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Introduction

Although efforts to make new materials, or to improve existing materials, are as old as mankind, only in our age has "materials science" matured into a unique area. In the earliest ages of civilization, materials were made using a "learning by doing" approach. For example, the first piece of iron – which does not occur in elemental form in nature – was most probably made by chance, when an iron ore and a carbon source were accidentally heated together. From today's point of view, the properties of this "new material" would be regarded as minimal, but at the time of its discovery, this was a quantum leap for mankind. Over the millennia, the iron- and steel-making process has been advanced to a highly sophisticated state, as has the quality of the materials produced. The manufacture of glass and ceramics has developed in a similar manner.

The improved properties and better performance of the traditional materials were achieved by advances in materials technology. However, this was only made possible through a better understanding of the underlying basic chemical and physical principles. The route from the first primitive man-made piece of glass to the highest-quality glass currently used in the lenses of large telescopes, for example, was paved by a detailed understanding of the glass chemistry, the structure of glass, crystallization phenomena, and the physics of melts.

During the twentieth century, materials science has led to major changes in the way that we live. For example, only 20 years ago the manuscript of this book would have been written on a typewriter after making time-consuming searches in several scientific libraries, the figures would have been drawn with ink, and the book would have been eventually produced after time-consuming cut-and-paste corrections, typesetting by the printer and photographic reproduction of the figures. Instead, writing of the book and drawing of the figures was done on personal computers and laptops, with much of the literature research having been done using electronic databases and by the Internet, and eventually the manuscript was delivered electronically to the publishing company. This major change in how we worked was only made possible by the dramatic advances in information technology and data-storage capacities that have been developed in a rather short period. As in many other areas, the rate of progress was, and is, determined by the speed at which materials are newly developed or improved, and by advances in their processing. Further development in information technology

Synthesis of Inorganic Materials, Third Edition. Ulrich Schubert and Nicola Hüsing.

Published 2012 by WILEY-VCH Verlag GmbH & Co. KGaA

will to a large degree depend on how materials science allows further miniaturization, and on the development of materials capable of optical or optoelectronic data transfer.

In our generation, many new materials have been discovered with properties that were beyond imagination, such as the high-temperature superconductors, "intelligent" and "adaptive" materials, or nanostructured materials. Furthermore, the demand for longer product lifetimes, higher quality and efficiency, and so on has also placed new challenges on the synthesis and processing methods of known materials. Major changes in materials production technologies were induced by the impact of environmental issues (→ "sustainable development"). An increasingly important goal for materials developments is the minimization of energy and raw materials consumption. For example, materials for moving components in motors or gas turbines with better thermomechanical properties or a lower mass improve the efficiency of the motor or turbine and, as a consequence, save fuel and reduce the emission of waste gases.

Many of the scientific and technological findings that have been discovered in a variety of laboratories, together with the worldwide increase in knowledge, form the basis for new technologies in the twenty-first century. Several trends are apparent:

- Materials become increasingly specialized and multifunctional. In contrast to many materials that have a broad range of applications, many modern materials are tailor-made for only one special application.
- The borders between traditional materials types, such as ceramics, organic polymers, or "natural" materials (wood, bones, wool, etc.) begin to disappear, as well as the border between "natural" and "artificial." New classes of materials are being developed that bridge the gaps between the traditional materials, such as inorganic–organic hybrid materials or biomimetic materials.
- It is realized that the transition between molecules and solids results in materials with unique physical or chemical properties. The so-called nanomaterials (see Chapter 7) with a characteristic dimension in the lower nanometer range have the potential of revolutionizing materials design for many applications.
- Theoretical methods have matured in a way that they are able to predict materials properties. A visionary example is carbon nitride (C_3N_4), which is reputed to be harder than diamond and to have interesting applications as a high-temperature semiconductor. However, this prediction has still to be verified by the synthesis of this compound.

Although modern materials science is interdisciplinary, and more than a blend of some established communities, such as chemistry, physics, or engineering, the experience from these disciplines is essential to carry the development of some material from the raw materials or precursors to the final application.

The triangle *Synthesis and Processing – Composition and Structure – Properties and Performance* represents the essential relations in material science. The properties of a material of a given composition depend to a very high degree on the way that it was made or processed, this being a consequence of different structures (on any length scale). Vice versa, certain applications require certain structural features and certain chemical compositions of the employed materials, which again require the deliberate design or modification of the synthesis and processing procedures.

For example, SiO_2 can be crystallized as quartz (for oscillator crystals, for example) by hydrothermal treatment (see Section 4.4.1). SiO_2 as an insulating layer in a microelectronic device would be made by chemical vapor deposition (see Section 3.2.4.1). Biogenic processes produce amorphous silica, for example as the aesthetically pleasing exoskeletons of diatoms (see Section 4.3.1.1). Silica with a high surface area, used as adsorbent or for thermally insulating materials, for example, is produced either by the aerosol process, where agglomerated spherical, amorphous particles are obtained (see Section 3.3) or as aerogels with a highly porous network structure via sol–gel processing (see Section 4.5.6). Sol–gel processing also allows the preparation of amorphous SiO_2 powders or dense films. Although the composition of the obtained material is SiO_2 in each case, completely different routes of preparation are required.

Traditional classification of materials (natural materials, metals, nonmetallic inorganic materials, organic polymers, composite materials, etc.) is based on the fundamental properties and somehow also reflects the different structural and bonding features. In this book, we wish to emphasize the chemical aspects of materials science. Chemistry is the science of transforming compounds into others on a molecular level, and of investigating the concomitant changes in composition, structure, and properties. We therefore organize the book according to methods of how compounds can be synthesized.

When does an inorganic compound qualify as a "material," in other words, how does this book differ from one on preparative inorganic chemistry? We do not attempt to define the term "material," because many chemical compounds are potential materials, and thus the distinction is not always obvious. Not being too conservative, we considered materials to be compounds that are utilized for some technical application, or that have at least the potential for being used in such a manner. We will, as examples, select several types of materials in order to discuss the ways in which (natural or artificial) chemical compounds are transformed into materials, and show both the options and problems that originate from the various preparation methods, independently of a particular chemical composition.