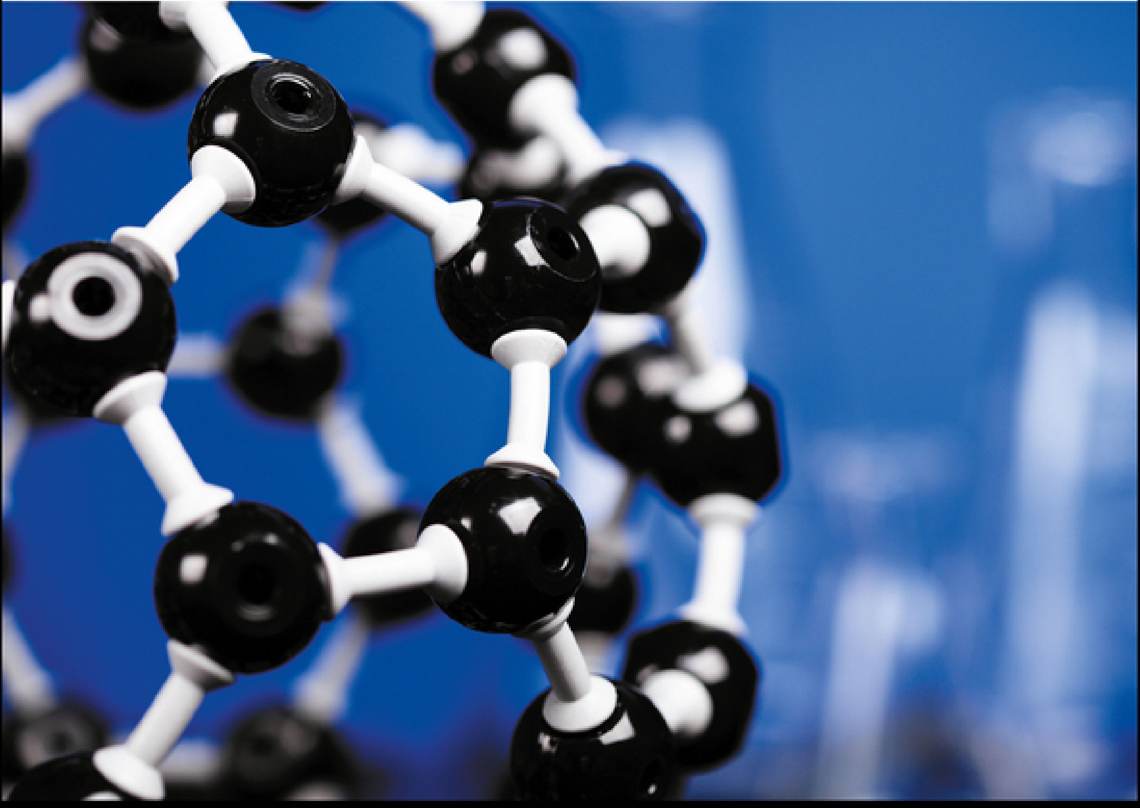
NANOTECHNOLOGY COMMERCIALIZATION

MANUFACTURING PROCESSES AND PRODUCTS

THOMAS O. MENSAH, BEN WANG, GEOFFREY BOTHUN, JESSICA WINTER, VIRGINIA DAVIS



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Nanotechnology Commercialization

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Manufacturing Processes and Products

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Preface

The Frontiers of Nanotechnology Book Series has the objective of advancing techniques for scale-up and transition of nanotechnology processes to industry. This book provides insight into the current status of advanced nanotechnology processes and their scale-up to semi-industrial and full-scale industrial levels, while addressing key scale-up challenges.

The impact such understanding has on full-scale nanotechnology manufacturing on business and marketing strategy, including expansion and execution, is necessary after years of major investments in the technology worldwide.

This book has the objective of also providing relevant technical and engineering framework and the latest innovative work in the area of nanotechnology manufacturing and scale-up. Chemical engineering and industrial engineer methods were adopted in addressing the manufacturing challenges.

In this first volume of the Frontiers of Nanotechnology Series, authors from leading US agencies, including Department of Defense, the National Science Foundation, National Laboratories, private companies, and leading US universities as well as international experts, have examined challenges in transitioning this technology from research to large-scale manufacturing environment. I want to express my gratitude to all of the authors for tackling such an important but complex engineering subject.

