Surface Microscopy with Low Energy Electrons

Ernst Bauer

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Springer

Ernst Bauer
Department of Physics
Arizona State University
Tempe, AZ, USA

ISBN 978-1-4939-0934-6 ISBN 978-1-4939-0935-3 (eBook)
DOI 10.1007/978-1-4939-0935-3
Springer New York Heidelberg Dordrecht London

Library of Congress Control Number: 2014938038

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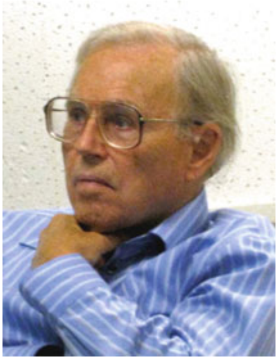
To Anastassia

About the Author



Professor Ernst Bauer is a distinguished German-American physicist and surface scientist who has made fundamental contributions to the understanding of epitaxial growth and to the development of microscopy techniques. He is one of the founders of surface physics and the physics of thin films.

In 1958 he derived the classification of the thin film growth mechanisms that provides the theoretical framework of epitaxy which is used worldwide to this day. In 1962 he invented LEEM (Low Energy Electron Microscopy), which came to fruition in 1985. In the late 1980s/early 1990s he extended the LEEM technique in two important directions by developing Spin-Polarized Low Energy Electron Microscopy (SPLEEM) and Spectroscopic Photo Emission and Low Energy Electron Microscopy (SPELEEM). The combination of these methods now allows a comprehensive (structural, chemical, magnetic, and electronic) characterization of surfaces and thin films on the 10 nm scale.

Ernst Bauer's interest in the development of synchrotron radiation microscopy techniques and his involvement with the Synchrotron source Elettra in Trieste, Italy resulted in the development of the Nanospectroscopy beamline, which is today one of the leading synchrotron radiation microscopy facilities worldwide.

His work directly or indirectly impacts many areas of modern materials science: surfaces, thin films, electronic materials, and instrumentation. The invention and development of surface microscopy with slow electrons has revolutionized the study of surface science and thin film science.

Ernst Bauer has authored or coauthored more than 450 publications (among them 85 review papers and book chapters) and one book ("Electron Diffraction: Theory, Practice and Applications," 1958, in German). His papers are widely cited.

Numerous LEEM instruments are now installed and are operating in many laboratories and synchrotron radiation facilities around the world (USA, Europe, Asia, and Australia). An important recognition for Ernst Bauer's efforts in the field of surface microscopy is the increasing number of the scientists involved in LEEM research, which is reflected in the organization of biannual LEEM/PEEM workshops, the first of which was organized by Ernst Bauer and Anastassia Pavlovska in Arizona in 1998.

Broad international collaboration is typical of Ernst Bauer's research. He had longstanding scientific cooperations with NASA, University of Pretoria (South Africa), Synchrotron Radiation Source in Trieste (Italy), Poland, Ukraine, Bulgaria, and Czech Republic. About 80 visiting scientists had a possibility to perform high-quality research in his group in Germany. Presently he has collaborations with Japan, Poland, Italy, Germany, and Hong Kong.

The scientific achievements of Ernst Bauer have been multiply honored. He was the recipient of the E.W. Muller Award in 1985, the Gaede Prize of the German Vacuum Society in 1988, the Medard W. Welch Award of the American Vacuum Society in 1992, the Niedersachsenpreis for Science (Germany) in 1994, the BESSY Innovation Award on Synchrotron Radiation in 2004, and the very prestigious Davisson-Germer Prize of the American Physical Society in 2005. In 2003 Ernst Bauer received the first Award of the Japan Society of Promotion of Science's 141st Committee on Microbeam Analysis and was made an honorary member of this organization. He was elected a Member of the Goettingen Academy of Sciences in 1989, Fellow of the American Physical Society in 1991, and Fellow of the American Vacuum Society in 1994. In 2008 he was honored with a Humboldt Research Prize and Doctor Honoris Causa at the Marie Sklodovska-Curie University, Lublin, Poland. In 2012 he was appointed Fellow of Elettra Sincrotrone Trieste and in 2014 he received the Doctor Honoris Causa title from the University of Wrocław, Poland.

More information can be found:
on Ernst Bauer's website at Arizona State University: http://ernstbauer.physics.asu.edu/ and in Wikipedia: Ernst G. Bauer.

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.

This book would never have been completed without the support of many people, foremost of my wife and coworker for more than 30 years, Anastassia Pavlovska. Without her encouragement it would never have been started and its completion would have been impossible without her strong steady support. She not only took care of all the figures, references, and permissions but also did a lot of editorial work, including correction of typographical and grammar errors, and making passages, which were difficult to read, more understandable. The amount and quality of work she did would justify including her as coauthor but then I could not have dedicated the book to her. Of all the other people whom I want to thank, I should first mention Ruud Tromp, Lothar Fritsche and John Spence, who helped me to understand a number of theoretical problems. There are many others who in some way or other contributed to this book. For figures I want to thank (listed alphabetically) M.S. Altman, R. Belkhou, J. Feng, K. Grzelakowski, E. Ilkova, M. Kiskinova, T. Koshikawa, M. Louwers (Philips), A. Locatelli, O. Menteş,

H. Ohldag, T. Osada (JEOL), A. Pang, T. Schmidt, S. Schramm and T. Yasue, some of whom have also contributed to the understanding of the background of the figures. In addition my thanks go to all the colleagues who have sent me their publication lists, preprints, and clarifications of their work. Finally I want to acknowledge the very important help in computer matters by J. Blackburn and the outstanding support by the library of my university and to thank David Packer and Sara Kate Heukerott (Springer), for their friendly and effective editorial guidance.

