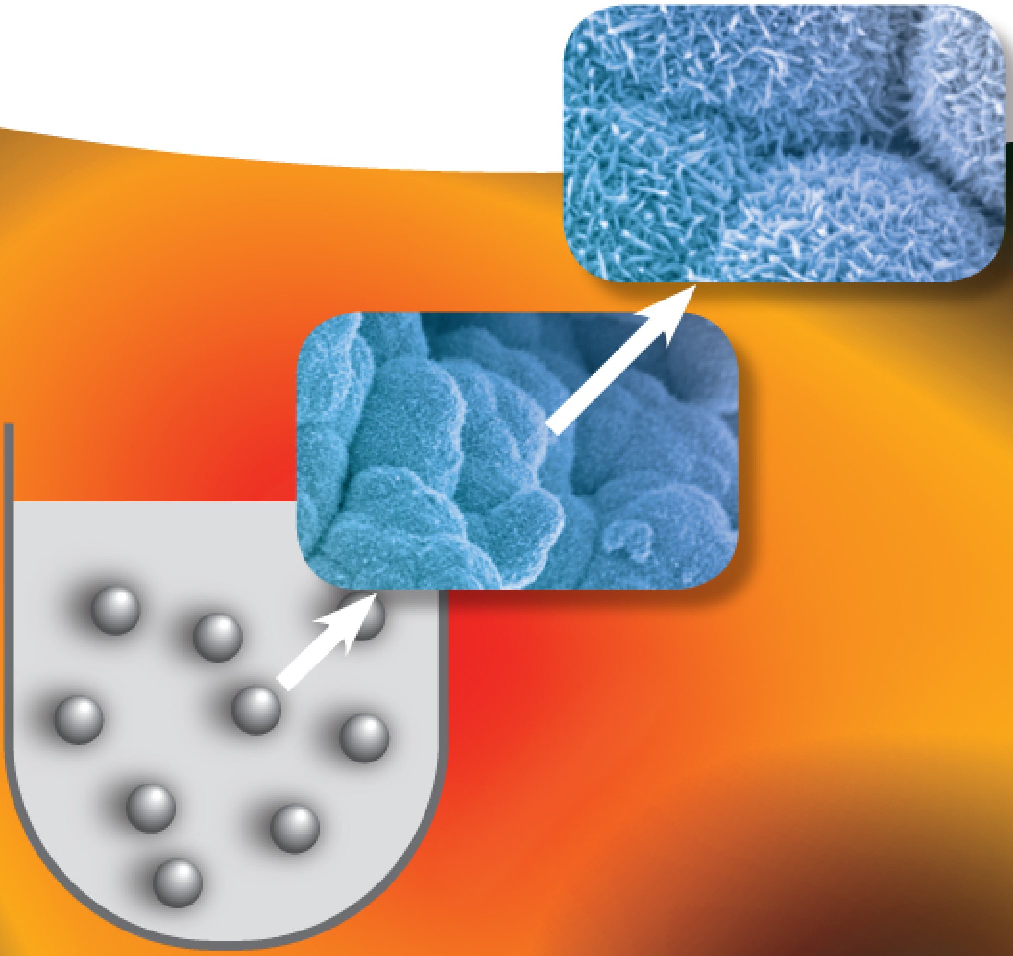
WILEY-VCH

Edited by
Satoshi Horikoshi and Nick Serpone

Microwaves in Nanoparticle Synthesis

Fundamentals and Applications



Edited by
Satoshi Horikoshi and
Nick Serpone

Microwaves in Nanoparticle Synthesis

Related Titles

Loupy, A., de la Hoz, A. (eds.)

Microwaves in Organic Synthesis

Third, Completely Revised and Enlarged Edition

2013
ISBN: 978-3-527-33116-1

Quinten, M.

Optical Properties of Nanoparticle Systems

Mie and Beyond

2011
ISBN: 978-3-527-41043-9

Gruttadauria, M., Giacalone, F. (eds.)

Catalytic Methods in Asymmetric Synthesis

Advanced Materials, Techniques, and Applications

2011
ISBN: 978-0-470-64136-1

Gubin, S. P. (ed.)

Magnetic Nanoparticles

2009
ISBN: 978-3-527-40790-3

Amabilino, D. B. (ed.)

Chirality at the Nanoscale

Nanoparticles, Surfaces, Materials and more

2009
ISBN: 978-3-527-32013-4

Edited by Satoshi Horikoshi and Nick Serpone

Microwaves in Nanoparticle Synthesis

Fundamentals and Applications

WILEY-
VCH

WILEY-VCH Verlag GmbH & Co. KGaA

The Editors

Prof. Satoshi Horikoshi
Sophia University
Dep. of Materials and
Life Sciences
7-1 Kioicho, Chiyodaku
Tokyo 102-8554
Japan

Prof. Nick Serpone
Visiting Professor
Universita di Pavia
Dipartimento di Chimica
Gruppo Fotochimico
Via Taramelli 10
Pavia 27100
Italy

The cover picture shows Scanning Electron Micrographs of γ-MnO2 synthesized for 2 h, in lower and higher magnification. Taken from Chapter 10 of this book, Figure 18, with permission.

Library of Congress Card No.: applied for

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library.

Bibliographic information published by the Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available on the Internet at <http://dnb.d-nb.de>.

