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Helium Ion Microscopy

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Helium Ion Microscopy

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Preface

Scientific research is often characterized by a combination of open questions and specific research tools that are designed to solve them. This interplay happens in both directions, and new scientific instruments can also bring attention to novel scientific questions, or can even define entire scientific periods. Nanotechnology brought us the invention of many instruments that can be used as microscopes to image small things and as fabrication tools to modify them. Prominent examples are charged particle beams: scanning electron microscopy (SEM) and electron beam lithography (EBL) are done with exactly the same instrument; and for transmission electron microscopy (TEM) samples are sliced with focused ion beams (FIB). Since the 1960s the four above-mentioned charged particle methods synergetically evolve, thereby pushing the frontiers of high-resolution microscopy as well as of micro- and nanofabrication technology. In this environment, in 2006 a novel charge particle instrument, the helium ion microscope (HIM), entered the field. With a unique combination of imaging and nanofabrication capabilities it placed itself right at the forefront of current research.

The key technological advantage of the HIM is the fact that it is an integrated multipurpose instrument that does not only excel in a single discipline but by a unique combination of several skills. Its resolution as a microscope is higher than that of the best available SEMs. In nanofabrication it outperforms the FIB with respect to small feature sizes. Without further modification, a HIM is capable to image untreated biological—or other insulating—samples with unprecedented resolution, depth of field, materials contrast and image quality. The HIM thus covers a wide range of tasks that otherwise would require multiple devices or special sample treatments. Since its introduction, the HIM has become a popular instrument that is frequently seen in nanotechnology centers throughout the globe.

Interestingly, the basic technology of the HIM is built on the combination of two long-established techniques, field ion microscopy and scanning electron microscopy. These were combined in one instrument by persistent engineering efforts that led to the development of a stable gas field ion source (GFIS), stable enough to be continuously operated in a scanning ion beam microscope. Currently, about 100

GFIS instruments are in operation worldwide. Many of them go beyond the use of helium ions and can also operate with neon and nitrogen and are often combined with a classical liquid metal FIB.

This book aims at providing an in-depth overview on the current status of HIM for imaging, analysis, and nanofabrication. It is written for the novice to the technique as it explains the basic operation principles and fundamental interaction mechanisms between medium energy light ions and matter. For the more experienced reader the book covers a range of specialized topics dealing with currently ongoing research efforts to further develop the technique in an extensive manner. Here, the chapters of this book range from basic scientific questions to innovative solutions in an industrial environment. All chapters have been written by specialists in their respective fields, their affiliations range from universities and research institutes to industrial laboratories.

Part I *Fundamentals* covers the instrumental and theoretical aspects on two levels. Chapter 1 *The Helium Ion Microscope* provides a detailed description of the components of the ion microscope and its operational principles. Although written for the novice, the chapter also contains valuable technical information for the experienced user that is not available elsewhere in this form. Chapter 2 *Single Atom Gas Field Ion Sources for Scanning Ion Microscopy* is an in-depth description of the gas field ion source (GFIS) its fabrication, modification and operation. The next two Chaps. 3 *Structural Changes in 2D Materials Due to Scattering of Light Ions* and 4 *Monte Carlo Simulations of Focused Ion Beam Induced Processing* contain theoretical descriptions of fundamental ion solid interactions which are important for understanding the processes during imaging as well as during nanolithography with ions. While Chap. 3 deals with the interaction of light ions with 2D materials such as graphene. Chapter 4 covers the processes important for material removal by sputtering and material addition via ion beam induced deposition. To complete this part Chap. 5 *Secondary Electron Generation in the Helium Ion Microscope: Basics and Imaging* describes the details of secondary electron generation which is crucial for the image formation.

