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北京航空航天大学“研究生英文教材”系列丛书

Design, Fabrication and CAD for MEMS Devices

微机电器件设计、制造及计算机辅助设计

Guo Zhanshe

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Abstract

This book firstly introduces the pertinent fundamental theory, important material and fabrication process of micro-electromechanical systems. Based on these theories, the design rule and important engineering examples are described in detail. Then, many engineering applications for MEMS including the acceleration measurement, the angular speed measurement and the pressure measurement are introduced. Finally, finite element method is introduced in order to prove the correctness of the design. This engineering application of simulation includes the static and modal analysis of the beam, capacitance analysis, thermal-structure analysis of the device and fatigue analysis etc.

It can be selected as the reference to the postgraduates, undergraduates and pertinent engineering staff whose research directions are instrumentation science and technology, control science and engineering, mechanical engineering etc.

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Preface

MEMS (Micro-ElectroMechanical Systems) is an emerging field developed in recent decades. It's a frontier technology in twenty-first century based on IC (Integrated Circuits) technology. It mainly refers to a technology of design, processing, manufacturing, measurement and control based on silicon materials. It is a micro-system which can integrate mechanical components, optical systems, driving components and electronic control systems on a single chip. It is a new type of multi-disciplinary technique developed in recent years. It involves machinery, electronics, chemistry, physics, optics, biology, materials and other disciplines. It is one of the key research fields at present.

In this book, the basic theory, important materials, the fabrication process, the rule of MEMS design and many engineering examples are introduced in detail combining the author's research experience and results. Then, some kinds of typical MEMS measuring devices including the MEMS accelerometer, angular measurement sensors, pressure sensors, micro-torque measuring methods are introduced in detail combining the author's research experience. Finally, many engineering examples for the application of finite element method in MEMS are introduced.

Chapter 1 introduces the definition of MEMS in two aspects: the dimension and the fabrication process. Then, the development process and the application of CAD in MEMS are also introduced.

Chapter 2 introduces the detailed theory of MEMS components such as the single clamped beam, the double-enddamped beam, the comb finger actuator and the diagraph etc.

In Chapter 3, the mechanical characters and some important problems to be noticed for some kinds of typical materials are mentioned.

Chapter 4 introduces some kinds of MEMS fabrication processes such as the MEMS lithography technology, the bulk silicon technology, the surface silicon technology, the LIGA process and the bonding technology in detail based on many engineering examples. Detailed design idea of the masks is also introduced according to the fabrication process.

In Chapter 5, the micro friction characters of MEMS devices based on micro scale effect are introduced. Based on this theory, the design, simulation, fabrication and experiment for a kind of on-chip micro friction measurement system is mentioned in detail to offer some theoretical help for pertinent research.

Chapter 6 introduces some measuring methods for some kinds of typical parameters including the acceleration measurement, the angular speed measurement, the pressure measurement, the micro-torque measurement and the micro topography measurement.

In Chapter 7, the engineering examples of finite element methods are introduced in detail. This includes the static analysis, the modal analysis, the thermal-structure analysis, the fatigue analysis and the micro capacitor analysis etc. This will give some useful help to pertinent researchers.

This book is written by Associate Professor Guo Zhanshe in Beihang University. Thanks a lot to the subeditor Professor Bai Shaoxian in Zhejiang University of Technology for the writing of Chapter 5 and the modification work, and Ph. D. Huang Manguo in Beijing Changcheng Aeronautical Measurement and Control Technology Research Institute for the writing of Chapter 6. Thanks a lot for the help of my postgraduate students Cheng Fucheng, Li Boyu, Lu Chao, An Ying, Han Jingxuan and Song Ke during the course of translation work. Thanks a lot for the supporting of the Aviation Research Foundation with grant No.: 20153451023.

This book can be used as the reference book for pertinent researchers on MEMS and the teaching book for pertinent postgraduate students.

MEMS is a wide range of research field. Some mistakes and inappropriate content may exist in this book due to the limitation of authors' knowledge. Comments and suggestions from any reader will be appreciated.