Print ISBN: 978-3-527-33197-0
ePDF ISBN: 978-3-527-64815-3
ePub ISBN: 978-3-527-64814-6
mobi ISBN: 978-3-527-64813-9
oBook ISBN: 978-3-527-64812-2

Cover Design Simone Benjamin, McLeese Lake, Canada

Typesetting Toppan Best-set Premedia Limited, Hong Kong

Printing and Binding Markono Print Media Pte Ltd, Singapore

Printed on acid-free paper

Contents

Preface

The special optical characteristics imparted by metallic nanoparticles have been used in producing colored glass ever since the 4th century AD, even though the craftsmen were unable to see the nanoparticles and thus explain the true character of metallic colloids. The first scientific evaluation of a colloid (gold) was done by Michael Faraday in 1857; he remarked that colloidal gold sols have properties different from bulk gold (Chapter 1, Table 1.2). The history of nanomaterials dates back to 1959, when Richard P. Feynman, a physicist at Cal Tech, forecasted the advent of nanomaterials. In one of his classes he stated that “there is plenty of room at the bottom” and suggested that scaling down to the nano-level and starting from the bottom-up was the key to future technologies and advances. The remarkable progress in characterizing nanoparticles and unravelling novel physical and chemical properties of nanoparticles has opened the possibility of new materials. Simple preparation methods using various techniques to produce high-quality nanoparticles are now available (Chapter 1, Figure 1.4), one of which is the use of microwave heating that has attracted considerable attention worldwide. Several books have been written mostly on microwave-assisted organic syntheses in the past decade, yet none have dealt specifically with microwaves and inorganic materials except perhaps in the use of microwave radiation in the sintering of ceramics. The latter notwithstanding, research in nanoparticle syntheses with microwaves has seen a remarkable growth in the last several years.

The main purpose of this book is to give an overview of nanoparticle synthesis using the microwave method, with the first chapter providing an introduction to nanoparticles followed by two other chapters that explain some of the fundamentals of microwave heating (Chapters 2 and 3). In the remaining chapters several specialists in the field describe some of the specifics and variations in nanoparticle synthesis. As the data available in the literature were enormous, we had to make the difficult choice of including only the most relevant and up-to-date literature; we apologize to the reader if we missed to include other worthwhile contributions. Prominent in the book are abundant chemical information and some beautiful TEM data that define the structural features of nanoparticles. We are thankful to all the contributors who have answered the call, and also to the Wiley-VCH editorial staff for their thorough and professional assistance. The data presented would not have been possible without the fruitful collaboration of many university and industrial researchers, and not least without the cooperation of students whose names appear in many of the earlier publications. We are indeed very grateful for their effort.

We hope this book becomes a starting point for researchers in other fields to become interested in pursuing microwave chemistry, in general, and microwave-assisted nanoparticle syntheses, in particular.

January 2013
Satoshi Horikoshi
Nick Serpone

List of Contributors

Farah Benyettou
UMR 7244 CNRS, University of Paris 13
CSPBAT Laboratory
74 rue Marcel Cachin, 93017 Bobigny
France

Luisa Boffa
Università di Torino
Dipartimento di Scienza e Tecnologia del Farmaco
via P. Giuria 9
10125 Torino
Italy

Zhi Chen
Tokyo Institute of Technology
Department of Applied Chemistry
Graduate School of Science and Engineering
2-12-1 Ookayama
Meguro, Tokyo 152-8552
Japan

Giancarlo Cravotto
Università di Torino
Dipartimento di Scienza e Tecnologia del Farmaco
via P. Giuria 9
10125 Torino
Italy

Caroline de Montferrand
UMR 7244 CNRS, University of Paris 13
CSPBAT Laboratory
74 rue Marcel Cachin, 93017 Bobigny
France

Davide Garella
Università di Torino
Dipartimento di Scienza e Tecnologia del Farmaco
via P. Giuria 9
10125 Torino
Italy

Frederic Geinguenaud
UMR 7244 CNRS, University of Paris 13
CSPBAT Laboratory
74 rue Marcel Cachin, 93017 Bobigny
France

Erwann Guenin
UMR 7244 CNRS, University of Paris 13
CSPBAT Laboratory
74 rue Marcel Cachin, 93017 Bobigny
France

Satoshi Horikoshi
Sophia University
Faculty of Science and Technology
Department of Materials and Life Sciences
7-1 Kioicho
Chiyodaku, Tokyo 102-8554
Japan

Xianluo Hu
Huazhong University of Science and Technology
College of Materials Science and Engineering
State Key Laboratory of Material Processing and Die & Mould Technology
Wuhan 430074
China

Hui Huang
University of Connecticut
Department of Chemistry
55 North Eagleville Road
Storrs, CT 06269-3060
USA

Yoann Lalatonne
UMR 7244 CNRS, University of Paris 13
CSPBAT Laboratory
74 rue Marcel Cachin, 93017 Bobigny
France

Irena Milosevic
UMR 7244 CNRS, University of Paris 13
CSPBAT Laboratory
74 rue Marcel Cachin, 93017 Bobigny
France

Dai Mochizuki
Tokyo Institute of Technology
Department of Applied Chemistry
Graduate School of Science and Engineering
2-12-1 Ookayama
Meguro, Tokyo 152-8552
Japan

Laurence Motte
UMR 7244 CNRS, University of Paris 13
CSPBAT Laboratory
74 rue Marcel Cachin, 93017 Bobigny
France