Part II *Microscopy* covers the best known application of the HIM, i.e., the imaging of small objects. Chapter 6 *Introduction to Imaging Techniques in the HIM* is the natural starting point for each new HIM user as it provides a flavor of what is possible in terms of high-quality imaging. The following Chap. 7 *HIM of Biological Samples* compiles recent bioimaging studies with the HIM, a special emphasis is laid on a comparison with SEM and optical techniques. It can be read as a motivation for scientists working in biology and medicine to make use of the unprecedented imaging capabilities provided by the Helium Ion Microscope. Chapter 8 *HIM Applications in Combustion Science: Imaging of Catalyst Surfaces and Nascent Soot* touches an environmentally important imaging task that requires the highest resolution and chemical contrasts. In *The Channeling and Backscatter Imaging* (Chap. 9) subsurface imaging and the utilization of channeling for obtaining crystallographic information is presented. Chapters 10 *Helium Ion*

Microscopy of Carbon Nanomembranes and 11 *Helium–Ion Microscopy for Two–Dimensional Materials* deal with a currently very important class of materials. While Chap. 10 focuses on the imaging of a specific example of membranes made from molecules, Chap. 11 also covers various two-dimensional materials and discusses issues such as beam induced damage. In general, Part II contains a manifold of quite aesthetic HIM pictures that will act as a source of inspiration for the novice as well as the experienced reader.

Part III *Analysis* discusses current efforts to implement methodical additions and to overcome existing technical challenges. In Chap. 12 *Backscattering Spectrometry in the Helium Ion Microscope: Imaging Elemental Compositions on the nm Scale* a technique that usually requires large accelerators is adapted to the HIM, where it outperforms the analytic resolution limit of Backscatter Spectroscopy by orders of magnitude. This chapter is complimented by the following Chap. 13 *SIMS on the Helium Ion Microscope: A Powerful Tool for High-resolution High-sensitivity Nanoanalytics* which set the current standard in the achievable lateral resolution limit in analytic applications. Chapter 14 on *Ionoluminescence* describes the possibilities and limitations of using photons to obtain information on the specimen beyond high quality images. Part III is more aimed at experienced users, and it demonstrates potential future development of the HIM technology platform.

Part IV *Modification* deals with the most frequent application of the Helium Ion Microscope, the controlled materials modification by focused ions. Chapter 15 *Direct–write Milling and Deposition with Noble Gases* serves as an introduction. It is full of practical hints on the operation of the HIM for the creation of nanostructures. Chapter 16 *Resist Assisted Patterning* summarizes a number of successful research efforts to use the HIM for resist patterning. It also discusses the resolution limits as well as the modeling of fundamental processes. The next two chapters, Chaps. 17 *Focused Helium and Neon Ion Beam Modification of High–T_C Superconductors and Magnetic Materials* and 18 *Helium Ion Microscope Fabrication of Solid-State Nanopore Devices for Biomolecule Analysis*, discuss three specialized applications of HIM. While Chap. 17 treats the modification of materials properties by partly extremely low ion fluences, Chap. 18 discusses the drilling of fine nanopores for DNA sequencing and other biotechnology applications. The final chapter, Chap. 19 *GFIS Applications in Semiconductors*, provides an in-depth view of the current use of HIM in the semiconductor industry and describes how semiconductor prototyping benefits from HIM-based circuit editing. This chapter is full of information about the industrial application of HIM and is recommended for novices as well as experts.

The book ends with *The ALIS Story*, a personal view on the history of the HIM written by Bill Ward, the inventor of the HIM ion source used today and the founder of the first helium ion microscope company "ALIS Corporation".

Finally, we would like to thank the University of Bielefeld, the University of Twente and the Helmholtz–Zentrum Dresden–Rossendorf for the privilege to be

among the first users of HIM. We also acknowledge Carl Zeiss and in particular the Ion Microscopy Innovation Center for their continuous technical support. We further thank the American Vacuum Society (AVS) for providing our small group of early HIM adaptors a regular discussion forum that eventually created an active HIM community and ignited the spark for this book.

Dresden, Germany Gregor Hlawacek
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