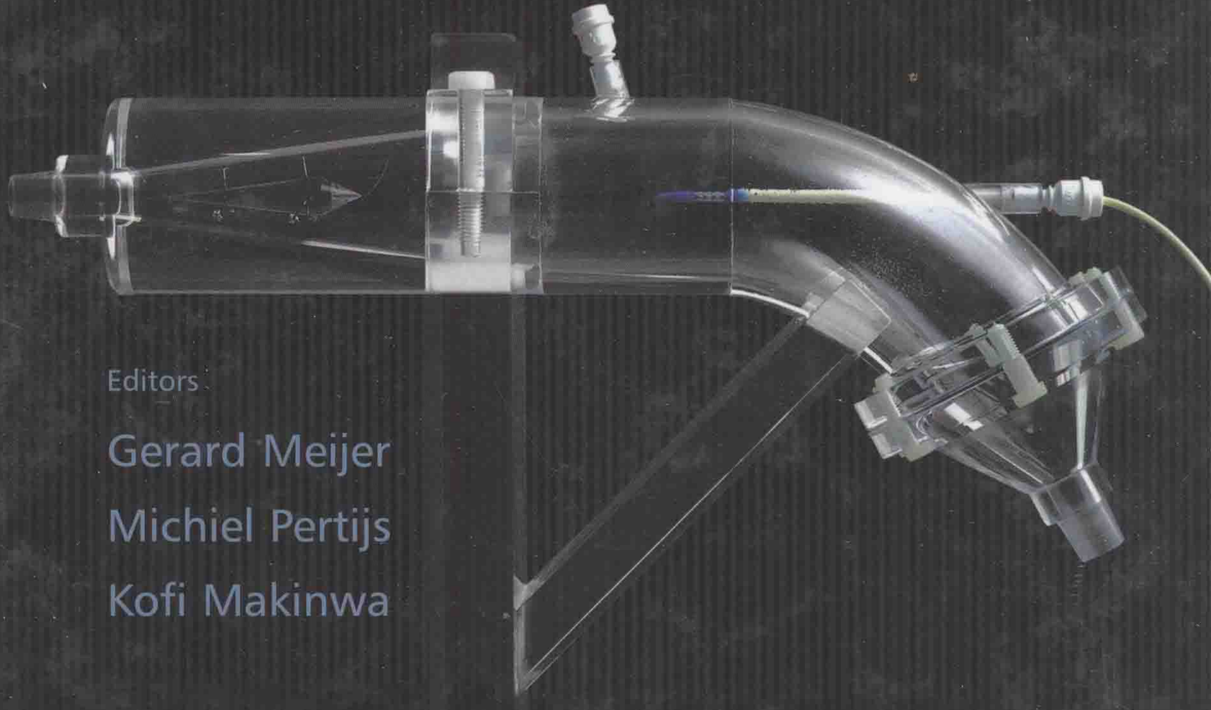
smart sensor systems

Emerging Technologies and Applications



Editors

Gerard Meijer

Michiel Pertijs

Kofi Makinwa

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SMART SENSOR SYSTEMS: EMERGING TECHNOLOGIES AND APPLICATIONS

Edited by

Gerard Meijer

Delft University of Technology and SensArt, The Netherlands

Michiel Pertijs

Delft University of Technology, The Netherlands

Kofi Makinwa

Delft University of Technology, The Netherlands

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SMART SENSOR SYSTEMS

About the Editors

Gerard Meijer

Gerard Meijer received his M.Sc. and Ph.D. degrees in Electrical Engineering from Delft University of Technology, Delft, The Netherlands, in 1972 and 1982, respectively. Since 1972, he has been a member of the research and teaching staff of Delft University of Technology, and since 2001, an Antoni van Leeuwenhoek Professor. His major interests are in the field of Analog Electronics and Electronic Instrumentation. In 1984, and on a part-time basis from 1985–1987, he was seconded to Delft Instruments Company, Delft, The Netherlands, where he was involved in the development of industrial level gauges and temperature transducers. In 1996 he co-founded the company SENSART, where he is a consultant for the design and development of sensor systems. In 1999 the Dutch Foundation of Technical Sciences STW awarded Meijer with the honorary title of Simon Stevin Meester. Meijer is chairman of the National STW Platform on Sensor Technology.

