

传感材料与传感技术丛书

Sensing Material and Sensing Technology Series

CHEMICAL SENSORS SIMULATION AND MODELING

Volume 3 Solid-State Devices

EDITED BY GHENADII KOROTCENKOV

影印版

化学传感器：仿真与建模

第3卷 固态设备

下册



哈尔滨工业大学出版社
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Ghenadii Korotcenkov

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PREFACE

This series, *Chemical Sensors: Simulation and Modeling*, is the perfect complement to Momentum Press's six-volume reference series, *Chemical Sensors: Fundamentals of Sensing Materials* and *Chemical Sensors: Comprehensive Sensor Technologies*, which present detailed information about materials, technologies, fabrication, and applications of various devices for chemical sensing. Chemical sensors are integral to the automation of myriad industrial processes and everyday monitoring of such activities as public safety, engine performance, medical therapeutics, and many more.

Despite the large number of chemical sensors already on the market, selection and design of a suitable sensor for a new application is a difficult task for the design engineer. Careful selection of the sensing material, sensor platform, technology of synthesis or deposition of sensitive materials, appropriate coatings and membranes, and the sampling system is very important, because those decisions can determine the specificity, sensitivity, response time, and stability of the final device. Selective functionalization of the sensor is also critical to achieving the required operating parameters. Therefore, in designing a chemical sensor, developers have to answer the enormous questions related to properties of sensing materials and their functioning in various environments. This five-volume comprehensive reference work analyzes approaches used for computer simulation and modeling in various fields of chemical sensing and discusses various phenomena important for chemical sensing, such as surface diffusion, adsorption, surface reactions, sintering, conductivity, mass transport, interphase interactions, etc. In these volumes it is shown that theoretical modeling and simulation of the processes, being a basic for chemical sensor operation, can provide considerable assistance in choosing both optimal materials and optimal configurations of sensing elements for use in chemical sensors. The theoretical simulation and modeling of sensing material behavior during interactions with gases and liquid surroundings can promote understanding of the nature of effects responsible for high effectiveness of chemical sensors operation as well. Nevertheless, we have to understand that only very a few aspects of chemistry can be computed exactly.

However, just as not all spectra are perfectly resolved, often a qualitative or approximate computation can give useful insight into the chemistry of studied phenomena. For example, the modeling of surface-molecule interactions, which can lead to changes in the basic properties of sensing materials, can show how these steps are linked with the macroscopic parameters describing the sensor response. Using quantum mechanics calculations, it is possible to determine parameters of the energetic (electronic) levels of the surface, both inherent ones and those introduced by adsorbed species, adsorption complexes, the precursor state, etc. Statistical thermodynamics and kinetics can allow one to link those calculated surface parameters with surface coverage of adsorbed species corresponding to real experimental conditions (dependent on temperature, pressure, etc.). Finally, phenomenological modeling can tie together theoretically calculated characteristics with real sensor parameters. This modeling may include modeling of hot platforms, modern approaches to the study of sensing effects, modeling of processes responsible for chemical sensing, phenomenological modeling of operating characteristics of chemical sensors, etc.. In addition, it is necessary to recognize that in many cases researchers are in urgent need of theory, since many experimental observations, particularly in such fields as optical and electron spectroscopy, can hardly be interpreted correctly without applying detailed theoretical calculations.

Each modeling and simulation volume in the present series reviews modeling principles and approaches particular to specific groups of materials and devices applied for chemical sensing. *Volume 1: Microstructural Characterization and Modeling of Metal Oxides* covers microstructural characterization using scanning electron microscopy (SEM), transmission electron spectroscopy (TEM), Raman spectroscopy, in-situ high-temperature SEM, and multiscale atomistic simulation and modeling of metal oxides, including surface state, stability, and metal oxide interactions with gas molecules, water, and metals. *Volume 2: Conductometric-Type Sensors* covers phenomenological modeling and computational design of conductometric chemical sensors based on nanostructured materials such as metal oxides, carbon nanotubes, and graphenes. This volume includes an overview of the approaches used to quantitatively evaluate characteristics of sensitive structures in which electric charge transport depends on the interaction between the surfaces of the structures and chemical compounds in the surroundings. *Volume 3: Solid-State Devices* covers phenomenological and molecular modeling of processes which control sensing characteristics and parameters of various solid-state chemical sensors, including surface acoustic wave, metal-insulator-semiconductor (MIS), microcantilever, thermoelectric-based devices, and sensor arrays intended for “electronic nose” design. Modeling of nanomaterials and nanosystems that show promise for solid-state chemical sensor design is analyzed as well. *Volume 4: Optical Sensors* covers approaches used for modeling and simulation of various types of optical sensors such as fiber optic, surface plasmon resonance, Fabry-Pérot interferometers, transmittance in the mid-infrared region,

