

Preface

“Seeing is believing” has not always been true and still is not. When Galileo saw more than 400 years ago that there were some moons circling around Jupiter many astronomers and philosophers initially did not believe this. Four hundred years later most scientists see in the steady temperature rise and extreme weather events clear signs of human-caused climate change but some scientists and many people do not believe this. Fortunately exact science is fact-based and if something is seen and independently confirmed it is generally believed. Since Galileo’s worldview-changing discoveries, seeing has expanded our worldview immensely beyond the narrow range that our eyes can recognize without instruments. Seeing with telescopes using electromagnetic waves ranging from X-rays to radio waves has given us deep insight into the universe. Microscopes using electromagnetic waves ranging from the infrared to X-rays have also opened our eyes to the microworld in and around us. Their wavelength-limited access to the nanoworld has been overcome by microscopes using electron waves, which now allow us to see down into the sub-nanometer world, an ability of utmost importance in modern technology, medicine, biology, and other disciplines.

The dimensions encountered in these fields are increasingly in the sub-micrometer range, which has the consequence that the ratio of surface to volume becomes important to such an extent that the surface either increasingly determines the properties of the material or *is* the material as in graphene and other so-called two-dimensional structures. Understanding these properties calls for methods which allow us to “see” the surface with all its properties, not only its geometric structure. Numerous methods have been developed in the last several decades with this goal, including field electron microscopy, field ion microscopy, and various scanning probe microscopies, which have given deep insight into the surface nanoworld.

This book describes one of these methods, cathode lens or immersion lens electron microscopy, which was born already in the early 1930s as a twin of its faster maturing brother, high energy electron microscopy. Because its aim is to image surfaces, which tend to be covered with a wide variety of surface contaminants, it did not come out of adolescence until ultrahigh vacuum and related cleaning methods became available. This opened the door to a new scientific

discipline, surface science, which in turn stimulated the development of methods for seeing surfaces better than was possible using ultraviolet light in photoelectron emission microscopy (PEEM). Thus Low Energy Electron Microscopy (LEEM) was born in the early 1960s, motivated by the desire to see and believe what Low Energy Electron Diffraction (LEED) suggested. Later results of these developments are synchrotron radiation and pulsed laser excited photoemission electron microscopy, which now play an increasingly dominant role in cathode lens microscopy.

Just as we experience our environment multimodally by seeing, smelling, and hearing, we not only want to see surfaces but also to “smell” and “hear” them. What do they consist of and what are their properties? The smelling wish has been fulfilled by combining imaging and spectroscopy, primarily X-ray photoelectron spectroscopy, with the original LEEM instrument in the Spectroscopic Photo Emission and Low Energy Electron Microscope (SPELEEM). The hearing wish has been satisfied to some degree, too, for example in the understanding of magnetic microstructures, by banging on them with the angular momentum of photons in magnetic dichroism PEEM and electrons in Spin-Polarized Low Energy Electron Microscope (SPLEEM) and seeing their response. Thus by combining microscopy and diffraction with spectroscopy, and making full use of the properties of the electrons and photons, surface microscopy with slow electrons has grown far beyond what the fathers of cathode lens electron microscopy could have imagined in the 1930s. Today’s instruments are no longer pure imaging systems but small laboratories for the analysis of the properties of surfaces, thin films, and nanostructures. As a result, full field cathode lens microscopy occupies a unique position in this field of materials science.

This book tries to lead the reader through the world of surface microscopy with slow electrons, starting with a brief recount of the history of the field before the advent of surface science (Chap. 1). This introduction shows the high level that the field had achieved in instrumentation before it faded away because of the lack of sufficiently good vacuum. Before continuing with the evolution of the instrumentation in the ultrahigh vacuum age, Chap. 2 describes the fundamental interactions of photons and electrons with matter, which are necessary to the understanding of the methods used in imaging. Chapter 3 is an overview of the wide variety of instruments and their components that have been developed, but not all of them completely. Since most researchers in surface microscopy work with only one type of instrument, this chapter hopefully will give them some ideas about other instruments of potential interest. In any case, many components such as the objective lens are common to all instruments and the user should be aware of their possibilities and limitations. The fundamental understanding of resolution and contrast in imaging with slow electrons is the subject of Chap. 4. It is necessarily based on wave optics, where coherence plays a fundamental role which distinguishes reflection from emission microscopy. This presentation demonstrates that, presently, the image detection system rather than the optics limits the resolution.

With this background the remaining chapters in the book describe the wide variety of applications of modern cathode lens electron microscopy. Applications occupy a large fraction of the book because only they can justify the human efforts

and costs of developing the instruments as described in Chap. 3. These results should also give the reader not currently working in this field an idea of the capabilities and limitations of imaging with slow electrons. In the early years the emphasis was on surface science and work in this field is still continuing. Therefore Chap. 5, which covers this field, is by far the longest and most detailed. Applications to younger fields such as graphene and plasmonics, which are described in Chap. 6, are still evolving so that the book presents only their early phases. A case study at the end of this chapter illustrates that the cathode lens microscope is not only powerful for studying known materials but also for identifying unknown materials by making full use of its seeing and smelling capabilities. Magnetic imaging, largely based on X-ray photoemission, is not so young but has grown to such an extent that it deserved a separate treatment in Chap. 7. While most of the surface science studies in Chap. 5 make full use of the in situ capabilities of the microscopes, most of the work described in Chaps. 6 and 7 uses ex situ prepared samples and is combined with many complementary methods. Chapter 8 discusses briefly other surface imaging methods with electrons, which complement and/or compete with cathode lens electron microscopy and ends the book with some concluding remarks.

A few comments on the presentation of the material included in this book should be made. While the original intention was to cover all published work in the field, an intention still partially realized in Chap. 5, it soon turned out that this was not feasible, in particular because of the rapid growth of the number of publications in the fields covered in Chaps. 6 and 7. Nevertheless the book should give a good presentation of the state of the art in late 2013 shortly before the completion of the manuscript in early 2014, with the support of references to related reviews. The book does not intend to explain the scientific problems studied with cathode lens electron microscopy but only to show what it can contribute to their solution. For the science aspect of the problems the reader is referred to the references, which include the names of all authors and the complete titles of the publications. This should make it easier to decide which publications to read. No quality or importance criteria were used in their selection.

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Ernst Bauer

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Bauer, E.

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