Markus Niederberger
ETH Zürich
Laboratory for Multifunctional Materials
Department of Materials
Wolfgang-Pauli-Strasse 10
8093 Zürich
Switzerland

Naftali N. Opembe
University of Connecticut
Department of Chemistry
55 North Eagleville Road
Storrs, CT 06269-3060
USA

Nick Serpone
Universita di Pavia
Dipartimento di Chimica
Gruppo Fotochimico
Via Taramelli 10
Pavia 27100
Italy

Steven L. Suib
University of Connecticut
Department of Chemistry
55 North Eagleville Road
Storrs, CT 06269-3060
USA

Silvia Tagliapietra
Università di Torino
Dipartimento di Scienza e Tecnologia del Farmaco
via P. Giuria 9
10125 Torino
Italy

Dorothée Vinga Szabó
Karlsruhe Institute of Technology
Institute for Applied Materials – Materials Process Technology
Hermann-von-Helmholtz-Platz 1
76344 Eggenstein-Leopoldshafen
Germany

Yuji Wada
Tokyo Institute of Technology
Department of Applied Chemistry
Graduate School of Science and Engineering
2-12-1 Ookayama
Meguro, Tokyo 152-8552
Japan

Jimmy C. Yu
The Chinese University of Hong Kong
Department of Chemistry
Shatin, New Territories, Hong Kong
China

1
Introduction to Nanoparticles

Satoshi Horikoshi and Nick Serpone

1.1
General Introduction to Nanoparticles

Nanotechnology is the science that deals with matter at the scale of 1 billionth of a meter (i.e., 10^{-9} m = 1 nm), and is also the study of manipulating matter at the atomic and molecular scale. A nanoparticle is the most fundamental component in the fabrication of a nanostructure, and is far smaller than the world of everyday objects that are described by Newton's laws of motion, but bigger than an atom or a simple molecule that are governed by quantum mechanics. The United States instituted the National Nanotechnology Initiative (NNI) back in 2000, which was soon followed (2001) by a plethora of projects in nanotechnology in nearly most of the U.S. Departments and Agencies [1]. About 20 Research Centers were subsequently funded by the Nationa1 Science Foundation (NSF), an agency responsible solely to the President of the United States and whose mandate is to fund the best of fundamental science and technology projects. NSF was the lead U.S. agency to carry forward the NNI. The word "nanotechnology" soon caught the attention of various media (TV networks, the internet, etc.) and the imagination and fascination of the community at large.

In general, the size of a nanoparticle spans the range between 1 and 100 nm. Metallic nanoparticles have different physical and chemical properties from bulk metals (e.g., lower melting points, higher specific surface areas, specific optical properties, mechanical strengths, and specific magnetizations), properties that might prove attractive in various industrial applications. However, how a nanoparticle is viewed and is defined depends very much on the specific application. In this regard, Table 1.1 summarizes the definition of nanoparticles and nanomaterials by various organizations.

Of particular importance, the optical property is one of the fundamental attractions and a characteristic of a nanoparticle. For example, a 20-nm gold nanoparticle has a characteristic wine red color. A silver nanoparticle is yellowish gray. Platinum and palladium nanoparticles are black. Not surprisingly, the optical characteristics of nanoparticles have been used from time immemorial in sculptures and

Microwaves in Nanoparticle Synthesis, First Edition. Edited by Satoshi Horikoshi and Nick Serpone.

Table 1.1 Definitions of nanoparticles and nanomaterials by various organizations: International Organization for Standardization (ISO), American Society of Testing and Materials (ASTM), National Institute of Occupational Safety and Health (NIOSH), Scientific Committee on Consumer Products (SCCP), British Standards Institution (BSI), and Bundesanstalt für Arbeitsschutz und Arbeitsmedizin (BAuA).

	Nanoparticle	Nanomaterial
ISO	A particle spanning 1–100 nm (diameter)	–
ASTM	An ultrafine particle whose length in 2 or 3 places is 1–100 nm	–
NIOSH	A particle with diameter between 1 and 100 nm, or a fiber spanning the range 1–100 nm.	–
SCCP	At least one side is in the nanoscale range.	Material for which at least one side or internal structure is in the nanoscale
BSI	All the fields or diameters are in the nanoscale range.	Material for which at least one side or internal structure is in the nanoscale
BAuA	All the fields or diameters are in the nanoscale range.	Material consisting of a nanostructure or a nanosubstance

Figure 1.1 Photographs of the famous Lycurgus cup which displays a different color depending on whether it is illuminated externally (a) or internally (b). For details, consult the website of the British Museum [2].

paintings even before the 4th century AD. The most famous example is the Lycurgus cup (fourth century AD) illustrated in Figure 1.1.

This extraordinary cup is the only complete historic example of a very special type of glass, known as dichroic glass, that changes color when held up to the light. The opaque green cup turns to a glowing translucent red when light is shone through it internally (i.e., light is incident on the cup at 90° to the viewing direction). Analysis of the glass revealed that it contains a very small quantity of tiny

(~70 nm) metal crystals of Ag and Au in an approximate molar ratio of 14 : 1, which give it these unusual optical properties. It is the presence of these nanocrystals that gives the Lycurgus Cup its special color display. The reader can marvel at the cup now in the British Museum [2].