luminescence-based devices, etc. Approaches used for design and optimization of optical systems aimed for both remote gas sensing and gas analysis chambers for the nondispersive infrared (NDIR) spectral range are discussed as well. A description of multiscale atomistic simulation of hierarchical nanostructured materials for optical chemical sensing is also included in this volume. *Volume 5: Electrochemical Sensors* covers modeling and simulation of electrochemical processes in both solid and liquid electrolytes, including charge separation and transport (gas diffusion, ion diffusion) in membranes, proton–electron transfers, electrode reactions, etc. Various models used to describe electrochemical sensors such as potentiometric, amperometric, conductometric, impedimetric, and ion-sensitive FET sensors are discussed as well.

I believe that this series will be of interest of all who work or plan to work in the field of chemical sensor design. The chapters in this series have been prepared by well-known persons with high qualification in their fields and therefore should be a significant and insightful source of valuable information for engineers and researchers who are either entering these fields for the first time, or who are already conducting research in these areas but wish to extend their knowledge in the field of chemical sensors and computational chemistry. This series will also be interesting for university students, post-docs, and professors in material science, analytical chemistry, computational chemistry, physics of semiconductor devices, chemical engineering, etc. I believe that all of them will find useful information in these volumes.

G. Korotcenkov

ABOUT THE EDITOR

Ghenadii Korotcenkov received his Ph.D. in Physics and Technology of Semiconductor Materials and Devices in 1976, and his Habilitate Degree (Dr. Sci.) in Physics and Mathematics of Semiconductors and Dielectrics in 1990. For a long time he was a leader of the scientific Gas Sensor Group and manager of various national and international scientific and engineering projects carried out in the Laboratory of Micro- and Optoelectronics, Technical University of Moldova. Currently, Dr. Korotcenkov is a research professor at the Gwangju Institute of Science and Technology, Republic of Korea.

Specialists from the former Soviet Union know Dr. Korotcenkov's research results in the field of study of Schottky barriers, MOS structures, native oxides, and photoreceivers based on Group III-V compounds very well. His current research interests include materials science and surface science, focused on nanostructured metal oxides and solid-state gas sensor design. Dr. Korotcenkov is the author or editor of 11 books and special issues, 11 invited review papers, 17 book chapters, and more than 190 peer-reviewed articles. He holds 18 patents, and he has presented more than 200 reports at national and international conferences.

Dr. Korotcenkov's research activities have been honored by an Award of the Supreme Council of Science and Advanced Technology of the Republic of Moldova (2004), The Prize of the Presidents of the Ukrainian, Belarus, and Moldovan Academies of Sciences (2003), Senior Research Excellence Awards from the Technical University of Moldova (2001, 2003, 2005), a fellowship from the International Research Exchange Board (1998), and the National Youth Prize of the Republic of Moldova (1980), among others.



CONTRIBUTORS

Samir H. Mushrif (Chapter 1)

Catalysis Centre for Energy Innovation and Department of
Chemical Engineering
University of Delaware
Newark, Delaware 19716, USA

Gilles H. Peslherbe (Chapter 1)

Centre for Research in Molecular Modeling and
Department of Chemistry and Biochemistry
Concordia University Montréal, Québec, Canada H4B 1R6

Alejandro D. Rey (Chapter 1)

Department of Chemical Engineering
McGill University, Montréal, Québec, Canada H3A 2B2

Karin Larsson (Chapter 2)

Department of Chemistry—Ångström Laboratory
Uppsala University
753 10 Uppsala, Sweden

James L. Gole (Chapter 3)

Schools of Physics and Mechanical Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332, USA

William Laminack (Chapter 3)

Schools of Physics and Mechanical Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332, USA

Vinod Kumar Khanna (Chapter 4)

MEMS & Microsensors

CSIR—Central Electronics Engineering Research Institute

Pilani-333031 (Rajasthan), India

Linfeng Zhang (Chapter 5)

Department of Electrical Engineering

University of Bridgeport

Bridgeport, Connecticut 06604, USA

Gerhard Fischerauer (Chapter 6)

Chair of Metrology and Control Engineering

Universität Bayreuth

95440 Bayreuth, Germany

Florian Thalmayr (Chapter 6)

Micro Electro Mechanical Systems Design

Sand 9 Inc.

