Nanoscale Processes on Insulating Surfaces

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About the authors

Dr. Enrico Gnecco was awarded his Ph.D. from the University of Genova in 2000. He started his research activities as an undergraduate student with investigations of current noise in Hg and Tl based high-temperature superconductors. His Ph.D. thesis focused on nanotribology, i.e. the study of friction and wear processes occurring on the nanometer scale. Within the group of Prof. Ugo Valbusa he characterized the growth of amorphous carbon films by scanning probe microscopy, and studied the relationship between friction and self-affine properties of these films. In the second part of his Ph.D. studies, he joined the group of Prof. Ernst Meyer in Basel, where he investigated friction processes on alkali halide surfaces in ultra high vacuum (UHV). The main result was the observation of a logarithmic velocity dependence of atomic friction, which was interpreted within a combination of the classical Tomlinson and Eyring models.

After his Ph.D. he joined the Swiss National Center of Competence of Research in Nanoscale Science, where he studied other basic nanotribological phenomena, such as abrasion wear on ionic crystals in UHV, various forms of superlubricity onset transitions, and electromechanical methods to reduce friction on the atomic scale. Most of these experiments were performed on insulating surfaces, and have found promising applications in the development of micro- and nano-devices. He also investigated self-assembly of organic molecules on insulators, using an original technique to trap molecules in rectangular nanopits produced by electron irradiation. He is also interested in surface nanomanipulation on different systems (from metal clusters to single molecules) with the goal of evaluating the dissipative forces accompanying the manipulation process.

E.G. has co-authored more than 40 scientific publications, including articles on Science, Nanoletters, Nanotechnology, and Physical Review. He was also awarded a diploma in piano from the Conservatory of Music of his hometown, Genova.

Prof. Marek Szymonski was awarded his Ph.D. from the Jagiellonian University, Krakow, in 1978. He joined the Physics Department of the Jagiellonian University in 1973, he was awarded a higher doctoral degree (so called ‘habilitation’) in 1982, and he was appointed to the full professor position at this University in 1991. He held several positions during his academic carrier, such as Vice-Rector of the Jagiellonian University (1993-1999), Chairman of the Supervisory Board for the ‘Krakow Center for

Advanced Technologies' (1998-1999), Chairman, Scientific Council of the Regional Laboratory for Physicochemical Analysis, Jagiellonian University (1999-2006), Dean of the Faculty of Physics of the Jagiellonian University (2003-2005), and President of the Polish Vacuum Society (1996-1998 and 2004-2007). He also served several international posts, such as Councilor (1992-1998 and 2004-2007) and Alternate Councilor (2001-2004) to the Executive Council of the Int. Union for Vacuum Science, Technology and Applications and Chairman of the European Representative Committee of IUVESTA (2004-2007). Currently he is heading the Division of Physics of Nanostructures and Nanotechnology of the Institute of Physics, Jagiellonian University, and he is Director of the Research Center on Nanometer-Scale Science and Advanced Materials, NANOSAM, at the Jagiellonian University.

His scientific record includes over 130 scientific publications and several dozens of invited lectures at scientific conferences. He was Ph.D. thesis supervisor for 12 Ph.D. students and for many M.Sc. graduates. He organized several national and international research workshops and conferences, among them the 20th European Conference on Surface Science (ECOSS-20), 2001, and the 12th International Conference on Organized Molecular Films (LB 12), 2007.

His research activities are concentrated on those topics of materials research which are related to properties of nano-size materials with particular focus on scanning probe methods, to design and characterization of functional materials with emphasis on semiconductors, dielectrics and molecular structures, to quantum phenomena in mesoscopic systems, to manufacturing and characterization of self-assembling structures, and to research on biomedical materials. His interest in ionic insulators dates back to 1977 when he participated in the pioneering experiments on electron-stimulated desorption of alkali halides together with Hans Overijnder and Dolf de Vries from the FOM Institute of Atomic and Molecular Physics in Amsterdam.

Preface

The rapid development of scanning probe microscopy (SPM) has made possible investigations of morphological and physical properties of insulating surfaces with unprecedented resolution. Since the ‘father’ of the SPM family — the scanning tunneling microscope (STM) — can only be applied to image ultrathin insulating films grown on conducting surfaces, most of the SPM investigations on insulators have been performed using the atomic force microscope (AFM). The principle of AFM is simple: an ultrasharp tip is driven over a surface, and the tip-surface interaction is reconstructed by monitoring the deflection of a flexible cantilever supporting the tip. Thanks to the extraordinary sensitivity of the piezo-elements used for positioning the tip with respect to the surface, atomically resolved images of several insulating crystal surfaces can be readily obtained in such a way.