Until the Middle Ages, the reputation of soluble gold was based mostly on its fabulous curative powers of various diseases, for example, heart and venereal diseases, dysentery, epilepsy, and tumors; it was also used in the diagnosis of syphilis. The history of the nanoparticle from ancient times to the Middle Ages has been summarized by Daniel and Astruc [3]. The first book on colloidal gold was published in 1618 by the philosopher and medical doctor Francisci Antonii. This book includes considerable information on the formation of colloidal gold sols and their medical uses, including successful practical cases. The book noted that soluble gold appeared around the fifth or fourth century B.C. in Egypt and China. On the other hand, industrial manufacturing of stained glass with colloidal particles was established by Kunckel in the seventeenth century (1676). He also published a book whose Chapter 7 was concerned with "drinkable gold that contains metallic gold in a neutral, slightly pink solution that exerts curative properties for several diseases" [4]. He concluded that gold must be present in aqueous gold solutions to a degree of contamination such that it is not visible to the human eye. A colorant in glasses, that is, the "Purple of Cassius", was a colloid resulting from the presence of gold particles and tin dioxide and was highly popular in the seventeenth century. A complete treatise on colloidal gold was published in 1718 by Helcher [5]. In the treatise, this philosopher and doctor stated that the use of boiled starch in its drinkable gold preparation noticeably enhanced its stability. These ideas were common in the eighteenth century, as indicated in a French chemical dictionary dated 1769 [6], under the heading "*or potable*" it was said that drinkable gold contained gold in its elementary form, albeit under extreme sub-division suspended in a liquid. In 1794, Fuhlame reported in a book that she had dyed silk with colloidal gold [7]. In 1818, Jeremias Benjamin Richters suggested an explanation for the differences in color shown by various preparations of drinkable pink or purple gold solutions in that these solutions contained gold in the finest degree of subdivision, whereas yellow solutions were found when the fine particles had aggregated. In 1857, in a well-known publication, Michael Faraday [8] reported the formation of deep red solutions of colloidal gold by reduction of an aqueous solution of chloroaurate ($AuCl_4^-$) by phosphorus in CS_2 (a two-phase system). He also investigated the optical properties of thin films prepared from dried colloidal solutions and observed reversible color changes of the films upon mechanical compression (from bluish-purple to green). Since that pioneering work, thousands of scientific papers have been published on the synthesis, modification, properties, and assembly of metal nanoparticles, using a wide variety of solvents and other substrates.

Nanotechnology is easily evident in various old churches. A well-known application of early nanotechnology is the ruby red color that was used for stained glass windows during the Middle Ages. Beautiful examples of these applications can be found in glass windows of many Gothic European cathedrals, among which the

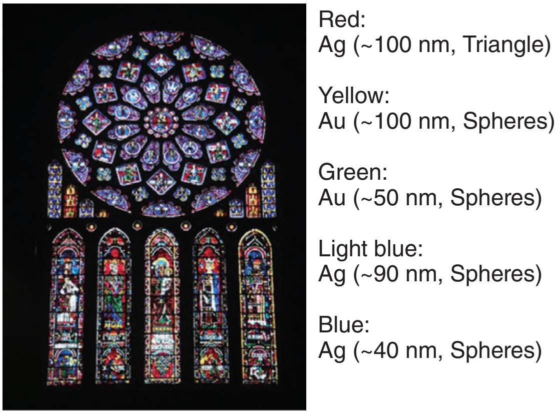
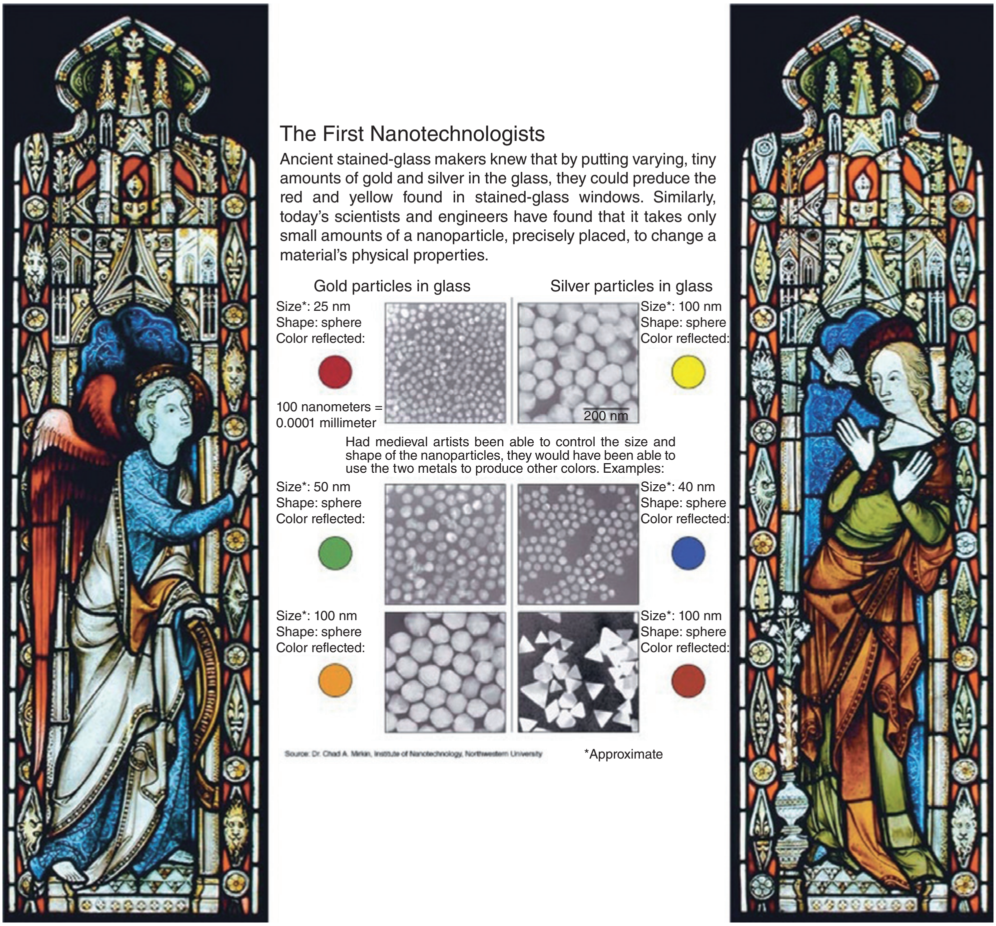


