微纳技术著作丛书（影印版）

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Micro and Nanomanufacturing

Mark J. Jackson

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内 容 简 介

纳米技术是当前科学研究与工业开发的热门领域之一。本书全面阐述了微纳器件的设计和制造方面的知识，以及在设计和制造时所要考虑的诸多因素。书中涵盖了多种制造技术，包括微纳制造技术、体和表面微加工技术、LiGA 技术、薄膜沉积技术、纳加工技术等。

本书内容丰富，讲解透彻，是一本相关领域电子工程师、材料科研工作者开发微纳米材料应用的全面的指南，同时也可作为微纳米机械和微纳米技术专业研究生的参考书。

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序

科学出版社准备出版一套《微纳技术著作丛书》，包括原创作品和引进作品（影印或翻译）两种形式，并聘请专家组成编委会。这是一件大事，希望能坚持把它办好。

微纳米技术作为21世纪重要的一项技术，已成为国际科学界和工程技术界研究的热点。近年来，微米纳米技术进展迅速，已经发展成为一个包含机械、材料、电子、光学、化学、生物、基因工程、医学等基础学科的综合领域，而不仅仅属于任何单一的科学和技术门类。就其产品而言，也早已超越了人们广为熟悉的微型加速度传感器和纳米碳管等，呈现出向各个科学和技术领域全面渗透的趋势。

由于微纳米技术使得人们除了可以在同一基片上实现包括机械、流体、化学、生物、光学等器件外，也可以将信号处理和传输系统集成在同一基片上用以处理信息，决定计划，控制周围环境，从而大大提高最终产品的综合性能，实现高度智能化。在未来的航空航天、生物医学、环境监控、无线通信、汽车和交通、石油化工、能源、工农业、国家安全、食品和消费的各个领域都将有广泛应用，对国民经济、科学技术、社会发展与国家安全具有重要意义。今后的几十年里，随着微米纳米技术的迅速发展和向现代科学和技术的各个门类渗透，其对我们现代生活的各个方面带来的影响将是长期和深远的。从某种意义上来说，微米纳米技术的发展，可能改变人类的工作和生活方式，乃至基本概念，其潜在的影响有可能和以计算机技术为代表的微电子工业对世界的影响相提并论。

正是由于其诱人的应用前景和巨大的潜在市场，微米纳米技术目前已成为世界各国大力投资进行研究和发展的热点领域，其研究范围包括了材料、器件和系统，涉及的技术包含机理研究、设计分析、计算仿真、制造工艺、系统集成或组装、测控技术和应用研究等。随着微纳米技术的迅猛发展，近年来国外有大量这方面的专业书籍出版。

《微纳技术著作丛书》涵盖材料开发、系统设计、检测技术、集成技术、通信网络、传感系统、微加工技术等方面，它们都是本领域的研究热点。这套丛书的出版对促进我国微米纳米技术的发展将有很大的推动作用。

这套丛书中，原创作品收录的都是国内从事微纳技术的一线研究人员在本领域的研究成果与心得，具有很强的独立性、创造性和系统性。引进作品都是与国际知名的出版集团合作，经国内专家的甄别，挑选出能反映国外最新研究成果、对国内读者又有借鉴价值的作品，具有权威性、前瞻性和可读性。因为微纳米技

术是一个交叉学科领域，我们有意识的选择了一些由多人合写的专著。通常这类著作都是由相关领域的知名专家，各自在每一章节涵盖一个专题，既有进行综合性的论述，也有个人的具体独创性研究。这样的书籍，通常能帮助读者既获得某一领域的研究概况，又能从一个具体的应用专题中获得收益。

2007 年初推出的第一批影印版图书，我和王万军教授进行了评读，此套丛书很实用，不少作者在该领域有很高的声望。我们建议致力于微米纳米技术的研究人员，包括研究生、技术人员，能够花些时间阅读。

