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Microsensors, MEMS, and Smart Devices

微传感器、微机电系统和灵巧器件

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清华大学出版社

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出　版　说　明

郑大钟
清华大学信息科学与技术学院

当前，在我国的高等学校中，教学内容和课程体系的改革已经成为教学改革中的一个非常突出的问题，而为数不少的课程教材中普遍存在的“课程体系老化，内容落伍时代，本研层次不清”的现象又是其中的急需改变的一个重要方面。同时，随着科教兴国方针的贯彻落实，要求我们进一步转变观念扩大视野，使教学过程适应以信息技术为先导的技术革命和我国社会主义市场经济体制的需要，加快教学过程的国际化进程。在这方面，系统地研究和借鉴国外知名大学的相关教材，将会对推进我们的课程改革和推进我国大学教学的国际化进程，乃至对我们一些重点大学建设国际一流大学的努力，都将具有重要的借鉴推动作用。正是基于这种背景，我们决定在国内推出信息技术学科和电气工程学科国外知名大学原版系列教材。

本系列教材的组编将遵循如下的几点基本原则。(1)书目的范围限于信息技术学科和电气工程学科所属专业的技术基础课和主要的专业课。(2)教材的范围选自于具有较大影响且为国外知名大学所采用的教材。(3)教材属于在近5年内所出版的新书或新版书。(4)教材适合于作为我国大学相应课程的教材或主要教学参考书。(5)每本列选的教材都须经过国内相应领域的资深专家审看和推荐。(6)教材的形式直接以英文原版形式印刷出版。

本系列教材将按分期分批的方式组织出版。为了便于使用本系列教材的相关教师和学生从学科和教学的角度对其在体系和内容上的特点和特色有所了解，在每本教材中都附有我们所约请的相关领域资深教授撰写的影印版序言。此外，出于多样化的考虑，对于某些基本类型的课程，我们还同时列选了多于一本的不同体系、不同风格和不同层次的教材，以供不同要求和不同学时的同类课程的选用。

本系列教材的读者对象为信息技术学科和电气工程学科所属各专业的本科生，同时兼顾其他工程学科专业的本科生或研究生。本系列教材，既可采用作为相应课程的教材或教学参考书，也可提供作为工作于各个技术领域的工程师和技术人员的自学读物。

组编这套国外知名大学原版系列教材是一个尝试。不管是书目确定的合理性，教材选择的恰当性，还是评论看法的确切性，都有待于通过使用和实践来检验。感谢使用本系列教材的广大教师和学生的支持。期望广大读者提出意见和建议。

Microsensors, MEMS, and Smart Devices

影 印 版 序

从 20 世纪 90 年代中期以来，Microsensors（微传感器）以及在微传感器基础上发展起来的 MEMS（微机电系统）已经逐渐被人们所熟悉，并越来越受到重视，目前已成为国际上的研究热点。由于认识到发展微传感器及 MEMS 是信息化进程的重要内容，它们在现代工业、农业、交通、生物、医学、航空、航天、国防以及日常生活和家电等领域都有重要与广泛的应用，因此微传感器及 MEMS 也同样成为我国信息科技与产业的重点研究与发展对象。

微传感器和 MEMS 与现代微纳米科技密切相关，它们的制作技术就是在现代微电子制作技术的基础上发展形成的。微电子制作技术是一种二维的平面微加工技术，而微传感器和 MEMS 则是三维的立体加工技术。微传感器与微机电系统是一门与电子学、物理学、化学、生物学、医学、材料科学等多学科交叉的高新技术，而微动力学、微静力学、微流体力学、微传热学、微光学、微声学、生物化学、微分析等都是发展微传感器与微机电系统必须研究的课题。本书的目的就是向大家阐述这方面的知识、理论与技术。

本书内容丰富，主要论述微传感器及微机电系统的结构、原理、特性、制作方法与工艺技术。例如在材料与制作技术方面，介绍了微电子学中各种薄膜材料和制备方法，以及重要的微电子工艺技术（标准的硅平面工艺），讲述了两类重要的硅三维加工技术，即体微加工技术与表面微加工技术。此外，重点介绍了三维光刻技术。在器件与系统方面，论述了热、辐射、力、声、磁、生物等多类传感器的结构、原理与特性，并且重点介绍了叉指式声表面波传感系统以及智能型传感系统。这些内容都是目前研究的前沿课题。