Figure 1.2 Rosace nord stained glass in the Cathédrale Notre-Dame de Chartres (France), color changes depend on the size and shape of gold and silver nanoparticle. From ref. [9].

León Cathedral (Spain) represents one of these unique masterpieces, located on the medieval French pilgrimage path to Santiago de Compostela (Spain); its impressive 2000 m^2 colored windows offer a unique view that certainly warrants a visit. Of course, the medieval artisans were unaware that they were using nanotechnology. They just knew that a particular process produced a beautiful effect. For example, the stained glass of a wonderful rose can be seen at the world heritage Cathédrale Notre-Dame de Chartres in France. The stained glass made in medieval times is displayed in Figure 1.2. Later chemistry clarified the reasons behind the generation of the color. These vivid colors were controlled by the size and the form (or shape) of the nanoparticles of gold and silver. The relation between particles and their associated colors has been discussed recently by Jin and coworkers [9]. In an article of 22 February 2005, the New York Times [10] summarized the relationship between the color of stained glass and the size/shape of the nanoparticles (see Figure 1.3). After several decades, the ingredients present in the stained glass (colored glass) of various churches were clarified subsequent to the development of analytical instruments. People without professional expertise in nanotechnology are also increasingly contributing to the technology.

An outline of the historical background in connection with nanoparticles (nanotechnology) is summarized in Table 1.2. The current technology that deals with nanoparticles, or simply nanotechnology, began from the special optical phenomenon and the establishment of a theory to describe the various physical phenomena that were followed subsequent to the development of analytical instruments. This continues as we speak, with various nanostructures being proposed and discovered, and their applications described.



The First Nanotechnologists

Ancient stained-glass makers knew that by putting varying, tiny amounts of gold and silver in the glass, they could preduce the red and yellow found in stained-glass windows. Similarly, today's scientists and engineers have found that it takes only small amounts of a nanoparticle, precisely placed, to change a material's physical properties.

Had medieval artists been able to control the size and shape of the nanoparticles, they would have been able to use the two metals to produce other colors. Examples:

Source: Dr. Chad A. Mirkin, Institute of Nanotechnology, Northwestern University

*Approximate

Figure 1.3 Comparison of the effect of size and shape of nanoparticles on the coloring of stained glass (Stained Glass Museum, Great Britain); see ref. [10].

Industrial production of nanomaterials saw its origins in the twentieth century. For example, nanoparticles of carbon black (tire soot) have been used in the fabrication of rubber tires of automobiles from the beginning of the twentieth century. Pigments such as SiO_2 and TiO_2 have been prepared by a high-temperature combustion method. Since the 1970s, the innovative development of nanoparticles is due to a combination of theory and experiments in the fields of physics, chemistry, materials science, and biosciences. Specific phenomena (chemical properties and physical properties), other than the optical property of a nanoparticle, have led to new possibilities in various fields. Applications of nanoparticles in various fields require an inexpensive and simple process of synthesizing high quality shaped-nanoparticles. In this regard, recent years have witnessed significant research being done in the use of microwave radiation in nanoparticle syntheses.

Table 1.2 Chronological table of nanotechnology.

Year	Remarks	Country/people
1200–1300 BC	Discovery of soluble gold	Egypt and China
290–325 AD	Lycurgus cup	Alexandria or Rome
1618	First book on colloidal gold	F. Antonii
1676	Book published on drinkable gold that contains metallic gold in neutral media	J. von Löwenstern-Kunckel (Germany)
1718	Publication of a complete treatise on colloidal gold	Hans Heinrich Helcher
1857	Synthesis of colloidal gold	M. Faraday (The Royal Institution of Great Britain)
1902	Surface plasmon resonance (SPR)	R. W. Wood (Johns Hopkins University, USA)
1908	Scattering and absorption of electromagnetic fields by a nanosphere	G. Mie (University of Göttingen, Germany)
1931	Transmission electron microscope (TEM)	M. Knoll and E. Ruska (Technical University of Berlin, Germany)
1937	Scanning electron microscope (SEM)	M. von Ardenne (Forschungslaboratorium für Elektronenphysik, Germany)
1959	Feynman's Lecture on "There's Plenty of Room at the Bottom"	R. P. Feynman (California Institute of Technology, Pasadena, CA,USA)
1960	Microelectromechanical systems (MEMS)	I. Igarashi (Toyota Central R&D Labs, Japan)
1960	Successful oscillation of a laser	T. H. Maiman (Hughes Research Laboratories, USA)
1962	The Kubo effect	R. Kubo (University of Tokyo, Japan)
1965	Moore's Law	G. Moore (Fairchild Semiconductor Inc., USA)
1969	The Honda–Fujishima effect	A. Fujishima and K. Honda (University of Tokyo, Japan)
1972	Amorphous heterostructure photodiode created with bottom-up process	E. Maruyama (Hitachi Co. Ltd., Japan)
1974	Concept of nanotechnology proposed	N. Taniguchi (Tokyo University of Science, Japan)