Researchers from US Army ARDEC Huntsville, national agencies, and leading universities and engineering departments, such as Georgia Institute of Technology, University of Texas, Austin, Purdue University, Auburn University, University of Rhode Island, University of West Virginia, Ohio State University, Florida State University, as well as the South China University and others have contributed significantly to this book.

In this first book of the Frontiers Series, authors have focused on the chemical engineering aspects of nanotechnology scale-up such as the chemistry and nanocatalyst applications in commercial processes, mixing and integration into solutions, analyzing interfacial aspects of nanotube dispersion, a critical step in nanomanufacturing, and an important challenge in scale-up. Statistical analysis for controlling continuous processing and predicting nanomaterials performance of sheets of nanostructures, fundamentals of nanomanufacturing using spray techniques are also covered.

Also presented in this book are high-temperature ablative materials for rocket motors and reentry vehicles for space applications, including finite element modeling of transport phenomena in ablative materials performance, advanced missile shell structures and nanocomposites incorporating nanosensors for advanced military applications, and vacuum-assisted resin transfer molding processing of nanocomposites including finite element analysis of processes. Also examined is the use of mechanical properties of fabricated composites as a method of evaluating process control and product performance. The authors have also explored applications of bioinspired approaches for fabricating nanocircuits, and finally toxicity, environmental, and safety issues regarding nanomaterials processing are presented in the last two chapters.

Environmental, safety, and toxicity of carbon nanotubes is important in the commercialization process since workers can be exposed to these nanoparticles, with serious health implications and adverse economic impact on the profitability of nanomanufacturing companies. EHS (Environmental Health and Safety) area must be addressed through engineering methods for this industry to thrive and be sustainable.

I want to thank all my coeditors, professors Ben Wang, Georgia Tech Manufacturing Institute; Jessica Winters, Ohio State University; Virginia Davis, Auburn University; and Geoffrey Bothun, University of Rhode Island, for assisting me as chapter contributors and reviewers of the technical manuscripts for this important book.

I want to express my special gratitude to Mike Roco at the National Science Foundation, a champion of the National Nanotechnology Initiative, NNI, in the United States for authoring the overview chapter for the book and giving me insights into critical gaps that exist in the commercialization of nanotechnology.

There is a paradigm shift in engineering design of processes as demonstrated by the US National Materials Genome project and key parts of this approach were employed in some of the work presented in this book, and it is our hope that this approach will continue to guide all future research into the scale-up of nanotechnology.

Thomas O. Mensah

Editor in Chief

Dr Thomas Mensah is a fellow of the National Academy of Inventors (NAI), fellow of the American Institute of Chemical Engineers (AIChE), and associate fellow of the American Institute of Aeronautics and Astronautics (AIAA). He holds seven US patents in fiber optics awarded in a 6-year time frame.

He worked at AT&T Bell Laboratories and Corning Glass Works and was one of the key innovators and inventors of large-scale processes that moved fiber optics from the research laboratories to manufacturing and commercial environments in the United States. He is currently the president of Georgia Aerospace Systems and served as a coprincipal investigator on the Carbon Nanotube Weapons Platform Development for the US Department of Defense. He also served as the director at large of the Nanoscale Engineering Forum at AIChE. This forum continues to organize feature conferences and technical sessions and symposium in nanotechnology at AIChE Annual Meetings around the country.

1

Overview: Affirmation of Nanotechnology between 2000 and 2030

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1.1 Introduction

In the nanoscale domain, nature transitions from the fixed physical behavior of a finite number of atoms to an almost infinite range of physical–chemical–biological behaviors of collections of atoms and molecules. The fundamental properties and functions of all natural and man-made materials are defined and can be modified efficiently at that scale. The unifying definition of nanotechnology, based on specific behavior at the nanoscale and the long-term nanotechnology research and education vision, was formulated in 1997–1999, and its implementation begun with National Nanotechnology Initiative (NNI) in 2000. We have estimated that it would take about three decades to advance from a scientific curiosity in 2000 to a science-based general purpose technology with broad societal benefits toward 2030 [1–3] (see www.wtec.org/nano2/).

A long-term strategic view is needed because nanotechnology is a foundational general purpose field. *Three development stages* of nanotechnology, corresponding to the level of complexity of typical outcomes, have been envisioned: passive and active nanostructures in the first stage of development (*Nano 1*), nanosystems and molecular nanosystems in the second stage (*Nano 2*), and converging technology platforms and distributed interconnected nanosystems in the last stage (*Nano 3*).