本书作者是来自于英国和美国的三位教授，他们在微传感器、微机电系统以及智能（灵巧）器件方面都有深厚的研究基础和教学经验，都发表过大量的学术论文并著有多部有关书籍，是该领域的知名学者。本著作的写作方法也颇具特色，避免了过多的推导，而着重于物理概念的阐述，不但使那些对本著作内容比较熟悉的微电子学与电子工程的学生，而且对于其他专业，如机械工程、物理学、材料科学甚至生物科学的学生都能很好地理解和接受。

该著作不但可以作为相关专业大学高年级学生和研究生的教材与参考书，而且对于在微传感器与微机电系统方面感兴趣的科学家、工程师、技术人员都是很有价值的参考书。

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2004 年 1 月

Preface

The miniaturisation of sensors has been made possible by advances in the technologies originating in the semiconductor industry, and the emergent field of microsensors has grown rapidly during the past 10 years. The term *microsensor* is now commonly used to describe a *miniature* device that converts a nonelectrical quantity, such as pressure, temperature, or gas concentration, into an electrical signal. This book basically reports on the recent developments in, firstly, the miniaturisation of a sensor to produce a microsensor; secondly, the integration of a microsensor and its microelectronic circuitry to produce a so-called *smart sensor*; and thirdly, the integration of a microsensor, a microactuator, and their microelectronic circuitry to produce a *microsystem*.

Many of the microsystems being fabricated today employ silicon microtechnology and are called *microelectricalmechanical systems* or *MEMS* in short. Consequently, the first part of this book concentrates on the materials and processes required to make different kinds of microsensors and MEMS devices. The book aims to make the reader familiar with these processes and technologies. Of course, most of these technologies have been derived from those currently employed in the semiconductor industry and so we also review the standard microelectronics technologies used today to produce silicon wafers, process them into discrete devices or very large-scale integrated circuits, and package them. These *must* be used when the microelectronics is being integrated to form either a *hybrid* device, such as a *multichip module* (MCM), or a fully integrated device, such as a smart sensor. We then describe the new techniques that have been developed to make microsensors and microactuators, such as bulk and surface silicon micromachining, followed by the emerging technology of microstereolithography that can be used to form true three-dimensional micromechanical structures.

The reader is now fully prepared for our description of the different types of microsensors made today and the way in which they can be integrated with the microelectronics to make a smart device (e.g. an electronic eye, electronic nose, or microtweezers) or integrated with a microactuator to make a microsystem. Several of these chapters have been dedicated to the important topic of IDT microsensors, that is, surface acoustic wave devices that possess an interdigital transducer and so can be used to sense a wide variety of signals from mechanical to chemical. This type of microsensor is attractive, not only because it offers both high sensitivity and compatibility with the microelectronics industry but also because it can be operated and even powered by a wireless radio frequency link. The latter overcomes the initial constraints of communicating with small, low energy budget, and even mobile MEMS – now referred to as micromachines!

Our aim has been to write a book that serves as a text suitable both for an advanced undergraduate course and for a master's programme. Some of the material may well be familiar to students of electrical engineering or electronics. However, our comprehensive treatment will make it equally familiar to mechanical engineers, physicists, and materials scientists.

We have provided more than 10 appendices to aid the reader and serve as a source of reference material. These appendices explain the key abbreviations and terms used in the book, provide suggestions for further reading, give tables of the properties of materials important in microsensors and MEMS, and finally provide a list of the web sites of major journals and active institutions in this field. In addition, this book is aimed to be a valuable reference text for anyone interested in the field of microsensors and MEMS (whether they are an engineer, a scientist, or a technologist) and the technical references at the end of each chapter will enable such readers to trace back the original material.

Finally, much of the material for this book has been taken from short courses prepared by the authors and presented to students and industrialists in Europe, North America, and the Far East. Their many valuable comments have helped us to craft this book into its final form and so we owe them our thanks. The authors are also grateful to many of their students and colleagues, in particular Professor Vasundara V. Varadan, Dr. K. A. Jose, Dr. P. Xavier, Mr. S. Gangadharan, Mr. William Suh, and Mr. H. Subramanian for their valuable contributions.

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September 2001

About the Authors

Julian W. Gardner is the Professor of Electronic Engineering at Warwick University, Coventry, UK. He has a B.Sc. in Physics (1979) from Birmingham University, a Ph.D. in Physical Electronics (1983) from Cambridge University, and a D.Sc. in Electronic Engineering (1997) from Warwick University. He has more than 15 years of experience in sensor engineering, first in industry and then in academia, in which he specialises in the development of microsensors and, in collaboration with the Southampton University, electronic nose instrumentation. Professor Gardner is currently a Fellow of the Institution of Electrical Engineers (UK) and member of its professional network on sensors. He has authored more than 250 technical papers and 5 books; the textbook *Microsensors: Principles and Applications* was first published by Wiley in 1994 and has enjoyed some measure of success, now being in its fourth reprint.