Table 1.2 (*Continued*)

Year	Remarks	Country/people
1976	Carbon nanofiber	M. Endo (Shinshu University, Japan)
1976	Amorphous silicon solar cells	D. E. Carlson and C. R. Wronski (RCA, USA)
1980	Quantum hall effect (Nobel Prize)	K. von Klitzing (University of Würzburg, Germany)
1982	Scanning tunneling microscope (STM) (Nobel Prize)	G. Binnig and H. Rohrer (IBM Zurich Research Lab., Switzerland)
1986	Atomic force microscope (AFM)	G. Binnig (IBM Zurich Research Lab., Switzerland)
1986	Three-dimensional space manipulation of atoms demonstrated (Nobel Prize)	S. Chu (Bell Lab., USA)
1987	Gold nanoparticle catalysis	M. Haruta (Industrial Research Institute of Osaka, Japan)
1990	Atoms controlled with scanning tunneling microscope (STM)	D. M. Eigler (IBM, USA)
1991	Carbon nanotubes discovered	S. Iijima (NEC Co., Japan)
1992	Japan’s National Project on Ultimate Manipulation of Atoms and Molecules begins	
1995	Nano-imprinting	S. Y. Chou (University of Minnesota, USA)
1996	Nano sheets	T. Sasaki (National Institute for Research in Inorganic Materials, Japan)
2000	National Nanotechnology Initiative (NNI), USA	
2003	21st Century Nanotechnology Research and Development Act, USA	
2005	Nanosciences and Nanotechnologies: An action plan, Europe	

Synthesis of nanoparticles using microwave heating has been on the increase in recent years. Fabrication of high quality nanoparticles can be achieved by simple operations compared with the more conventional nanoparticle synthetic methods. This chapter describes the various features and provides examples of the use of microwaves in nanoparticle synthesis. Moreover, in order to clarify the feature (or features) of the microwave method, a general description of the nanoparticle is also included.

1.2
Methods of Nanoparticle Synthesis

Various preparation techniques for nanoparticles (nanomaterials) are summarized in Figure 1.4. Two approaches have been known in the preparation of ultrafine particles from ancient times. The first is the breakdown (top-down) method by which an external force is applied to a solid that leads to its break-up into smaller particles. The second is the build-up (bottom-up) method that produces nanoparticles starting from atoms of gas or liquids based on atomic transformations or molecular condensations.

The top-down method is the method of breaking up a solid substance; it can be sub-divided into dry and wet grinding. A characteristic of particles in grain refining processes is that their surface energy increases, which causes the aggregation of particles to increase also. In the dry grinding method the solid substance is ground as a result of a shock, a compression, or by friction, using such popular methods as a jet mill, a hammer mill, a shearing mill, a roller mill, a shock shearing mill, a ball mill, and a tumbling mill. Since condensation of small particles also takes place simultaneously with pulverization, it is difficult to obtain particle sizes of less than 3 μm by grain refining. On the other hand, wet grinding of a solid substrate is carried out using a tumbling ball mill, or a vibratory ball mill, a planetary ball mill, a centrifugal fluid mill, an agitating beads mill, a flow conduit beads mill,

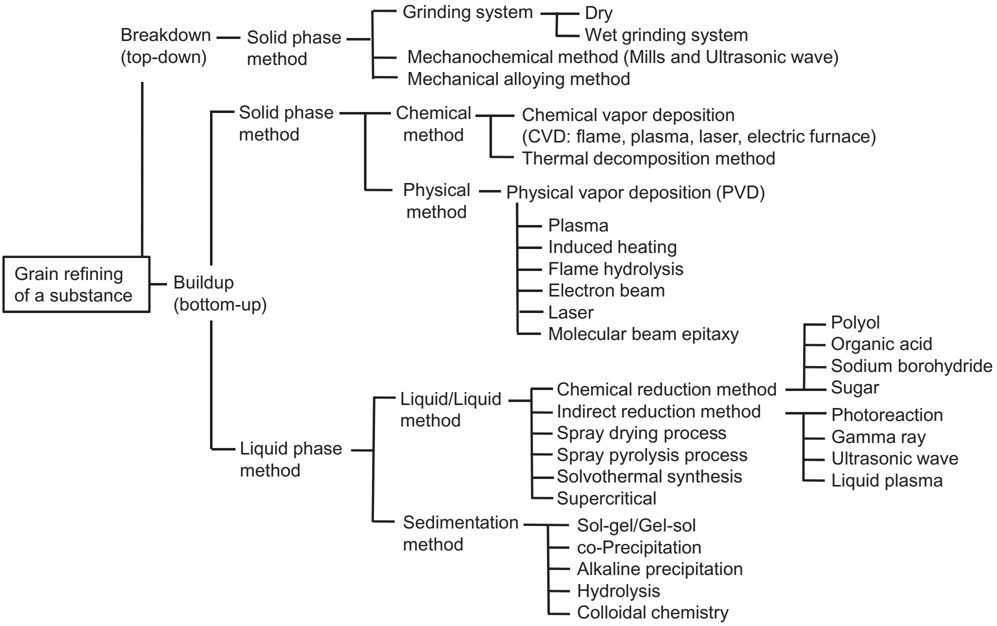


Figure 1.4 Typical synthetic methods for nanoparticles for the top-down and bottom-up approaches.