Cambridge, Massachusetts 02139, USA

Viatcheslav Barkaline (Chapter 7)

System Dynamics & Material Mechanics Laboratory

Belarusian National Technical University

Minsk, 220013, Belarus

Aliaksandr Chashynski (Chapter 7)

System Dynamics & Material Mechanics Laboratory

Belarusian National Technical University

Minsk, 220013, Belarus

Sophie Martin (Chapter 8)

Institut des Matériaux Jean Rouxel (IMN), CNRS

Université de Nantes

44322 Nantes cedex 3, France

Guy Louarn (Chapter 8)

Institut des Matériaux Jean Rouxel (IMN), CNRS

Université de Nantes

44322 Nantes cedex 3, France

Sergi Udina (Chapter 9)

Departament d'Electrònica

Universitat de Barcelona

08028 Barcelona, Spain

and

Artificial Olfaction Group

Institute for Bioengineering of Catalonia (IBEC)

08028 Barcelona, Spain

Manuel Carmona (Chapter 9)

Electronics Department

Universitat de Barcelona

08028 Barcelona, Spain

Carlos Calaza (Chapter 9)

Instituto de Microelectrónica de Barcelona—Centro Nacional de Microelectrónica (IMB-CNM)

Consejo Superior de Investigaciones Científicas (CSIC)

08193 Barcelona, Spain

R. D. S. Yadava (Chapter 10)

Sensors & Signal Processing Laboratory

Department of Physics, Faculty of Science

Banaras Hindu University

Varanasi 221005, India

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MODELING AND SIGNAL PROCESSING STRATEGIES FOR MICROACOUSTIC CHEMICAL SENSORS

G. Fischerauer

F. Thalmayr

1. SENSING PRINCIPLES OF MICROACOUSTIC CHEMICAL SENSORS

1.1. INTRODUCTION

Microacoustic devices are miniaturized physical units based on the interaction of elastic waves with electric fields at kilohertz, megahertz, or gigahertz frequencies. The interaction is effected by plate or interdigital electrodes close to a piezoelectric material and connected with the electrical terminals of the device. As the efficiency of the electroacoustic transduction inside the microacoustic device depends on frequency, the device can be used as a frequency filter. In fact, such filters have been sold by the billions and are omnipresent in TV sets, cellular phones, remote controls, etc.

Figure 6.1 shows some common geometries of microacoustic devices. In principle, the device characteristics such as, e.g., the frequency response depend not only on the materials involved and the geometry, but also on disturbance variables such as temperature, mechanical stresses, atmospheric pressure, etc. When used for signal processing purposes, the devices are housed in packages

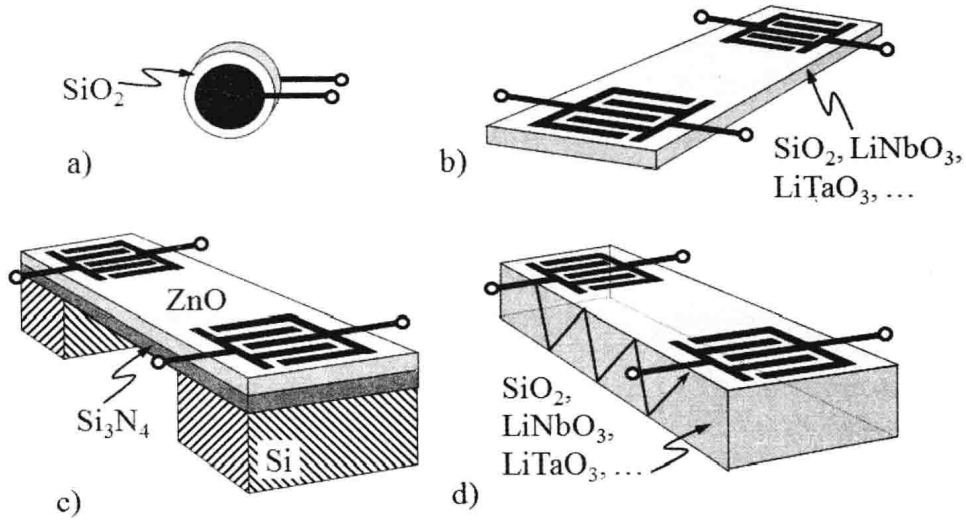


Figure 6.1. Microacoustic device geometries with plate electrodes (a) and interdigital electrodes (b–d), respectively. (a) Quartz crystal resonator. (b) Surface acoustic wave (SAW) device. (c) Membrane (Lamb wave) geometry. (d) Acoustic plate mode (APM) device. Single-crystal quartz (SiO_2), lithium niobate (LiNbO_3), lithium tantalate (LiTaO_3), and zinc oxide (ZnO) are all piezoelectric materials.

that shield them from environmental influences as much as possible. The wanted action path runs from an input voltage $v_{\text{in}}(t)$ applied between, e.g., the terminals of an interdigital transducer (IDT) to an output voltage $v_{\text{out}}(t)$ showing up between the two electrodes of another IDT (Figure 6.2). In between, $v_{\text{in}}(t)$ is converted to an acoustic wave, described, for instance, by the scalar wave amplitude $w_1(t)$ in a chosen reference plane. This wave propagates along the substrate surface and arrives at the output IDT with amplitude $w_2(t)$, which is reconverted to the voltage $v_{\text{out}}(t)$. A disturbance variable $z(t)$ from which the device is not sufficiently isolated will corrupt both $w_2(t)$ and $v_{\text{out}}(t)$.