We use the *definition of nanotechnology* as set out in *Nanotechnology Research Directions* [2]. Nanotechnology is the ability to control and restructure matter at the atomic and molecular levels in the range of approximately 1–100 nm, and exploiting the distinct properties and phenomena at that scale as compared to those associated with single atoms or bulk behavior. The aim is to create materials, devices, and systems with fundamentally new properties

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and functions for novel applications by engineering their small structure. This is the ultimate frontier to economically change materials and systems properties, and the most efficient length scale for manufacturing and molecular medicine. The same principles and tools are applicable to different areas of relevance and may help establish a unifying platform for science, engineering, and technology at the nanoscale. The transition from the behavior of single atoms or molecules to collective behavior of atomic and molecular assemblies is encountered in nature, and nanotechnology exploits this natural threshold.

This chapter describes the timeline and affirmation of nanotechnology, its three stages, key challenges, and discusses nanotechnology return on investment.

1.2 Nanotechnology – A Foundational Megatrend in Science and Engineering

Nanotechnology is a foundational, general purpose technology for all sectors of the economy dealing with matter and biosystems, as information technology is a general purpose technology for communication and computation. Biotechnology and cognitive technologies are two other foundational technologies growing at the beginning of the twenty-first century (Figure 1.1). Table 1.1

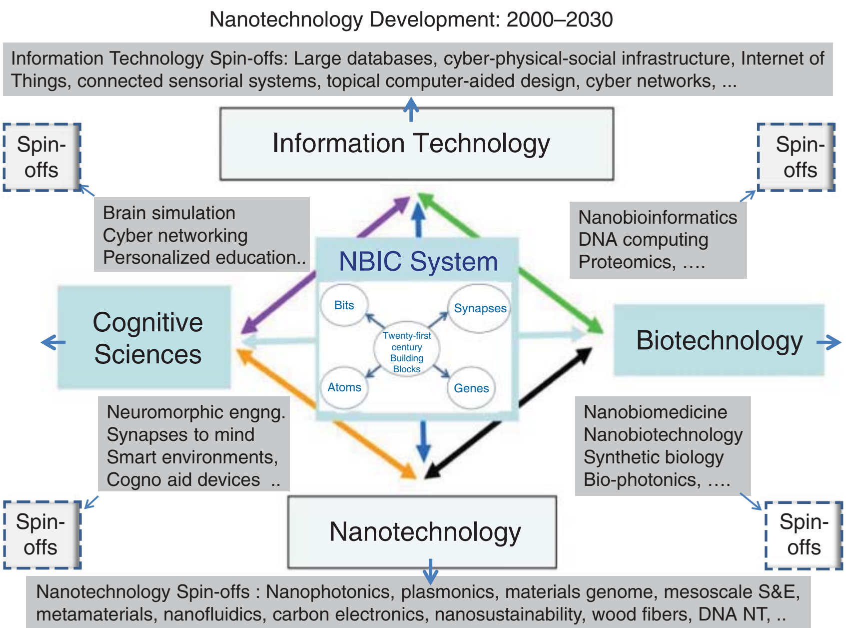

Figure 1.1 Converging foundational technologies, and their interdisciplinary and spin-offs subfields. Modified from Roco and Bainbridge [4].

Table 1.1 Proposed classification of science and technology platforms.

Category	**I. *Foundational* S&T platform (system architecture)**	**II. *Topical* S&T platform (hierarchical system from I)**	**III. *Application field* platform (branched, inter- and recombination)**	**IV. *Product and service* platform (spin-off, inter- and recombination)**
S&T Platforms	• **Nanotechnology**: (atom architecture) • **Information S&T** (bit architecture) • **Modern bio S&T** (gene architecture) • **Cognitive S&T** (synapsis architecture) • **Artificial Intelligence S&T** (system design)	***Essential:*** Photonics Semiconductors Genomics Biomedicine ***Contributing:*** Synthetic biology Neuromorphic eng Proteomics Nanofluidics Metamaterials	Cell phone system Transportation Medicine Energy conversion and storage Agriculture Space exploration	Car components Medical devices Nano coatings LEDs Nano lasers ....
Typical timescales	25–50 years	10–25 years	5–10 years	3–5 years
One-step investment amplification factor	$k_{f\text{(undamental)}}$	$k_{t\text{(opical)}}$	$k_{a\text{(pplication)}}$	$k_{p\text{(product and service)}}$
Cumulative investment amplification factor	$k_f\, k_t\, k_a\, k_p$	$k_t\, k_a\, k_p$	$k_a\, k_p$	k_p
Game changer for:	Knowledge	Technology approach	Application field	User consumption