Guo Zhanshe

March 2, 2016

Contents

Chapter 1 Introduction

1.1 Concept of MEMS

MEMS (Micro-ElectroMechanical Systems) is an emerging field developed in recent decades. It's a frontier technology in the twenty-first century based on micro-nanotechnology, and it mainly refers to a technology of design, processing, manufacturing, measurement and control based on silicon materials. It is a micro-system which can integrate mechanical components, optical systems, drive components and electronic control systems into a whole unit. It uses a manufacturing process combined with microelectronics technology and micromachining technology (including silicon bulk micromachining, silicon surface micromachining, LIGA and wafer bonding technologies), to create a variety of excellent performance, low cost, miniaturization of sensors, actuators, drivers and micro-systems. It's a new type of multi-disciplinary technic developed in recent years, which involves machinery, electronics, chemistry, physics, optics, biology, materials and other disciplines.

Currently, the researchers divide the electromechanical system into three categories based on the size of its functional dimensions D: Conventional Electromechanical System, MEMS and NEMS (Nano-ElectroMechanical System). The details are as follows:

Size Range	System Name
$D \geqslant 100\ \mu m$	Conventional ElectroMechanical System
$100\ \mu m \geqslant D \geqslant 0.1\ \mu m$	Micro-ElectroMechanical System
$100\ nm \geqslant D \geqslant 0.1\ nm$	Nano-ElectroMechanical System

Due to the size effect, many physical properties (including mechanical properties, heat transfer characteristics) of conventional electromechanical systems, MEMS and NEMS have a great difference, and the theoretical research and the process technology are almost completely different. In some MEMS and NEMS, molecular dynamics, quantum mechanics and other microscopic theory have been the primary rationale for the study (shown in Figure 1.1). In NEMS, however, the device processing mainly uses focused ion beam technology, excimer laser direct writing nanometer process technology, and nanoimprint technology, which are rarely used in the traditional electromechanical systems and the micro-electromechanical systems.

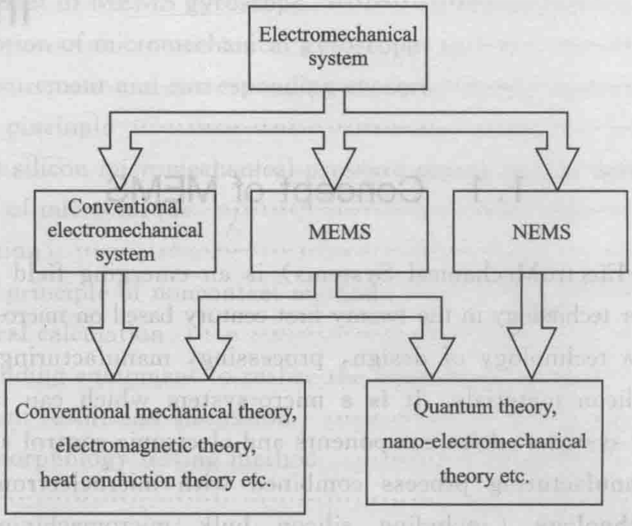

Figure 1.1 The classification of electromechanical systems and the applications of related theories

Compared to the conventional electromechanical system, MEMS has undergone large changes in mechanics and kinematics, material properties, processing technology, detection method and control theory etc. Its main features can be summarized as follows:

(1) Miniaturization: The MEMS device has the advantages of small size and light weight. Usually, the volume of a complete MEMS device is similar to that of a common integrated circuit, and compared with the volume of the sensor and actuator in conventional sense, the volume is usually reduced by more than two orders of magnitude. Thus, in many areas such as the areas with higher requirements for the size and power consumption such as aerospace and other fields, the MEMS device has great advantages.

(2) Integration: MEMS devices can integrate multiple sensors or actuators with different functions and different sensitive directions, forming micro sensor arrays or micro actuator arrays, and they can even constitute more complex microsystems with integrated circuits.