The latter effect can be used to monitor the disturbance variable $z(t)$. This is the basic principle of microacoustic sensors. In this context, the variable $z(t)$ is not a disturbance at all, but the wanted input variable, the value of which must be retrieved from a suitable feature of the output voltage $v_{\text{out}}(t)$ of the microacoustic device. Commonly used features are related to the frequency response $G_v(j\omega)$ of the device, defined as

$$G_v(j\omega) = \frac{V_{\text{out}}(j\omega)}{V_{\text{in}}(j\omega)} = |G_v(j\omega)| \cdot e^{j\varphi_v(\omega)} \quad (6.1)$$

where $V_{\text{in}}(j\omega)$ and $V_{\text{out}}(j\omega)$ are the Fourier transforms of $v_{\text{in}}(t)$ and $v_{\text{out}}(t)$, respectively. Such features are, for instance, the center angular frequency ω_0 (where

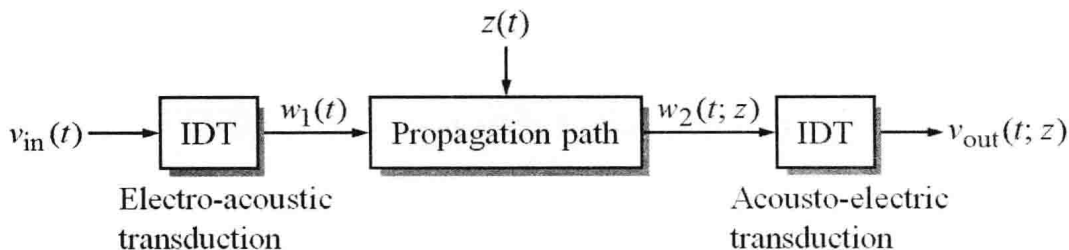


Figure 6.2. Functional diagram of a microacoustic device (see text).

the gain response $|G_v(j\omega)|$ peaks) or the group delay time at center frequency, $\tau_{gr} = -d\phi_v/d\omega|_{\omega=\omega_0}$ (roughly the time it takes an acoustic wave packet to propagate from the input IDT to the output IDT).

1.2. MICROACOUSTIC CHEMICAL SENSORS

From the preceding section, it is obvious that any variable that influences the propagation velocity v of the acoustic waves in a microacoustic device will modulate certain features of the output voltage $v_{out}(t)$. We are here concerned with the ambient, or external, concentration $c_e(t)$ of an analyte molecule. To make it act on the microacoustic device, the latter is coated with a thin layer which selectively incorporates the analyte molecules of interest (Figure 6.3). In this manner, one obtains a chemical sensor converting $c_e(t)$ to a feature of the voltage $v_{out}(t)$. The thin film can be deposited by spraying, brushing, dipping, spin-on, physical vapor deposition, chemical vapor deposition, or a number of other methods.

Both the acoustic wave velocity and the propagation attenuation depend on the substrate material parameters, the sensor film material parameters, and the boundary conditions at the surface. As a consequence, there exist several

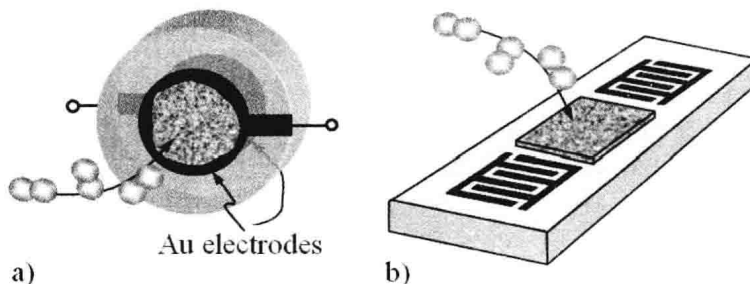


Figure 6.3. Examples of microacoustic chemical sensors. (a) Quartz crystal microbalance (QMB), obtained by coating a quartz crystal resonator with a selective layer. (b.) Surface acoustic wave (SAW) sensor, obtained by coating a SAW delay line with a selective layer.