Vijay K. Varadan is Alumni Distinguished Professor of Engineering at the Pennsylvania State University, USA. He received his Ph.D. degree in Engineering Science from the Northwestern University in 1974. He has a B.E. in Mechanical Engineering (1964) from the University of Madras, India and an M.S. in Engineering Mechanics (1969) from the Pennsylvania State University. After serving on the faculty of Cornell University and Ohio State University, he joined the Pennsylvania State University in 1983, where he is currently Alumni Distinguished Professor of Engineering science, Mechanics, and Electrical Engineering. He is involved in all aspects of wave-material interaction, optoelectronics, microelectronics, photonics, microelectromechanical systems (MEMS): nanoscience and technology, carbon nanotubes, microstereolithography smart materials and structures; sonar, radar, microwave, and optically absorbing composite media; EMI, RFI, EMP, and EMF shielding materials; piezoelectric, chiral, ferrite, and polymer composites and conducting polymers; and UV conformal coatings, tunable ceramics materials and substrates, and electronically steerable antennas. He is the Editor of the *Journal of Wave-Material Interaction* and the Editor-in-Chief of the *Journal of Smart Materials and Structures* published by the Institute of Physics, UK. He has authored more than 400 technical papers and six books. He has eight patents pertinent to conducting polymers, smart structures and smart antennas, and phase shifters.

Osama O. Awadelkarim is a Professor of Engineering Science and Mechanics at the Pennsylvania State University. Dr. Awadelkarim received a B.Sc. Degree in Physics from the University of Khartoum in Sudan in 1977 and a Ph.D. degree from Reading University in the United Kingdom in 1982. He taught courses in soild-state device physics, microelectronics, material science, MEMS/Smart structures, and mechanics. Prior to joining the Pennsylvania State University in 1992, Dr. Awadelkarim worked as a senior scientist at Linkoping University (Sweden) and the Swedish Defence Research Establishment. He was also a visiting researcher at the University of Oslo (Norway), Kammerlingh Onnes Laboratories (Netherlands), and the International Centre for Theoretical Physics (Italy). Dr. Awadelkarim's research interests include nanoelectronics, power semiconductor devices, and micro-electromechanical systems. Dr. Awadelkarim has authored/co-authored over 100 articles in journals and conference proceedings.

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Contents

Appendices

1

Introduction

1.1 HISTORICAL DEVELOPMENT OF MICROELECTRONICS

The field of microelectronics began in 1948 when the first transistor was invented. This first transistor was a point-contact transistor, which became obsolete in the 1950s following the development of the bipolar junction transistor (BJT). The first modern-day junction field-effect transistor (JFET) was proposed by Shockley (1952). These two types of electronic devices are at the heart of all microelectronic components, but it was the development of integrated circuits (ICs) in 1958 that spawned today's computer industry.

IC technology has developed rapidly during the past 40 years; an overview of the current bipolar and field-effect processes can be found in Chapter 4. The continual improvement in silicon processing has resulted in a decreasing device size; currently, the minimum feature size is about 200 nm. The resultant increase in the number of transistors contained within a single IC follows what is commonly referred to as *Moore's law*. Figure 1.1 shows that in just 30 years the number of transistors in an IC has risen from about 100 in 1970 to 100 million in 2000. This is equivalent to a doubling of the number per chip every 18 months. Figure 1.1 plots a number of different common microprocessor chips on the graph and shows the clock speed rising from 100 kHz to 1000 MHz as the chip size falls. These microprocessors are of the type used in common personal computers costing about €1000 in today's prices[1].

Memory chips consist of transistors and capacitors; therefore, the size of dynamic random access memories (DRAM) has also followed Moore's law as a function of time. Figure 1.2 shows the increase of a standard memory chip from 1 kB in 1970 to 512 MB in 2000. If this current rate of progress is maintained, it would be possible to buy for €1000 a memory chip that has the same capacity as the human brain by 2030 and a memory chip that has the same brain capacity as everyone in the whole world combined by 2075! This phenomenal rise in the processing speed and power of chips has resulted first in a computer revolution and currently in an information revolution. Consequently, the world market value of ICs is currently worth some 250 billion euros, that is, about 250 times their processing speed in hertz.

[1] 1 euro (€) is currently worth about 1 US dollar.