Michiel Pertijs

Michiel Pertijs received the M.Sc. and Ph.D. degrees in electrical engineering (both *cum laude*) from Delft University of Technology, Delft, The Netherlands, in 2000 and 2005, respectively. From 2005 to 2008, he was with National Semiconductor, Delft, where he designed precision operational amplifiers and instrumentation amplifiers. From 2008 to 2009, he was a Senior Researcher with imec / Holst Centre, Eindhoven, The Netherlands. In 2009, he joined the Electronic Instrumentation Laboratory of Delft University of Technology, where he is now an Associate Professor. He heads a research group working on integrated circuits for medical ultrasound and energy-efficient smart sensors. Dr. Pertijs is an Associate Editor of the IEEE *Journal of Solid-State Circuits* (*JSSC*) and a member of the technical program committees of the International Solid-State Circuits Conference (ISSCC), the European Solid-State Circuits Conference (ESSCIRC), and the IEEE Sensors Conference. He received the ISSCC 2005 Jack Kilby Award for Outstanding Student Paper, the JSSC 2005 Best Paper Award, and the 2006 Simon Stevin Gezel Award from the Dutch Technology Foundation STW.

Kofi Makinwa

Kofi Makinwa received the B.Sc. (First class honors) and M.Sc. degrees from Obafemi Awolowo University, Ile-Ife, Nigeria in 1985 and 1988 respectively. In 1989, he received the M.E.E. degree (*cum laude*) from the Philips International Institute, Eindhoven, The Netherlands and in 2004, the Ph.D. degree from Delft University of Technology, Delft, The Netherlands. From 1989 to 1999, he was a Research Scientist with Philips Research Laboratories, Eindhoven, The Netherlands, where he worked on interactive displays and on optical and magnetic recording systems. In 1989 he joined the Electronic Instrumentation Laboratory of Delft University of Technology, where he is currently an Antoni van Leeuwenhoek Professor and head of the laboratory. His main interests are in the design of precision analog circuitry, smart sensors and sensor interfaces.

Dr. Makinwa is on the technical program committees of the European Solid-State Circuits Conference (ESSCIRC) and the Advances in Analog Circuit Design (AACD) workshop. He was on the Program Committee of the International Solid-State Circuits Conference (ISSCC) from 2006 to 2012. He has also been a three-time guest editor of the *Journal of Solid-State Circuits* (*JSSC*) and a two-term distinguished lecturer of the IEEE Solid-State Circuits Society. He is a co-recipient of the 2005 Simon Stevin Gezel Award from the Dutch Technology Foundation, as well as of several best paper awards: from the *JSSC* (2005, 2011), the ISSCC (2005, 2008, 2011) and the ESSCIRC (2006, 2009), among others. In 2013, at the 60th anniversary of ISSCC, he was recognized as one of its top ten contributors. He is an IEEE fellow, an alumnus of the Young Academy of the Royal Netherlands Academy of Arts and Sciences and an elected member of the IEEE Solid-State Circuits Society AdCom, the society's governing board.

List of Contributors

Pedram Afshar, Medtronic Neuromodulation, Minneapolis, USA

Bernhard Boser, Berkeley Sensor & Actuator Center, University of California, Berkeley, USA

Zu-Yao Chang, Electronic Instrumentation Laboratory, Delft University of Technology, Delft, The Netherlands

Peng Cong, Medtronic Neuromodulation, Minneapolis, USA

Tim Denison, Medtronic Neuromodulation, Minneapolis, USA

Chinwuba Ezekwe, Robert Bosch, Palo Alto, California, USA

Ali Heidari, Guilan University, Rasht, Iran

Johan Huijsing, Electronic Instrumentation Laboratory, Delft University of Technology, Delft, The Netherlands

Blagoy Iliev, Martil Instruments, Heiloo,The Netherlands

Xiujun Li, Exalon, Delft, The Netherlands and Sensytech, Delft, The Netherlands

Kofi Makinwa, Electronic Instrumentation Laboratory, Delft University of Technology, Delft, The Netherlands

Gerard Meijer, Electronic Instrumentation Laboratory, Delft University of Technology and SensArt, Delft, The Netherlands

Stoyan Nihtianov, Electronic Instrumentation Laboratory, Delft University of Technology, Delft, The Netherlands