Tempe, AZ, USA
February, 2014

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List of Abbreviations

AEM	Auger electron microscopy
AES	Auger electron spectroscopy
AFC	Antiferromagnetic coupling
AFM	Antiferromagnetic, Atomic force microscopy (depending on context)
ARPES	Angle-resolved photoelectron spectroscopy
ARUPS	Angle-resolved ultraviolet photoelectron spectroscopy
CCD	Charge-coupled device
CFE	Cold field emission
CHA	Concentric hemispherical analyzer
CMOS	Complementary metal oxide semiconductor
CTF	Contrast transfer function
CVD	Chemical vapor deposition
CW	Continuous wave
DLD	Delay line detector
DQE	Detective quantum efficiency
EM	Electromagnetic
ESCA	Electron spectroscopy for chemical analysis
ESD	Electron-stimulated desorption
EXAFS	Extended X-ray absorption spectroscopy
FC	Ferromagnetic coupling
FEL	Free electron laser
FELPEEM	Free electron laser PEEM
FM	Ferromagnetic
FWHM	Full width at half maximum
HRTEM	High-resolution transmission electron microscopy
IMFP	Inelastic mean free path
ITR	Interferometric time resolution

LEED	Low energy electron diffraction
LEEM	Low energy electron microscopy
LEETS	Low energy electron transmission spectroscopy
LITD	Laser-induced thermal desorption
LSP	Localized surface plasmon
MCD	Magnetic circular dichroism
MCDPEEM	Magnetic circular dichroism photoemission electron microscopy
MCP	Multichannel plate
MEED	Medium energy electron diffraction
MEM	Mirror electron microscopy
MFM	Magnetic force microscopy
MIEEM	Metastable impact electron emission microscopy
MIES	Metastable impact electron spectroscopy
MLD	Magnetic linear dichroism
MTF	Modulation transfer function
NEXAFS	Near edge X-ray absorption fine structure
*n*PPE ($n = 2, 3, \ldots$)	*n*-Photon photoemission
*n*PPEEM	*n*-Photon photoemission electron microscopy
NPS	Noise power spectrum
OFET	Organic field effect transistor
PE	Photoelectron
PED	Photoelectron diffraction
PEEM	Photoemission electron microscopy
PFM	Piezoelectric force microscopy, piezoresponse force microscopy
PM	Paramagnetic
PSF	Point spread function
QE	Quantum efficiency
QSE	Quantum size effect
REM	Reflection electron microscopy
RHEED	Reflection high energy electron diffraction
RLD	Richardson-Laue-Dushman
SE	Secondary electron
SEEM	Secondary electron emission microscopy
SEM	Scanning electron microscopy
SEMPA	Scanning electron microscopy with polarization analysis
SLEEM	Scanning low energy electron microscopy
SP	Surface plasmon
SPELEEM	Spectroscopic photoemission and low energy electron microscopy

SPEM	Scanning photoemission microscopy
SPLEED	Spin-polarized low energy electron diffraction
SPLEEM	Spin-polarized low energy electron microscopy
SPP	Surface plasmon polariton
SREM	Scanning reflection electron microscopy
SRT	Spin reorientation transition
STEM	Scanning transmission electron microscopy
STM	Scanning tunneling microscopy
STXM	Scanning transmission X-ray microscopy
TCS	Total current spectroscopy
TE	Thermionic electron
TEEM	Thermionic electron emission microscopy
TEM	Transmission electron microscopy
TR-PEEM	Time-resolved photoemission microscopy
UHV	Ultrahigh vacuum
UPS	Ultraviolet photoelectron spectroscopy
UVMCDPEEM	Ultraviolet magnetic circular dichroism photoemission microscopy
UVPEEM	Ultraviolet photoemission microscopy
VLEED	Very low energy electron diffraction
VUV	Vacuum ultraviolet
XANES	X-ray absorption near edge structure
XAS	X-ray absorption spectroscopy
XLD	X-ray linear dichroism
XLDPEEM	X-ray linear dichroism photoemission microscopy
XMCD	X-ray magnetic circular dichroism
XMCDPEEM	X-ray magnetic circular dichroism photoemission microscopy
XMLD	X-ray magnetic linear dichroism
XMLDPEEM	X-ray magnetic linear dichroism photoemission microscopy
XNLD	X-ray natural linear dichroism
XNLDPEEM	X-ray natural linear dichroism photoemission microscopy
XPEEM	X-ray photoemission microscopy
XPS	X-ray photoemission spectroscopy
XSPEM	X-ray scanning photoemission microscopy
XUV	Extreme ultraviolet