(3) Mass production: With the micro manufacturing process that originates from the semiconductor process, it is able to produce hundreds of thousands of micro electromechanical devices on one substrate at the same time, thus greatly reduces the production costs. Figure 1. 2 shows the process layout of a MEMS accelerometer made by bulk silicon technology. As can be seen from this figure, numerous acceleration chips in completely different shapes and sizes are arrayed in a 4-inch-square of the glass, thereby realizing the function that multiple chips can be produced by only one process. Since each sensor chip is produced by once through the same processing technology, the consistency of the unit is good, which can not be achieved by once through traditional machining processing methods.

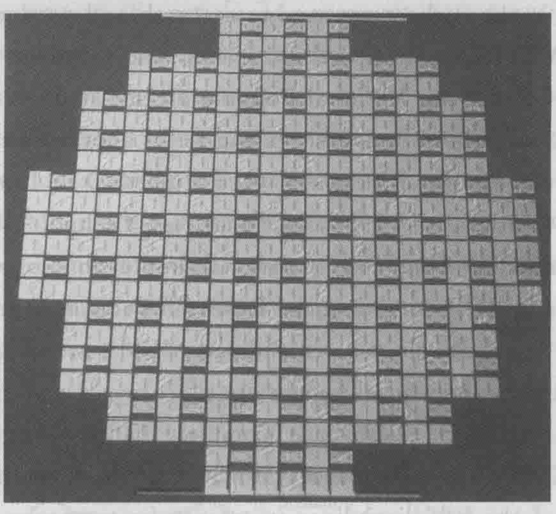

Figure 1. 2 The process layout of a MEMS accelerometer

(4) Low cost: The processing technology of MEMS devices is similar to microelectronic technology. Hundreds of thousands of micromechanical parts with good consistency, even the complete MEMS, can be made in a piece of silicon at the same time. Therefore, the manufacturing cost can also be greatly reduced.

(5) Excellent mechanical and electrical properties: The main production material of MEMS devices is silicon, of which the strength, hardness and Young's modulus are similar to those of iron, so the system has good mechanical properties.

(6) Low power consumption: The feature of MEMS devices that have the advantage of small size determines the inevitability of corresponding low power consumption.

The emergence and development of MEMS have improved the miniaturization, versatility, intelligence and reliability level of the information system to a new height. Due to the limits of technic and economic, MEMS was confined to the field of automotive electronics application in the past. But with the volume of MEMS devices becoming smaller and smaller, the price becoming lower and lower and the performance becoming better and better, the design and application space of MEMS devices expands continuously. At present, MEMS has great application prospects in industry, information, communication, national defense, aviation, spaceflight, navigation, medicine, biological engineering, agriculture, environment, family service and other areas. It has attracted the world's attention, as well as a lot of manpower and material resources for development. Therefore, MEMS technology will certainly become another major high-tech industry following the microelectronics technology.

The United States is the earliest country to research and produce MEMS successfully. America's research on MEMS began in the mid-1960s, and attracted widespread attention in the late 1980s. In 1988, American National Foundation invested \$1 000 000 to fund MIT, University of California and other 8 universities and Bell Laboratory to begin to carry out the main MEMS research, and the fund increased to \$2 000 000 in 1989. Moreover, the fund increased to \$5 000 000 in 1993. In 1994, National Key Technology Committee of America listed "micro-, nano-manufacturing" as a national key technology project in the report submitted to the president. Defense Advanced Research Projects Agency of America, which aims at developing dual-use technologies, considered MEMS as a high-tech directly relating to national defense and economic development in 1995 fiscal year plan and focused on its development. Besides, the U. S. Aerospace Company had investigated and evaluated the potential impact of MEMS on future space systems in 1993. Currently American Congress has put MEMS as one of the key disciplines in twenty-first century. Subsequently, Japan, Germany and so on have also carried on the research of MEMS technology. At present, the MEMS technology is involved in almost all fields, and its product sale is increasing at an annual rate of nearly 15 percent.