总之，我们对科学出版社组织出版这套丛书的举措很赞赏，也希望他们能将这一工作认真、长期地做下去。同时，我们也希望国内的专家能够积极、踊跃地加盟，为我国微米纳米技术的推进做出贡献。

周兆英 王万军

2006 年 12 月 7 日

Preface

When Nobel Laureate Richard Feynman presented his vision on miniaturization at the California Institute of Technology in 1959, he promoted a scientific curiosity in what is now known as "nanotechnology". His revolutionary vision was captured in a paper published in the February 1960 issue of Caltech's journal, *"Engineering and Science"*. In this paper, Feynman speaks about controlling and manipulating atoms and constructing products atom-by-atom, and molecule-by-molecule. Feynman described the scaling down of lathes and drilling machines, and talks about drilling holes, turning, molding, stamping parts, and so forth. Even in 1959, Feynman described the need for micro- and nanomanufacturing as the basis for creating a microscopic world that would benefit mankind. Since the 1960s, Feynman's vision has created the basis for the foundation of the semiconductor industry and within the last decade, has rapidly contributed to the development of micro electro- mechanical systems (MEMS). At the same institution, President Bill Clinton talked about the exciting promise of nanotechnology in January 2000, and later announced an ambitious national nanotechnology initiative (NNI) that was enacted in 2001 with a budget of $497 million to promote nanoscale research that would benefit society. Nanotechnology encompasses technology performed at the nanoscale that has real-world applications. Nanofabrication includes methods that manipulate atoms and molecules to produce single artifacts to produce sub micron-sized components and systems. Nanomanufacturing is a challenge presented to us to produce single-nanoscale artifacts in a mass production fashion that obviously produces the accompanying economies of scale. Nanotechnology will have a profound effect on our society that will lead to breakthrough discoveries in materials and manufacturing, electronics, medicine, healthcare, the environment, sustainability, energy, biotechnology, information technology, national security, and prevention of the spread of global terrorism. Nanotechnology will lead the next industrial revolution.

The purpose of this book is to present information and knowledge on the emerging field of micro- and nanomanufacturing. The book is written in the spirit of scientific endeavor outlined by Richard Feynman, who stated that one of the greatest challenges to scientists in the field of miniaturization is the manufacture of tiny objects using techniques such as turning, molding, stamping, and drilling. The book presents information on subjects such as fabrication, molding, lithography, machining, milling, water drop machining, self assembly, manipulation, cutting, to name but a few.

The book should serve as a text for undergraduate and graduate courses in micro- and nanomanufacturing in subject areas such as mechanical engineering, materials science, physics, chemistry, and electrical and electronic engineering. The structure of the book is based on matter provided by many colleagues and the author wishes to thank Professor Waqar Ahmed, University of Ulster, U.K., Htet Sein, Manchester Metropolitan University, Grant Robinson, Purdue University, Luke Hyde, Purdue University, David Tolfree, Daresbury Laboratory, U.K., Emeritus Professor Milton Shaw, Arizona State University, Professor V. C. Venkatesh, Malaysia University of Technology, Sam McSpadden, Oak Ridge National Laboratory, Professor Kai Cheng, Brunel University, U.K., and Dr. Xun Luo, Cranfield University, U.K., for helping construct a source of knowledge and information on micro- and nanomanufacturing and for granting the author permission to use such matter.

The author expects that the textbook will stimulate further interest in this field of nanotechnology and hopes that there still is, "plenty of room at the bottom".

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Contents

1. Principles of Micro- and Nanofabrication

1.1 Introduction

Innovations in the area of micro and nanofabrication have created opportunities to manufacture structures at the nanometer and millimeter scales. These opportunities can be used to fabricate electronic, optical, magnetic, and chemical/biological devices ranging from sensors to computation and control systems. In this chapter, we introduce the dominant micro and nanofabrication techniques that are currently used to fabricate structures in the nanometer scale up to the millimeter scale. The first part of this chapter focuses on microfabrication of MEMS and semiconductor devices as an example of microfabrication. Next, the chapter focuses on nanofabrication techniques including several top-down and bottom-up techniques. Again, we use semiconductor devices as an example that shows the promising techniques that can be used to manufacture nanofabricated structures.

