Functional Thin Films and Nanostructures for Sensors

Integrated Analytical Systems

Series Editor: Dr. Radislav A. Potyrailo
GE Global Research, Niskayuna, NY

For other titles published in this series, go to
www.springer.com/series/7427

Anis Zribi • Jeffrey Fortin
Editors

Functional Thin Films and Nanostructures for Sensors

Synthesis, Physics, and Applications

Springer

Editors
Anis Zribi
United Technologies Corporation
Fire and Security
Kidde Detection Technology Research
Development and Engineering
Colorado Springs, CO
USA

Jeffrey Fortin
GE Global Research Center
Micro and Nano Structures Technologies
Niskayuna, NY
USA

ISBN: 978-0-387-36229-8 e-ISBN: 978-0-387-68609-7
DOI: 10.1007/978-0-387-68609-7

Library of Congress Control Number: 2008944096

Printed on acid-free paper

springer.com

To our families and parents.
Olena, Nadia
Michelle, Abi, Libby

Foreword

In recent years, there has been a convergence of fundamental materials science and materials processing methods. This convergence, although highly interdisciplinary in nature, has been brought about by technologies such as bandgap engineering and related techniques that have led to application-specific devices such as lab-on-a-chip and system-on-a-chip. The demand for reduced device size, device portability, and low power dissipation coupled with high speed of operation continues to dictate terms and conditions for the evolution of nanotechnology. The present trend in approaches to systems manufacturing continues to focus on integration of multi-functionalities on the same chip. These functionalities include, for example, on-board laser sources, sensors, and amplifiers. Both the military and civilian markets continue to drive the research and development component. In recent years, the emergency preparedness guidance systems have added excitement and curiosity to this expanding industry. The outgrowth of technologies of interest for emergency preparedness includes the development of terahertz sources and detectors and systems for detection of explosives and concealed weapons, among others.

Sensors made from bulk materials have been around for a long time. Enormous advances in the processing technologies of thin films have led to the ability to manufacture application-specific functional thin films. These include transparent electrodes and antireflection films such as indium tin oxide, which serve as interface components between humans and electronic devices, or optical circuit elements used in optical communication networks, or as contacts and antireflection coatings in solar cells. Products are also being developed with magneto-optical, electrochromic, or UV material for their use as functional thin films in optics. Photonic crystals contain a variety of functional thin films; they require processing of thin films under very stringent control of their structure and properties.

For microelectromechanical systems (MEMS), in addition to silicon-based technology, ferroelectric thin films are being used in the fabrication of microactuators and micromotors, capacitors, and other thin-film devices. Functional thin films are being used in the manufacture of devices such as surface acoustic wave (SAW) devices for high-frequency telecommunications filtering, infrared detectors, pressure sensors, accelerometers, force sensors, vibration, thickness, and chemical sensors and biosensors. The reduction in size from bulk to micro- and nanostructured transducers, while promising high sensitivity, high speed, and increased selectivity, requires new design considerations that should consider factors such as integration with other devices and device lifetime.

Functional thin films offer an enormous infrastructure for a highly interdisciplinary integration of inorganic/semiconducting, organic/bio, and electronic/optoelectronic sensor systems. The field is constantly evolving and will continue to do so by absorbing novel materials approaches such as carbon nanotubes, high Tc superconductors, ferroelectrics, and thermoelectrics.

The chapters in this book are designed to give the reader the big picture, from the design phase to the implementation and realization of a transducer. Every effort has been made to include the state-of-the-art in each chapter. The intended audience is scientists, researchers, and engineers, however, graduate students will find the book to be very useful in their research and understanding of sensors and beyond. The editors and contributors are leading researchers in industry and academia in their subject areas.

Newark, New Jersey N. M. Ravindra
February 2008

Series Preface

In my career I've found that "thinking outside the box" works better if I know what's "inside the box."

Dave Grusin, composer and jazz musician

Different people think in different time frames: scientists think in decades, engineers think in years, and investors think in quarters.

