' of primary resources to the 'grave' of recycling or disposal. For example, one of the areas of application foreseen for nanomaterials is in photovoltaic (PV) energy converters in order to increase efficiency. An LCA would investigate the extent to which the additional energy yield over the service life of a PV device would be offset by any additional energy used in manufacturing the device and in recovering or disposing of its material content at the end of its life.

31 To illustrate the importance and associated complexity of such analyses, an example can be taken from the possible use of nanotechnologies in the transport sector. As we have seen in section 3.2.3b, reducing the weight of aircraft is a foreseeable application, for example through use of CNT composites and thinner (that is, lighter) paints and coatings. Available LCA studies on aircraft show that the resource use and environmental impacts of aircraft in flight currently outweigh those from aircraft construction by several orders of magnitude (Energy Technology Support Group 1992). The first assumption has therefore been that technological developments towards 'lightweighting' are always beneficial. This assumption would need to be tested for nanoengineered materials where end-of-life disposal may have an adverse environmental impact. Also, the basis on which reducing aircraft weight is assessed needs to be defined carefully to avoid reaching simplistically optimistic conclusions. In practice, it is likely that reductions in aircraft weight will be exploited by increasing payload, i.e. carrying more passengers, which if the market were fixed would bring environmental benefits due to fewer flights. However, if this is used to decrease ticket costs, it could stimulate additional passenger movements, albeit using less fuel per passenger–kilometre flown. The true trade-off to be considered is between the benefits of additional passenger movements rather than the environmental performance of the aircraft and the impacts of producing nano-engineered materials. Thus the superficially simple environmental assessment ends up involving social and ethical issues.

32 LCA is now a standardised and accepted tool, covered by a set of international standards (ISO 14040–14044) and is the basis of much European environmental policy including the End-of-Life Directives (see section 8.3.5). We are aware of only one study (in progress at Carnegie Mellon University, USA, funded by the US Environmental Protection Agency) applying LCA approaches to nanotechnology-enabled products and processes, and we welcome the inclusion of LCA in a recent Communication from the EC (European Commission 2004a). **We recommend that a series of life cycle assessments be undertaken for the applications and product groups arising from existing and expected developments in nanotechnologies, to ensure that savings in resource consumption during the use of the product are not offset by increased consumption during manufacture and disposal. To have public credibility these studies need to be carried out or reviewed by an independent body.**

33 **Where there is a requirement for research to establish methodologies for life cycle assessments in this area, we recommend that this should be funded by the research councils through the normal responsive mode.**

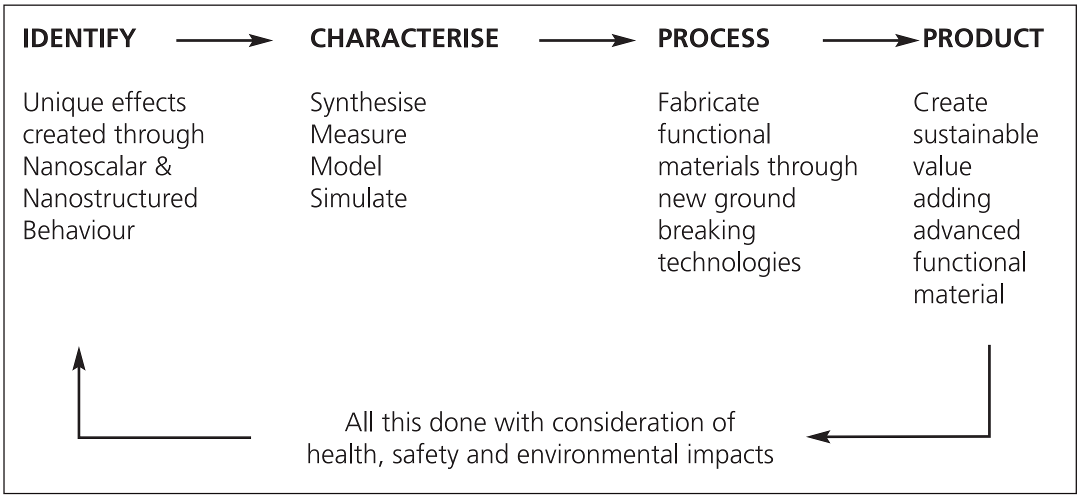
4.6 Barriers to progress

34 There are several factors that will influence whether nanotechnologies will be used routinely within industrial processes. Some of these are economic or social, others are technical.

