1

Introduction

Although efforts to make new materials, or to improve existing materials, are as old as mankind, 'materials science' has matured into a distinct discipline only since a few decades. In the earliest ages of civilization, materials were made by a learning-by-doing approach. The first piece of iron – which, apart from iron meteorites, 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. This was a quantum leap for mankind at the time of its discovery. 'New materials', with new chemical compositions and new morphologies, or materials with improved properties and better performances are still discovered today, but progress is essentially based on scientific and technological advances. For example, a detailed understanding of glass chemistry, the structure of glass, crystallization phenomena, the physics of melts, and so on paved the way from the first primitive man-made piece of glass to metallic glasses or the highest-quality optical glass used in the lenses of large telescopes. The development of ceramic materials from simple pottery, made from readily available raw materials, to today's sophisticated functional ceramics for high-tech applications is routed on the same grounds.

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. An increasingly important goal for materials developments is the minimization of energy and raw materials consumption. When it comes to developing new materials with a targeted set of properties, the question is no longer solely whether such a material can be made, but whether it can be made with a minimal environmental impact. This includes the replacement of rare elements by more abundant ones.

In many areas, the rate of progress was and is determined by the speed at which materials are newly developed or improved. New materials enable new applications, and – vice versa – new applications require new materials. An example is information and communication technologies, ranging from mobile phones to computers, which have led to major changes in the way we live but would have not been possible without unprecedented developments in all

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

materials categories, ranging from polymers to semiconductors and alloys. 'Those who control materials, control technology' (E. Kobayashi, Panasonic). Technologies for renewable energy production and storage pose formidable new challenges to materials science and especially the development of new materials, likewise advances in medical technologies.

Many scientific and technological findings, together with a better understanding of the underlying basic chemical and physical principles, form the basis for new technologies in the twenty-first century. Several trends are apparent:

- Materials become increasingly specialized and multi-functional. In contrast to many traditional materials that have a broad range of applications, many modern materials are tailor-made for one special application.
- Certain functions are often only accessible by complex systems rather than individual compounds. Paying special attention to interfaces between the components of such systems is an issue of increasing importance.
- The borders between traditional materials types, such as ceramics, organic polymers, or 'natural' materials begin to disappear. 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. Nanomaterials have the potential of revolutionizing materials design for many applications.
- Computational methods have matured in a way that they are able to model materials on different length scales with ever greater detail and precision and even to predict materials properties.

Modern materials science is interdisciplinary and more than just a blend of some established areas, such as chemistry, physics or engineering. The complementary know-how and approaches from these disciplines are essential to carry materials developments from the raw materials to the final application. Suitable methods to produce a material with the desired composition and properties, including the selection of suitable starting compounds, are what chemists can contribute.

The triangle *Synthesis and Processing–Composition and Structure–Properties and Performance* represents the essential relations in materials science. Different structures and morphologies (on any length scale) influence the properties of a material with a given composition and depend to a very high degree on the way how the material was made or processed. Vice versa, certain applications require particular structural features and specific chemical compositions of the employed materials, which again require the deliberate choice of synthesis and processing procedures.

For example, SiO_2 can be crystallized as quartz (for oscillator crystals, for example) by hydrothermal treatment (Section 4.4.2). SiO_2 as a dense insulating layer in a microelectronic device would be made by chemical vapour deposition (Section 3.2.5.1). Biogenic processes produce amorphous silica, for example, as the aesthetically pleasing exoskeletons of diatoms (see Section 4.2.4.1). Silica with a high surface area, used as adsorbent or for thermally insulating materials, for example, is produced either by aerosol processes, 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 4.5.7). Sol–gel processing also allows the preparation of amorphous SiO_2 powders or dense films. Porous silica spheres, prepared with the help of macromolecular templates, are used for targeted drug release (Section 7.3.3). Although the composition of all materials is SiO_2, completely different preparation routes are required. This example shows that many materials with a given chemical composition can be prepared by several methods. Organization of this book according to preparation processes thus has the inevitable consequence that some materials are treated in more than one chapter.

When does an inorganic compound qualify as a 'material', or 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 as compounds that are utilized for some application or that have at least the potential for being used in such a manner. We will select representative examples to discuss the ways in which 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.