Jos Oudenhoven, imec/Holst Centre, Eindhoven, The Netherlands

Valer Pop, imec/Holst Centre, Eindhoven, The Netherlands

Michael Renaud, imec/Holst Centre, Eindhoven, The Netherlands

Zhichao Tan, Electronic Instrumentation Laboratory, Delft University of Technology, Delft, The Netherlands

Albert Theuwissen, Harvest Imaging, Bree, Belgium and Electronic Instrumentation Laboratory, Delft University of Technology, Delft, The Netherlands

Roland Thewes, Technische Universität Berlin (Berlin Institute of Technology), Berlin, Germany

Hubregt Visser, imec/Holst Centre, Eindhoven, The Netherlands

Ruud Vullers, imec/Holst Centre, Eindhoven, The Netherlands

Ziyang Wang, imec/Holst Centre, Eindhoven, The Netherlands

Preface

This book is intended as a reference for designers and users of sensors and sensor systems, and as a source of inspiration and a trigger for new ideas. For a major part, it is based on material used in the multidisciplinary "Smart Sensor Systems" course, which has been held annually at Delft University of Technology since 1995. The goals of this course are to present the basic principles of smart sensor systems to a broad, multidisciplinary audience, to develop a common language and scientific background to discuss the challenges associated with the design of such systems, and to facilitate mutual cooperation. In this way, we hope to contribute to the continuous expansion of the community of people advancing the exciting field of smart sensor systems.

As diverse and widespread as smart sensors may be today, research and development in this field is far from complete. It is driven by the continuous demand for lower cost, size and power consumption, and for higher performance and greater reliability. Moreover, new sensing principles and technologies are continuously emerging, and so significant effort is required to bring them to maturity. Often, this process involves more than just improving the performance of the transducer concerned. The *system* around the transducer plays an equally important, if not a more important, role. This system includes the electronics that interface with the transducer, the package that protects the transducer from the environment, and the calibration procedure that ensures that a certain performance specification is met.

This book focuses on these important system aspects, and, in particular, on the design of *smart* sensor systems, in which sensors and electronics are combined in a single package or even on a single chip to provide improved functionality, performance and reliability. In a previous book entitled "Smart Sensor Systems," the basics of such systems were covered. This book complements this prior publication by covering a number of emerging sensing technologies and applications, as well as discussing, in more detail, the system aspects of smart sensor design.

The book opens by discussing the exciting possibilities afforded by the combination of sensors and electronics: the accurate processing of small sensor signals (Chapter 1), the adoption of self-calibration techniques (Chapter 2), and the integration of precision instrumentation amplifiers (Chapter 3). This is followed by a discussion of a number of sensor systems in which system aspects play a key role: sensing of physical and chemical parameters by means of impedance measurement (Chapter 4); low-power angular-rate sensing using feedback and background-calibration techniques (Chapter 5); sensor systems for the detection of biomolecules, such as DNA (Chapter 6); optical sensor systems-on-a-chip in the form of CMOS image sensors (Chapter 7); and smart sensors capable of interfacing with the human nervous system (Chapter 8). Finally, the book also describes emerging technologies for the generation and storage of energy, since these are the key to realizing truly autonomous sensor systems (Chapter 9).

During the course of writing this text, we have been assisted by many people. We gratefully acknowledge the feedback and suggestions provided by our reviewers: Reinoud Wolffenbuttel of Delft University of Technology, Michael Kraft of the Fraunhofer Institute for Microelectronic Circuits and Systems, Michiel Vellekoop of the University of Bremen, Jan Bosiers of Teledyne DALSA, Firat Yazicioglu of imec, and the authors who also acted as reviewers. At our publisher, John Wiley & Sons, Ltd., we would like to acknowledge the Project Editors Richard Davies, Liz Wingett, and Laura Bell, for their support, encouragement and help in arranging agreements as well as to Production Editor Genna Manaog and Sangeetha Parthasarathy of Laserwords for help throughout the production of this book. Furthermore, we want to express our gratitude to the universities, research institutes and companies who permitted the use of figures and illustrations to make this book attractive for our readers. Finally, we would like to thank our spouses, Rumiana, Hannah and Abi, for their love and support.