1.2 Development of MEMS

MEMS appeared along with the development of IC manufacturing technology in 1950s, and developed along with the development of MEMS technology. During this period, the main research contents of MEMS are the physical phenomenon of semiconductor materials and its application in the sensor. In 1954, Smith in Bell Laboratory found the piezoresistive effect of semiconductor silicon and germanium and produced the silicon strain device[1]. In

1959, the famous physicist Feynman gave the landmark speech *There is plenty of room at the bottom* on the famous Physics Annual Conference of America, formally putting forward the imagine of the research of MEMS and the possibility of implementing for the first time, which had a great influence on the development of MEMS. Since the 1960s, MEMS technology got rapid development, and promoted the development of the research technic of MEMS. In the mid-1960s, Bell Laboratory discovered and studied different etching effects of alkali metal solutions produced to different orientations of monocrystalline, and the technology laid the foundation for MEMS wet etching process. Kulite Corporation developed the world's first piezoresistive silicon pressure sensor and acceleration sensor in 1961 and 1970. In 1967, Harvey C. Nathanson put forward the concept of surface passivation technology for the first time in the article *The resonant gate transistor* published in IEEE Transactions on electron devices, and produced the cantilever beam structure with a resonant frequency of 5 000 Hz (shown in Figure 1. 3), which marked the emergence of surface passivation technology. In the 1960s, the bonding technology appeared. Nova Sensors Corporation used silicon glass bonding technology to produce pressure sensors, making it possible to produce MEMS chips of multilayered structure. Although these devices had shortcomings such as not being commercial due to the inadequate, these efforts did constitute a part of early outcomes of silicon micromachining technology.

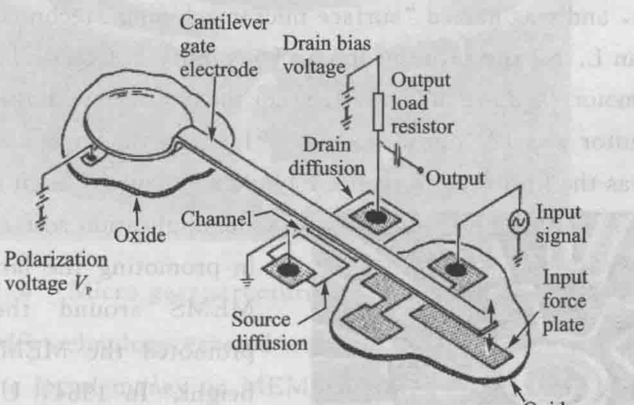

Figure 1. 3 The structure of cantilever beam

The 1970s is a period of accelerated development of MEMS. In 1977 and 1979, Stanford University developed the first capacitive pressure sensor and capacitive accelerometer respectively, and started researches of neural probes and silicon chromatographic devices and so on in biomedical field. IBM and HP, using MEMS technology, produced the inkjet printer nozzle respectively in 1977 and 1979[2-3] (shown in Figure 1. 4). At present, the printer nozzle is still one of the most important products in MEMS field, marking the beginning of the application of MEMS technology.