Most micro and nanofabrication techniques were developed by the semiconductor industry. The semiconductor industry has grown rapidly in the past 30 years, which is driven by the microelectronics revolution. The desire to place many transistors on to a silicon wafer has demanded innovative ways to fabricate electronic circuits and to fit more and more electronic devices into a smaller workable area. Early transistors were made from germanium but are now predominantly silicon, with the remainder made from gallium arsenide. While gallium arsenide has high electron mobility compared to silicon, it has low hole mobility, a poor thermal oxide, less stability during thermal processing, and much higher defect density than silicon. Silicon is the material of choice for most electronic application but gallium arsenide is useful for circuits that operate at high speeds with low-to-moderate levels of integration. This type of material is used for analog circuits operating at speeds in excess of 10^9 Hz. The performance of integrated circuits can be increased by placing transistors closer together and by depositing transistors in a precise way. The minimum feature size has reduced at an astonishing rate over the past thirty years. Figure 1.1 shows the reduction in the feature sizes as a function of the number of transistors per chip using conventional lithographic techniques. Figure 1.2 shows a single strand of human hair and an array of transistors on a single piece of silicon to reveal the relative size of transistors that can be accommodated on a piece of silicon.

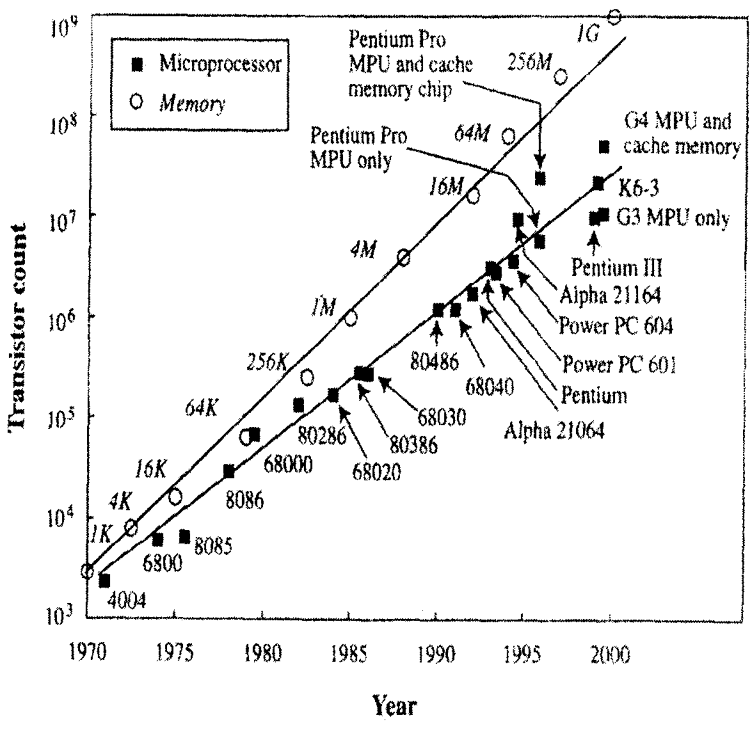

Fig. 1.1. Transistor count per chip as a function of time [1]