Gerard Meijer, Michiel Pertijs and Kofi Makinwa
Delft, The Netherlands

Contents

1

Smart Sensor Design*

Kofi Makinwa
Electronic Instrumentation Laboratory, Delft University of Technology, Delft, The Netherlands

1.1 Introduction

Sensors have become a ubiquitous part of today's world. Modern cars employ tens of sensors, ranging from simple position sensors to multi-axis MEMS accelerometers and gyroscopes. These sensors enhance engine performance and reliability, ensure compliance with environmental standards, and increase occupant comfort and safety. In another example, modern homes contain several sensors, ranging from simple thermostats to infrared motion sensors and thermal gas flow sensors. However, the best example of the ubiquity of sensors is probably the mobile phone, which has evolved from a simple communications device into a veritable sensor platform. A modern mobile phone will typically contain several sensors: a touch sensor, a microphone, one or two image sensors, inertial sensors, magnetic sensors, and environmental sensors for temperature, pressure and even humidity. Together with a GPS receiver for position location, these sensors greatly enhance ease of use and have extended the utility of mobile phones far beyond their original role as portable telephones.

Today, most of the sensors in a mobile phone, as well as most sensors intended for consumer applications, are made from silicon. This is mainly because silicon sensors can be mass-produced at low cost by exploiting the large manufacturing base established by the semiconductor industry. Another important motivation is the fact that the electronic circuitry required to bias a sensor and condition its output can be readily realized on the same substrate or, at least, in the same package. It also helps that semiconductor-grade silicon is a highly pure material with well-defined physical properties, some of which can be tuned by doping, and which can be precisely machined at the nanometer scale.

Silicon is a versatile material, one that exhibits a wide range of physical phenomena and so can be used to realize many different kinds of sensors [1]. For example, magnetic fields can

* This chapter is an expanded and updated version of [7].

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be sensed via the Hall effect, temperature differences can be sensed via the Seebeck effect, mechanical strain can be sensed via the piezo-resistive effect and light can be sensed via the photo-electric effect. In addition, measurands that do not directly interact with silicon can often be indirectly sensed with the help of silicon-compatible materials. For example, humidity can be sensed by measuring the dielectric constant of a hygroscopic polymer [2], while gas concentration can be sensed by measuring the resistance of a suitably adsorbing metal oxide [3]. It should be noted that although silicon sensors may not achieve best-in-class performance, their utility and increasing popularity stems from their small size, low cost and the ease-of-use conferred by their co-integrated electronic circuitry.

Sensors are most useful when they are part of a larger system that is capable of processing and acting upon the information that they provide. This information must therefore be transmitted to the rest of the system in a robust and standardized manner. However, since sensors typically output weak analog signals, this task must be performed by additional electronic circuitry. Such *interface electronics* is best located close to the sensor, to minimize interference and avoid transmission losses. When they are both located in the same package, the combination of sensor and interface electronics is what we shall refer to as a *smart* sensor [4].

In addition to providing a robust signal to the outside world, the interface electronics of a smart sensor can be used to perform traditional signal processing functions such as filtering, linearization and compression. But it can also be used to increase the sensor's reliability by implementing self-test and even self-calibration functionality (as will be discussed in Chapter 2). A recent trend is towards sensor fusion, in which the outputs of multiple sensors in a package are combined to generate a more reliable output. For example, the outputs of gyroscopes, accelerometers and magnetic sensors can be combined to obtain robust position estimates, thus enabling mobile devices with indoor navigational capability.

This chapter discusses the design of smart sensor systems, in general, and the design of smart sensors in standard integrated circuit (CMOS) technology, in particular. Examples will be given of the design of state-of-the-art CMOS smart sensors for the measurement of temperature, wind velocity and magnetic field. Although the use of standard CMOS technology constrains the performance of the actual sensors, it minimizes cost, and as will be shown, the performance of the overall sensor *system* can often be significantly improved with the help of the co-integrated interface electronics.

1.2 Smart Sensors

A smart sensor is a system-in-package in which a sensor and dedicated interface electronics are realized. It may consist of a single chip, as is the case with smart temperature sensors, image sensors and magnetic field sensors. However, in cases when the sensor cannot be implemented in the same technology as the interface electronics, a two-chip solution is required. Since this also decouples the production yield of the circuit from that of the sensor, a two-chip solution is often more cost effective, even in cases where the sensor could be co-integrated with the electronics. Examples of two-chip sensors are mechanical sensors, such as MEMS accelerometers, gyroscopes and microphones, whose manufacture requires the use of micro-machining technology.

Since silicon chips, and especially their connections to the outside world, are rather fragile, smart sensors must be protected by some kind of packaging. The design of an appropriate