Before introducing the AFM and STM techniques, we briefly discuss the crystallographic structures and preparation methods of various insulating surfaces in the first two chapters. Our attention will be limited to alkali halide surfaces and to oxide surfaces with large band gaps. We will not address other insulating surfaces, such as those of polymers, plastics, glasses and minerals like mica, where the interpretation of the SPM results is often not so conclusive. We will also not cover issues like chemical reactivity of the surfaces except when they become relevant to interpret SPM images.

Alkali halide surfaces have a simple structure and can be easily prepared and characterized in an ultra high vacuum environment (UHV). For these reasons, they have quickly become reference models to investigate crystal growth processes on the nanometer scale. Alkali halide surfaces are also important playgrounds for nanoscale phenomena such as self-assembly of metal clusters and large organic molecules, or friction and wear processes.

Insulating oxide surfaces find a broad use in several applications, ranging from interfaces for electronic ceramics to chemical catalysis. Even if they are more difficult to characterize, these surfaces are still amenable to fundamental investigations on the nanoscale, and high-resolution SPM images can be obtained after the surfaces have been carefully prepared.

The central part of the book begins with Chapters 4 and 5. Here we will focus on bulk and ultrathin insulating surfaces as imaged by SPM. Atomic resolution is unquestionable when single defects are imaged, which is now commonly achieved on several structures studied by AFM. Some defects like vacancies can be even created and subsequently imaged by the same AFM tip, which gives important information on the scanning process itself. Several experimental results have been also complemented by theoretical simulations of the imaging process, which allowed to identify the main forces responsible for atomic resolution.

Chapters 6, 7 and 8 introduce the interaction of ions, electrons and photons with halide surfaces, with special emphasis on the nanostructures created by the interaction processes. The discussion of the basic mechanisms responsible for crystal erosion and large surface nanopatterning with nanometer precision is supplemented by recent experimental results obtained by means of high resolution AFM imaging.

Chapters 9 and 10 deal with self-assembly of metals and organic molecules on bare and nanopatterned insulating surfaces. Once again the discussion of the experimental results is complemented by theoretical interpretations of the imaging process. Since the ordering of metal and molecular adsorbates is often hindered by the weak interaction between adsorbate and substrate, nanopatterns play an important role in improving the stability of the adsorbed species. For instance, self-assembly can be readily achieved along monatomic step edges or inside nanometer-sized pits produced by electron irradiation. As a further step, connecting well-defined molecular assemblies to external electrodes via metal nanowires grown on insulating surfaces might become feasible in the near future.

In Chapter 11 we discuss force spectroscopy measurements on insulating surfaces. In such cases, the response of the SPM tip is monitored at different separations between tip and surface, which gives important information on the tip-surface interaction. If a current flow between tip and sample can be established, by decreasing the band gap in the material, scanning tunneling spectroscopy (STS) is also possible. With this technique metals and organic molecules deposited on thin insulating films can be also investigated, and different electronic states of single molecules have been even identified.

The last two chapters deal with mechanical phenomena induced and observed using SPM on insulating surfaces. These processes include friction, wear, indentation and manipulation of tiny nano-objects. While several important results have been obtained in the first three topics — last but not least the achievement of superlubricity — nanomanipulation on insulating surfaces is still in its embryonic phase. However, nanomanipulation has such potential applications to molecular electronics and nanomechanics that exciting experiments are on sight, once again driven by theoretical models.

This book could have not been written without the collaboration of several people who supported us during the time of writing. Even if it is not possible to cite all of them, a special thanks goes to Jacek J. Kolodziej, Franciszek Krok, Bartosz Such, Piotr Cyganik, Piotr Goryl, Piotr Piatkowski, Janusz Budzioch and Salah Raza Saeed from the Jagiellonian University of Krakow, and Ernst Meyer, Roland Bennewitz, Luca Ramoino, Sabine Maier, Laurent Nony, Anisoara Socoliuc, Alexis Baratoff, Thilo Glatzel, Lars Zimmerli, Oliver Pfeiffer, Akshata Rao, Pascal Steiner and Raphael Roth from the University of Basel. We also thank Urszula Lustofin for administrative assistance and Tim Ashworth for carefully reviewing parts of the book. E.G. would like to thank his wife Tatiana for her patience and for continuous encouragement while writing this book. Financial support from the European Community under the Maria Curie Host Fellowship for Transfer of Knowledge (contract no. MTKD-CT-2004-003132), the Polish Foundation for Science (contract for subsidy no. 11/2007), and the Swiss National Science Foundation and NCCR Nanoscale Science is also gratefully acknowledged.

E. Gnecco and M. Szymonski

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