Stan Williams, Director of Quantum Science Research,Hewlett Packard Laboratories

Everything can be made smaller, never mind physics;
Everything can be made more efficient, never mind thermodynamics;
Everything will be more expensive, never mind common sense.

Tomas Hirschfeld, pioneer of industrial spectroscopy

Integrated Analytical Systems

Series Editor: Dr. Radislav A. Potyrailo, GE Global Research, Niskayuna, NY

The book series *Integrated Analytical Systems* offers the most recent advances in all key aspects of development and applications of modern instrumentation for chemical and biological analysis. The key development aspects include: (i) innovations in sample introduction through micro- and nanofluidic designs; (ii) new types and methods of fabrication of physical transducers and ion detectors; (iii) materials for sensors that became available due to the breakthroughs in biology, combinatorial materials science, and nanotechnology; and (iv) innovative data processing and mining methodologies that provide dramatically reduced rates of false alarms.

A multidisciplinary effort is required to design and build instruments with previously unavailable capabilities for demanding new applications. Instruments with more sensitivity are required today to analyze ultratrace levels of environmental pollutants, pathogens in water, and low vapor pressure energetic materials in air.

Sensor systems with faster response times are desired to monitor transient in vivo events and bedside patients. More selective instruments are sought to analyze specific proteins in vitro and analyze ambient urban or battlefield air. For these and many other applications, new analytical instrumentation is urgently needed. This book series is intended to be a primary source of both fundamental and practical information of where analytical instrumentation technologies are now and where they are headed in the future.

Looking back over peer-reviewed technical articles from several decades ago, one notices that the overwhelming majority of publications on chemical analysis has been related to chemical and biological sensors and has originated from departments of chemistry in universities and divisions of life sciences of governmental laboratories. Since then, the number of disciplines has dramatically increased because of the ever-expanding needs for miniaturization (e.g., for in vivo cell analysis, embedding into soldier uniforms), lower power consumption (e.g., harvested power), and the ability to operate in complex environments (e.g., whole blood, industrial water, or battlefield air) for more selective, sensitive, and rapid determination of chemical and biological species. Compact analytical systems that have a sensor as one of the system components are becoming more important than individual sensors. Thus, in addition to traditional sensor approaches, a variety of new themes has been introduced to achieve an attractive goal of analyzing chemical and biological species on the micro- and nanoscale.

Preface

Anyone with the most cursory knowledge of sensors must have had a chance to use such devices at some point in their life or career. Whether to collect data in a lab course, to automate an otherwise tedious process, to improve the efficiency of a delicately tuned process, or to do something as mundane as taking a family picture, sensors have become an integral part of our environment and our daily lives. Charge-coupled devices also known as CCD photodetector arrays, for example, have revolutionized photography, astronomy, spectroscopy, X-ray diffraction, and medical imaging to name but a few. A number of scientific discoveries have been enabled by CCDs including the possibility to determine molecular and lattice structures at intermediate stages of a chemical synthesis or a structural transformation. At the core of the widespread adoption of sensors are their rapidly decreasing footprint and cost and increased functionality. The miniaturization of solid-state devices in general and sensors in particular was made possible thanks to significant transformations and a large number of incremental and disruptive inventions in the area of thin-film and nanostructure science and fabrication technologies.

Thin films and nanostructures can play multiple roles in a sensor including structural support, reliability enhancement, filtering, and transduction. Thin films and nanostructures are called functional when they fulfill a function other than structural support. These micro- and nanostructured materials have applications that extend far beyond sensing to data storage, lighting, displays, hydrophobic coatings, decoration, and a large number of other fields that are outside the scope of this book. In this book, these materials are discussed in the context of transduction and how they contributed to the current sensor revolution.

Sensor design and fabrication are multidisciplinary and require broad and deep knowledge in diverse areas of science and engineering such as materials science, physics, chemistry, biology, and mechanical and electrical engineering. Covering a subject with so many roots in diverse scientific and engineering disciplines is undoubtedly a daunting task and any author who attempts it will do so with significant trepidation. Aware of the challenge at hand, the editors of this book attempted, ambitiously, to cover in one volume an account of general sensor theory, design considerations related to the use of functional thin films and nanostructures, and specific case studies of functional thin films and nanostructure applications in sensing. Part of our motivation in taking on this task is that no such work, to our knowledge, has been published. Having said this, we are strongly familiar with the large body of publications in this area that we refer to in this book and we are keenly indebted to the works of many authors in putting this book together.