35 Any new process or technology must be able to exceed (in terms of economic value) what is already in place, and it must be of value (or perceived value) to the consumer, to be adopted by industry. As we have heard in evidence from Don Eigler and others, the technology used in current industrial processes is already generally very advanced, and so nanotechnologies will only be used where the benefits are high. This economic reality may well act to moderate their rate of introduction.

36 The technical barriers should not be underestimated: as well as the difficulty in scaling a process up from the laboratory to an industrial operation, more fundamental barriers stem from a lack of understanding of nanoscale properties and the techniques to characterise and engineer them to form useful materials and products. Figure 4.5 summarises the

Figure 4.5 The generic steps that are undertaken to manufacture nanomaterials, from identification of properties through to production



generic technical steps that needed to be undertaken to produce a material with designed functionality.

37 The current technical barriers to achieving the steps outlined in Figure 4.5 are as follows:

- Inadequate characterisation and measurement tools and capabilities to enable on-line and in-line monitoring and processing control based on nanoscalar features.

- Insufficient understanding to enable the design and production of desired material properties through the development of multi-phase, multiple length-scale mathematical models that are capable of linking effectively across structure–property–processing boundaries. This is crucial if we are to preserve functionality from the nanoscalar synthesis through to the creation of macroscopic functional materials.

- Insufficient knowledge to synthesize complex heterogeneous nanostructured large-scale, self-assembled monolayers (SAMs) and directed assembly of monolayers (DAMs). Of great practical interest are DAMs whereby scale-out (reliable replication of a process) will be key to the development of continuous nanomanufacturing processes (NSF 2001; DTI 2002).

38 Alongside purely technical barriers to progress are those relating to regulation such as classification and standardisation of nanomaterials and processes, and the management of any health, safety and environmental risks that may emerge. Appropriate regulation and guidance informed by scientific evidence will help to overcome some of these barriers, and there are already discussions between industry and regulators on the above issues. Until these regulatory measures are in place, industry will be vulnerable to reduced consumer confidence, uncertainty over appropriate insurance cover (Swiss Re 2004) and litigation should some nanomaterials prove to be harmful. These issues will be of particular importance to the smaller, more innovative companies. Health, safety and environmental impacts of some nanomaterials are discussed in Chapter 5 and regulatory issues are discussed further in Chapter 8.

39 Naturally, the development and exploitation of new technologies or techniques cannot proceed without a sufficiently trained workforce. This point has been made strongly for the UK in the Taylor report (DTI 2002), by the EC in its recent communication on nanotechnology, and by the House of Commons Science and Technology Committee report on UK Government investment in nanotechnology (House of Commons Science and Technology Committee 2004a). However, it is not part of the remit of our study.

4.7 Summary

40 In their widest sense, nanotechnologies have been used by industries for decades (semiconductors), and in some cases considerably longer (chemicals). However, developments over the past 20 years in the tools used to characterise materials have led to an increased understanding of the behaviour and properties of matter at very small size scales. Increased knowledge of the relationship between the structure and properties of nanomaterials has enabled the production of materials and devices with higher performance and increased functionality. This progress has taken place steadily over several years; so, at least so far, the influence of nanotechnologies on industry can be described as evolutionary rather than revolutionary. This is also evident in the current production rates of nanoparticles and nanomaterials which, although increasing, are negligible compared with bulk chemicals and materials.

41 True nanomanufacturing is therefore very much in its infancy; however, there are strong economic, societal

and environmental reasons why its development is currently the focus of so much attention. At the same time, there are uncertainties about the direction the technology may take and about the hazards to humans or the environment presented by certain aspects of nanotechnologies. The health, environmental and safety aspects of nanoparticles and nanotubes are discussed in Chapter 5.