shows several category levels of science and technology (S&T) platforms according to their level of generality and societal impact: foundational S&T, topical S&T, application domain, and product/service platform. While there are only five foundational S&T platforms most dynamic at this moment (Figure 1.1), the number of topical S&T platforms increases with the number of spin-offs, interplatform and further recombination growth. Each topical S&T platform has several application domains, which at their turn each have a series of products and related services. The importance of foundational platforms – and in particular its most exploratory component part at this moment, nanotechnology – is underlined by the cumulative investment amplification factor by developing the respective S&T platform that is a product of the foundational platform investment amplification factor, with the topical, application area and product amplification factors.

Nanotechnology continues exponential growth by vertical science-to-technology transition, horizontal expansion to areas as agriculture/textiles/cement, and spin-off areas (~20) as spintronics/metamaterials/…, progressively penetrating in key economic sectors. The number of World of Science publications on nano-extended 20 new terms between 1990 and 2014 that now represent over ¼ of the total publications (Figure 1.2). For this reason, it is increasingly difficult to identify the R&D programs around the word supporting nanotechnology because they are called after an activity that

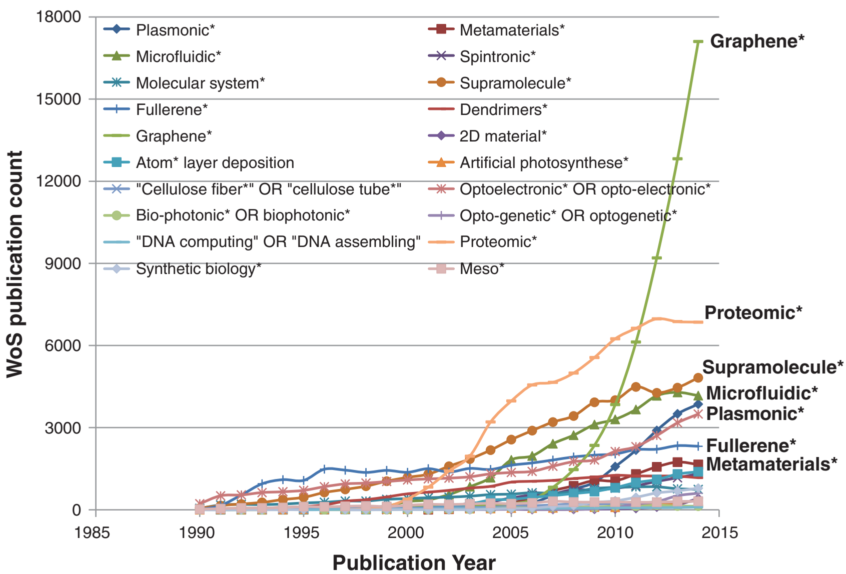

Figure 1.2 The number of World of Science (WoS) publications on nano-extended 20 new terms between 1990 and 2014.

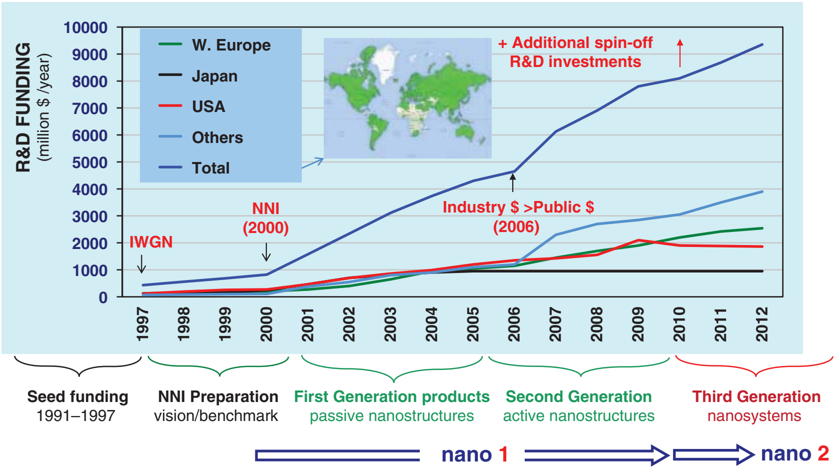

Figure 1.3 International government R&D funding the interval 2000–2012, after 2013 – increase use of new terms and platforms (using NNI definition, 81 countries, MCR direct contacts).

branched out of the foundational field. Figure 1.3 illustrates international government R&D funding the interval 2000–2012 [9].