This book is devoted to teaching the new sensor designer the key steps involved in developing sound transducer technology from materials selection, to design for performance, to process development, and finally to integration. Throughout the chapters, the authors emphasize and highlight the important role played by functional thin films in solving problems and discuss how to take advantage of such materials to build superior devices. The book is also intended to provide the more experienced designers with a condensed summary of sensor design methodology and excellent references that will prove useful in future sensor design endeavors. To put all of the shared design and fabrication knowledge into perspective and add a touch of reality to the concepts discussed in Chapters 1 through 4, Chapters 5 through 8 are completely dedicated to putting the theory into practice and demonstrating the whole design process using a number of concrete applications.

February 2008

Anis Zribi
Jeffrey Fortin

Editor Biographies

Anis Zribi is the manager of the Detection Technology Research, Development and Engineering group at Kidde UTC Fire and Security. Prior to joining UTC, he was a senior scientist and a principal investigator at the Global Research Center (GRC) of General Electric where he (leads) led research in the area of Microsystems and microfluidics for chemical and biological detection. He received an M.S.E. in physics from the Polytechnic Institute of Engineering (1996 France), an M.S. in materials physics from Chalmers University of Technology (1998 Sweden) and a Ph.D. in materials science from the State University of New York (2002 NY). Since joining GRC in 2002, Dr. Zribi has contributed to and led several projects including the Nanotechnology Advanced Technology Program, the Photonics Advanced Technology Program, and a number of MEMS sensors and actuators projects. His research interests and activities at GRC include MEMS spectrometers, chemical and biological sensing, magnetic field sensing, medical parameters sensing, fouling detection, and micro- and nanotransducers. Dr. Zribi holds 7 patents and over 40 pending patent applications in MEMS, photonics, and sensors. He authored or co-authored more than 32 articles in peer-reviewed journals and conference proceedings and two book chapters.

Jeff Fortin is the manager of the Microsystems and Microfluidics Lab at GE Global Research in Niskayuna, NY. His team's charter is to develop and deliver innovative micro- and nanosystems and microfluidics via the development and integration of MEMS and NEMS sensing, actuation, and microfluidic technologies, driving miniaturization, increased performance, portability, and low cost. Jeff holds a Ph.D. in engineering science from Rensselaer Polytechnic Institute, an M.S. in physics from RPI, and a B.A. in physics from the University of Southern Maine. He has over ten years of experience in semiconductor technology, MEMS, and microsensors. He joined GE GRC in 2000 and since this time his research has focused on MEMS and microsystems design and fabrication for a variety of microsensor and microactuator applications for GE. He holds ten patents and has co-authored over 12 refereed journal articles in the area of MEMS, thin polymer film development, and chemical vapor deposition as well as eight conference publications. He is also the co-author of a text on chemical vapor deposition polymerization of parylene and is a member of the MRS.

Contents

Contributors

Jeffrey Fortin
GE Global Research Center
Micro and Nano Structures Technologies

Chang Liu
Northwestern University
Department of Mechanical Engineering

Audry Nelson
GE Sensing, TelAire

Radislav Potyrailo
GE Global Research Center

Vicktor Ryzhii
University of Aizu
Computer Solid State Physics Laboratory

Wei-Cheng Tian
GE Global Research Center
Micro and Nano Structures Technologies

Magnus Willander
Linköping University
Institute of Science and Technology

Qingxiang Zhao
Linköping University
Institute of Science and Technology

Yiping Zhao
University of Georgia
Department of Physics and Astronomy

Anis Zribi
United Technologies Corporation Fire and Security, Kidde Detection
Technology Research, Development and Engineering Colorado Springs,
CO, USA