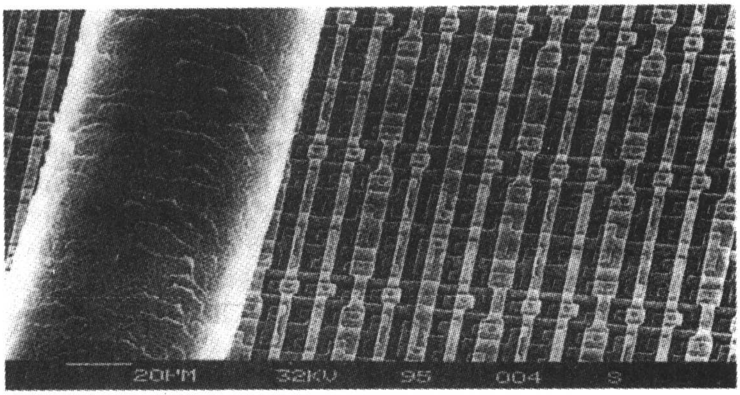

Fig. 1.2. Scanning electron micrograph of an integrated circuit chip in the mid-1980s. The human hair to the left of the image provides an indication of the relative size of the transistor wires [1]

Microfabrication begins when a set of photomasks are provided to the integrated circuit fabricator. The photomasks are physical representations of the design of the circuits to be manufactured in accordance with the rules of layout. A silicon wafer provides the basis of the integrated circuit. Wafers are processed using a grinding process that produces a flat surface that is still conductive at this stage. The wafer is insulated by growing a thermal oxide layer so that leakage of current between transistors is prevented. A conducting layer is deposited that will be used for producing transistors. Several techniques have been developed for depositing insulating and conducting layers such as sputtering, physical vapor deposition using a magnetron, chemical vapor deposition (CVD), and epitaxial growth of layers using techniques such as metal oxide CVD, molecular beam epitaxy, and chemical beam epitaxy. The conducting layer is divided up into individual resistors. Individual resistors are deposited to the wafer using photolithographic techniques. Further processing is required that forms the integrated circuit and uses techniques such as pattern transfer, etching, deposition, and growth. These same techniques have also been used to create a plethora of microscale products in silicon-based materials for applications other than integrated circuits.

1.1.1 Microfabrication of MEMS and Semiconductor Devices

Traditionally, integrated circuits have been manufactured using microfabrication techniques that have been classified as machining processes. Figure 1.3 shows the standard route followed to produce an integrated circuit. The same flowchart can be used for producing any microscale product produced using silicon-based materials. The chart shows the basic functions that are composed of initially cleaning the substrate, applying a thin film using many deposition techniques, applying lithographic techniques to apply mask material, etching to form the required shape of the microscale features, removal of the mask material using chemical or plasma etching, then finally characterizing the nature of the created structure. The final microstructures are then separated from the initial subtrate material and released for quality control.

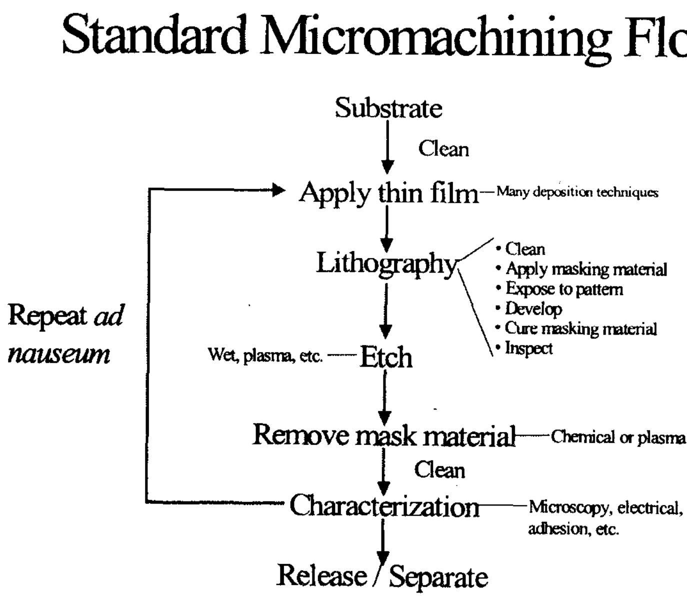

Fig. 1.3. Standard micromachining flow chart showing various processing steps