an annular gap beads mill, or a wet jet mill. Compared with the dry method, the wet process is suitable for preventing the condensation of the nanoparticles so formed, and thus it is possible to obtain highly dispersed nanoparticles. Other than the above, the mechanochemical method and the mechanical alloying method are also known top-down methods.

The bottom-up approach is roughly divided into gaseous phase methods and liquid phase methods. For the former, the chemical vapor deposition method (CVD) involves a chemical reaction, whereas the physical vapor deposition method (PVD) uses cooling of the evaporated material. Although the gaseous phase methods minimize the occurrence of organic impurities in the particles compared to the liquid phase methods, they necessitate the use of complicated vacuum equipment whose disadvantages are the high costs involved and low productivity. The CVD procedure can produce ultrafine particles of less than 1 μm by the chemical reaction occurring in the gaseous phase. The manufacture of nanoparticles of 10 to 100 nm is possible by careful control of the reaction. Performing the high temperature chemical reaction in the CVD method requires heat sources such as a chemical flame, a plasma process, a laser, or an electric furnace. In the PVD method, the solid material or liquid material is evaporated and the resulting vapor is then cooled rapidly, yielding the desired nanoparticles. To achieve evaporation of the materials one can use an arc discharge method. The simple thermal decomposition method has been particularly fruitful in the production of metal oxide or other types of particles and has been used extensively as a preferred synthetic method in the industrial world.

For many years, liquid phase methods have been the major preparation methods of nanoparticles; they can be sub-divided into liquid/liquid methods, and sedimentation methods. Chemical reduction of metal ions is a typical example of a liquid/liquid method, whose principal advantage is the facile fabrication of particles of various shapes, such as nanorods, nanowires, nanoprisms, nanoplates, and hollow nanoparticles. With the chemical reduction method it is possible to fine-tune the form (shape) and size of the nanoparticles by changing the reducing agent, the dispersing agent, the reaction time and the temperature. The chemical reduction method carries out chemical reduction of the metal ions to their 0 oxidation states (i.e., $M^{n+} \rightarrow M^0$); the process uses non-complicated equipment or instruments, and can yield large quantities of nanoparticles at a low cost in a short time. Of particular interest in this regard is the use of microwave radiation as the heat source that can produce high quality nanoparticles in a short time period. Besides the chemical reduction method which adds a reducing agent (direct reduction method), other reduction methods are known, such as photoreduction using gamma rays, ultrasonic waves, and liquid plasma which can be used to prepare nanoparticles. These methods that do not use a chemical reducing substance have the attractive feature that no extraneous impurities are added to the nanoparticles. Other than these methods, spray drying, spray pyrolysis, solvothermal synthesis, and the supercritical method are also known.

The general technique in the sedimentation method is a sol–gel process, which has been used extensively for the fabrication of metal oxide nanoparticles. This procedure transforms a solution of a metal alkoxide into a sol by hydrolysis, followed by polycondensation to a gel. Several books are available that provide details of the sol–gel process (see e.g., [11]). The wet process (liquid phase method) guarantees a high dispersivity of nanoparticles compared to the dry method. However, if the resulting nanoparticles are dried, aggregation of the particles soon follows. In this case, re-dispersion can be carried out according to the process used in the solid phase method.

Although various techniques have been summarized in Figure 1.4, there are some features to consider that are common to all the methods. That is, the synthesis of nanoparticles requires the use of a device or process that fulfills the following conditions:

- control of particle size, size distribution, shape, crystal structure and composition distribution
- improvement of the purity of nanoparticles (lower impurities)
- control of aggregation
- stabilization of physical properties, structures and reactants
- higher reproducibility
- higher mass production, scale-up and lower costs

1.3
Surface Plasmon Resonance and Coloring

The physical phenomenon of surface plasmon resonance (SPR) was reported long ago by Wood who could detect sub-monomolecular coverage [12]. Not only did Wood discover the plasmon resonance phenomenon, but also found that it changed with the composition of the liquid in touch with the metal surface. Although he speculated on how the light, grating and the metal interacted with each other, a clear rationalization of the phenomenon was not provided. He observed a pattern of “anomalous” dark and light bands in the refracted light when he shone polarized light on a mirror with a diffraction grating on its surface. The first theoretical treatment of these anomalies was put forward by Rayleigh in 1907 [13]. Rayleigh’s “dynamical theory of the grating” was based on an expansion of the scattered electromagnetic field in terms of outgoing waves only. With this assumption, he found that the scattered field was singular at wavelengths for which one of the spectral orders emerged from the grating at the grazing angle. He then observed that these wavelengths, which have come to be called the Rayleigh wavelengths, λ_R, correspond to the Wood anomalies. Further refinements were made by Fano [14], but a complete explanation of the phenomenon was not possible until 1968 when Otto [15], and in the same year Kretschmann and Raether [16], reported the excitation of the surface plasmon band. Surface plasmon resonance has also been similarly researched in solid state physics in recent years in application studies, especially in such applied research as biosensing, solar cells, and super high-density recording. Details on surface plasmon resonance from the point of view of solid state physics have been given by Schasfoort and Tudos [17].

