Sand and Silicon

It is amazing how sand has changed the world and our lives. Denis McWhan describes, in a beautiful and interesting way, all the developments that are simply based on sand. During the 20th century the application of thermodynamics, solid-state and surface physics, and quantum mechanics to the science of sand paved the way for the development of many devices and gadgets used in our daily lives, such as cigarette lighters, watches, submarine detectors, sensors, solar cells, computer chips, laptops, smartphones, satellites, navigational aids, and space applications, to name just a few.

The key was to understand the structure of sand and silica and to control and refine sand (silicon dioxide) to obtain ultrapure polysilicon (polycrystalline silicon) by fractional distillation of trichlorosilane. Today silicon is routinely purified to a level of some parts per billion, or 99.999999% purity. Polysilicon is the purest material produced by man on earth. Denis McWhan nicely describes how the laws of thermodynamics and their understanding became the driving force for this tremendous achievement.

This purified polysilicon as a starting material was the key to the next stage of development, by making it possible to grow mono-Si-crystals (single-crystal silicon) or poly-Si-crystals. Two processes were developed: the Czochralski method and the floating zone method. Both methods turn the purified polysilicon into silicon crystals, which are the basis of the modern electronics industry. Semiconductors, and in particular silicon in combination with the understanding and control of very small amounts of impurities (dopants), played a key role in the progress of science during the last century. Using those principles led to the manifold applications in our daily lives such as those already mentioned.

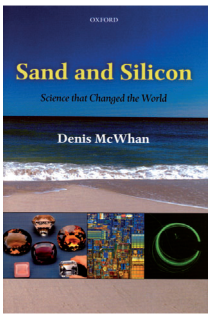
Denis McWhan summarizes these developments in an interesting manner. His book is especially useful for readers of general science literature, and might also be of interest as an entry to more detailed studies in a specific field, as it includes a comprehensive collection of literature references.

In the first two chapters, the author describes the structures of sand, silica, and quartz crystals, also including ceramics. Even the very first tools made by human beings, such as arrow heads, were made of flintstone (silica). Today, materials such as optical fibers for signal transmission are made of silica. The understanding of those crystal structures was made possible by the development of X-ray spectroscopy and electron microscopy.

Chapter 3 describes how the application of modern thermodynamics made it possible to produce pure (99.999999%) polysilicon. Using the Siemens process, trichlorosilane ($SiHCl_3$) is turned into purest polysilicon. In the next step, silicon single crystals that are almost free of defects are produced, either by the Czochralski process (invented by the Polish chemist Jan Czochralski at the AEG laboratories in Berlin in 1916) or by the float zone process (invented by Bill Pfann at Bell Laboratories in 1951). Since the first invention by Jan Czochralski was such a breakthrough in crystal development, it should have been mentioned and cited. These two processes are essentially the foundation of the communication age. The vast majority of silicon chip devices, such as microprocessors, DRAM (dynamic random access memory), and flash memories, as well as logic devices, are produced by the Czochralski method. A single crystal boule is shown on page 54 of the book. Although a 60 kg boule is very impressive, today's most advanced crystals have a diameter of 300 mm and a mass of up to 400–500 kg. Crystals of 450 mm diameter are expected by the end of the present decade.

Chapter 4 explains the power of small amounts of impurities. Whereas small amounts of different metal impurities are responsible for the nice colors of gemstones, it is the small amounts of intentionally added impurities or dopants that give semiconductors, especially silicon semiconductors, their special electrical properties. Denis McWhan describes how experiments with the p–n junction led to the invention of transistors by W. Shockley, J. Bardeen, and W. Brattain at Bell Laboratories in 1947, aimed at replacing the vacuum tube by a solid-state amplifier. Modern microprocessors use billions of transistors on one chip. The chapter emphasizes the interplay between the progress of science and the application of this increasing knowledge, for example in ion implantation, as well as in photolithography and in many other techniques developed and applied in the semiconductor field.

In Chapter 5, Denis McWhan emphasizes the importance of sand in the field of renewable energy sources. In 1921, Albert Einstein received the Nobel Prize for explaining the photoelectric effect. The sun delivers energy in abundance to the surface of the earth. Denis McWhan points out that the energy delivered in one hour is about the equivalent of mankind's consumption in a year. In 1.5 days the sun provides as much energy as the sum of all currently known oil reserves. The modern photovoltaic industry aims to capture more of this renewable and sustainable energy. The development of solar cells was initially driven by space



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technology. In the 1960s, Sputnik stopped transmitting signals after its batteries died. Today, more and more efficient and sophisticated solar cells are being developed. This chapter gives a comprehensive overview.

Chapter 6 focuses on surface physics. The bulk structures of crystals have been explored by X-ray diffraction, whereas now the surfaces of those crystals are being explored by electron diffraction (LEED, low energy electron diffraction) and many other surface characterization methods. Atomic force microscopy should also have been mentioned in this context. A detailed understanding of the surface properties, and the development of methods for depositing atomic layers of silicon and other semiconductor materials layer by layer, has led to the development of special electronic devices such as FETs (field effect transistors). Furthermore, it was shown that electron mobility could be increased by using strained silicon. Band-gap engineering opened up a wide field for special device applications.

In Chapter 7, Denis McWhan reviews developments in data transmission. The Internet now moves huge volumes of data around the globe every day. This was only made possible by the development of quartz fibers as an expressway for light waves, which increased the speed of data transmission tremendously.

In summary, our information age is literally built on sand, which is an abundant resource. Only a tiny fraction of it is used for information technology. Denis McWhan describes, in a very interesting way, what scientists and engineers have developed out of sand. From this historical perspective, mainly with examples of achievements at Bell Laboratories, Brookhaven National Laboratory, and IBM Laboratories, he shows how those developments have contributed to the progress of science, and emphasizes the interdependency of scientific advances and their applications in semiconductor physics, and finally in the technology that makes possible today's world of global communication.

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