Most of the larger science and technology initiatives have been justified in the United States and abroad mainly by application-related and societal factors. For example, the Manhattan Project during World War II (with centralized, goal-focused, and simultaneous approaches), the Apollo Space Project (with a centralized, focused goal), and Networking and Information Technology Research and Development (top-down initiated and managed, and established when mass applications justified the return of investment). The initiation of the NNI was motivated primarily by its long-term science and engineering goals and general purpose technology opportunity, and has been managed using a bottom-up approach combined with centralized coordination. A few comments underlying this characteristic are as follows:

> Charles Vest, President National Academy of Engineering (PCAST meeting, White House, 2005): “*NNI is a new way to run an initiative*”

> Steve Edwards, “Hall of Fame for Nanoscale Science and Engineering” (Jan. 1, 2006): “*…persuading the U.S. government, not to mention the rest of the world, to support nanotechnology. It was a masterful job of engineering the future*”

> Tim [5], President of the European Nanobusiness Association, and Cientifica Co. (2015): “*nanotechnology [is] the first truly global scientific revolution.*”

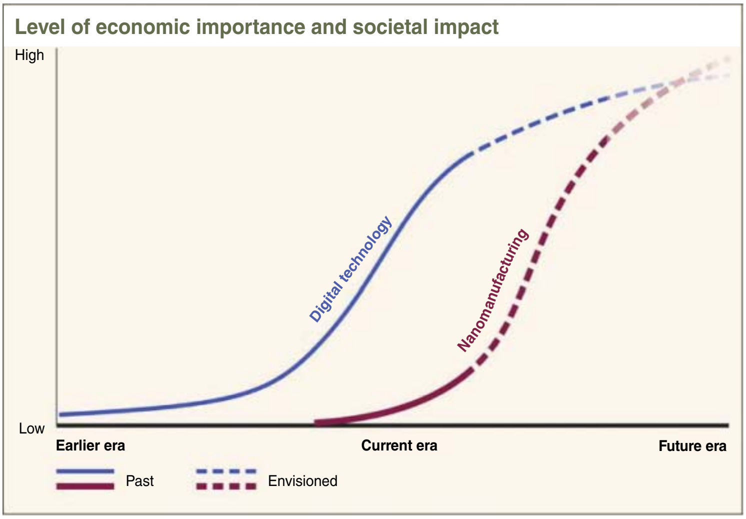

Figure 1.4 S-curves for two science and technology megatrends: past and envisioned conceptualization of "Nanomanufacturing" and "Digital Technology" [6].

Nanotechnology promises to become a general purpose technology with large-scale applications similar to digital technology. It could eventually match or outstrip the digital revolution in terms of economic importance and societal impact once the methods of investigation and manufacturing are developed and the underlying education and infrastructure are established. During about 2020–2030, nanotechnology could equal and even exceed the digital revolution in terms of technology breakthroughs, investments, and societal importance (Figure 1.4) [6].

The nanotechnology development S-curve shown in Figure 1.4 is supported by the data in Table 1.2 showing an increase of the world annual rate of revenues growth from 25% in 2000–2010 to 44% in 2010–2013.

Examples of S&E generic platforms with areas of high impact

Nanotechnology-enabled products by sectors with the most traded nano-products in 2014 according to Lux Research [7] and other industry sources:

- Materials and manufacturing: Fiber-reinforced plastics, nanoparticle catalysts, coatings, insulation, filtration, transportation (cars, trucks, trains, planes, and ships), and robotics (actuators and sensors). For example, Exxon-Mobil has multibillion dollar applications on nanostructured catalysts. TiO_2, MWCNTs, and quantum dots are some of the most frequently encountered nanocomponents. Nanoscale coatings, imprinting, and roll-to-roll are three most common manufacturing processes.