In this section we present a simple outline of the relation between surface plasmon resonance and the color of nanoparticles. In solid state physics, the plasmon represents the collective oscillation of a free charge in a metal, and may be considered as a kind of plasma wave. The positive electrical charge in the metal is fixed and the free electron is free to move around it. An applied external electric field, as from a light source, causes the free electrons at the surface of the metal to vibrate collectively, giving rise to surface plasmons.

Since electrons are also particles with an electric charge, when they vibrate they also generate an electric field, and when the electric field from the vibration of free electrons and the applied external electric field (e.g., electromagnetic waves) resonate the resulting phenomenon is referred to as a surface plasmon resonance that takes place at the surface of the metal. However, if light irradiates a solution that contains dispersed metal nanoparticles smaller than the wavelength of light, then depending on the electric field of light, the deviation produces a free electron at the surface of the metal. As a result, the weak or thick portions of the electric field appear on the nanoparticle surface (Figure 1.5) and can be considered as a kind of polarization. Such localized plasmon resonance is called localized surface plasmon resonance (LSPR).

The LSPR is typically concentrated in a very narrow region on the surface of a nanoparticle. The electric field distribution on the nanoparticle surface caused by LSPR can be visualized using an electromagnetic field analysis software with a finite element method (Comsol Multiphysics 4.2a). The LSPR distribution on the surface of a 20-nm (diameter) Au nanoparticle is shown in Figure 1.6a. When visible light at 520 nm, which corresponds to the maximum position of the LSPR band in the Au nanoparticle, is used to irradiate the nanoparticle, the electric field generated is concentrated on the right and left side of the Au nanoparticle, perpendicular to the incident light direction. On the other hand, the electric field generated in two adjacent Au nanoparticles is concentrated within the gap between the two particles. Figure 1.6b illustrates two particles with a 4-nm gap, while Figure

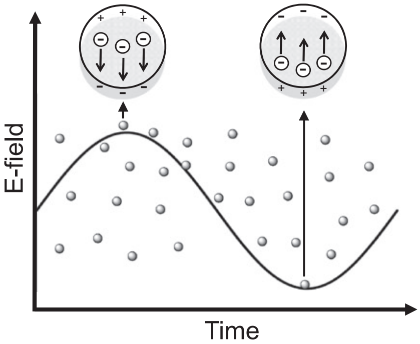


Figure 1.5 Mechanism of a localized surface plasmon resonance.

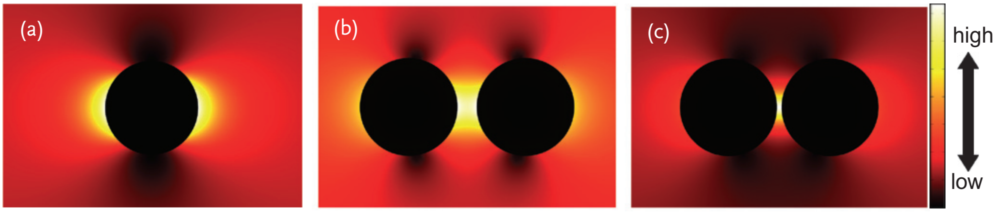


Figure 1.6 Images of the electric field distribution on the Au nanoparticle surface (20 nm diameter) under visible light irradiation visualized with Comsol Multiphysics 4.2a: (a) single Au nanoparticle, (b) two Au nanoparticles with 4 nm gap, and (c) two Au nanoparticles with 1 nm gap.

1.6c displays two particles separated by a gap of 1 nm. As the gap becomes narrower and narrower, the density of the generated electric field gets bigger and bigger.

The wavelength corresponding to the LSPR depends on the kind of metal, the shape of the metal nanoparticle, and the extent of aggregation of the metallic nanoparticles. Moreover, the surface plasma vibration also changes with the dielectric constant and the quality of the carrier fluid. The plasma oscillations in the metal occur mainly in the ultraviolet (UV) region. However, in the case of Au, Ag, and Cu, the plasma shifts nearer to the visible light domain with the band due to electrons in the s atomic orbitals. For example, the wavelength of the surface plasmon resonance band maximum of a spherical Au nanoparticle is 520–550 nm. If a colloidal Au nanoparticle solution is now irradiated with visible light at these wavelengths (520–550 nm), the visible light corresponding to the green color is absorbed and the particles now display a red purple color, which is the complementary color to green. In a colloidal Ag nanoparticle solution which has a plasmon resonance band maximum near 400 nm, the blue color of the visible light is absorbed and the Ag particles now take on a yellow color, the complementary color to blue.

1.4
Control of Size, Shape, and Structure

1.4.1
Size Control of Nanoparticles

The physical and chemical properties of nanomaterials depend not only on their composition but also on the particle size [18] and shape [19]. *Accordingly, a high quality synthesis protocol must first of all provide control over particle size and shape*. For example, if the diameter of an Au nanosphere is made to increase, the surface plasmon resonance will be gradually shifted from 530 nm to the longer wavelength side (see Figure 1.7) [20]. Thus, if nanoparticles differ in size, their optical characteristics will also change significantly.