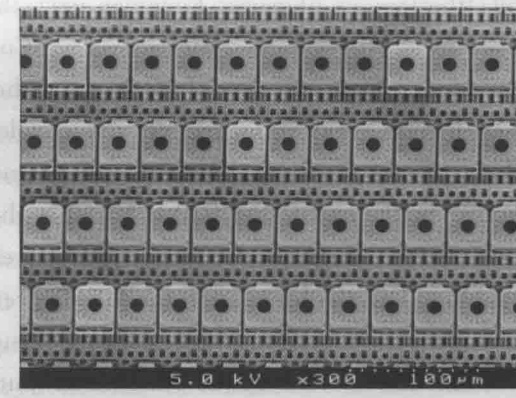

Figure 1. 4 Inkjet printer nozzle

Honeywell, Motorola and some other companies also introduced a mass production of pressure and acceleration sensors in the late 1970s. The 1980s is also a period of rapid development of MEMS, in which countries around the world began to study in the field of MEMS, therefore manufacturing technology continued to emerge and get perfect, applications continued to expand, researches on basic theory and design methodology continued to go further. In 1985, Howe and other people in UCB created the polycrystalline silicon resonant beam integrated with the MOS circuits, proving the compatibility between polysilicon and IC technology. Subsequently, UCB, MIT and University of Wisconsin perfected the sacrificial layers micro processing technology, and produced the complex MEMS system successfully, which laid on the foundation of MEMS and IC integration, and was named "surface micromachining" technology by Barth in HP in 1985. In 1987, Fan L. S. and other people in University of California, Berkeley created the electrostatic micro-motor[4] (shown in Figure 1. 5) for the first time with the surface micromachining technology. The motor was 120 μm in diameter, 1 μm in thickness, and its speed can reach 500 rpm, which was the first time to realize Feynman's plan. Though micro-motor hasn't got the application so far, it played a great role in promoting the large-scale emergence of MEMS around the world then, and promoted the MEMS research to a new height. In 1984, University of Michigan invented the dissolved silicon technology based on silicon glass bonding and thick boron block KOH etching, and the resonant silicon micromechanical pressure sensor came out in the same year. In 1979, Stanford University in America used

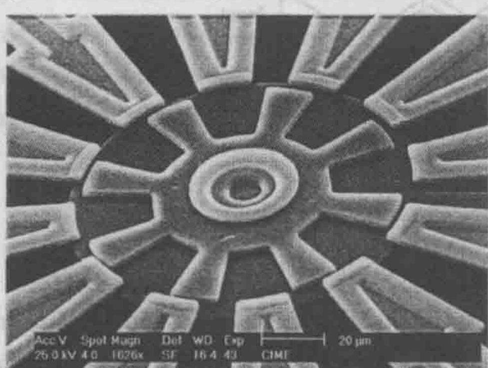

Figure 1. 5 The structure chart of electrostatic micro-motor

micromachining technology and silicon materials to create the open loop direct frequency output accelerometer for the first time; In 1989, Satchell D. W. and Greenwood J. C. used methods of thermal excitation and piezoelectric detection to design the three-beam structure silicon directly frequency output accelerometer[5] for the first time; In 1990, Chang C. S. and other people[6] used the double beam-structure to design a direct frequency output accelerometer which is sensitive in both directions, and they applied for a patent; LIGA (Lithographie, Galvanoformung and Abformtechnik) processing technology was born in Germany in 1985. The process can not only make high aspect ratio three-dimensional structure (shown in Figure 1. 6), but also make it possible to manufacture complex three-dimensional metal structure. In 1986, Binning in IBM invented the atomic force microscopy based on micromachining technology, achieving the measurement of light force at Newton, even the nano-Newton power level and the nano surface, and the research group then won the Nobel Prize. On the conference Micro-Tele-Operated Robotics held in Salt Lake City in 1989, Howe in UCB suggested using MEMS as the name of this field, which was the first time the name of MEMS was determined.

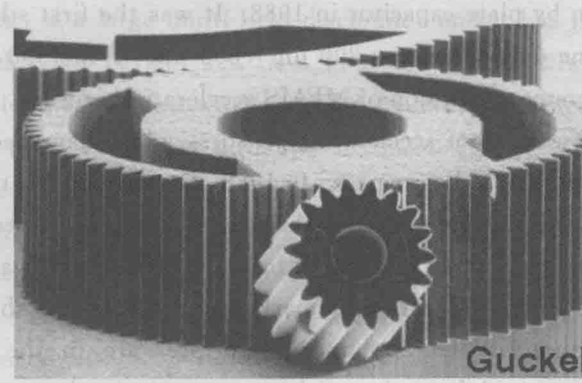

Figure 1. 6 Micro gear structure made by LIGA technology

In the 1990s, MEMS technology entered a period of high input and output. Countries around the world spent a lot of money on MEMS research and made a great progress, and many MEMS products came out. At the same time, the level of processing also reached a very high level. The Summit V surface micromachining technology developed by American National Laboratory Sandia could manufacture polycrystalline silicon micromechanical structure of 5 layers, and had achieved complex resonators, motors, gears, adjustable micromirrors and other devices, which represented the highest level of micromachining in the world. Figure 1. 7 shows the scanning electron microscopy image of the adjustable micromirror of

MEMS made for the mechanism, and the structure is still the highest level of the process at present.

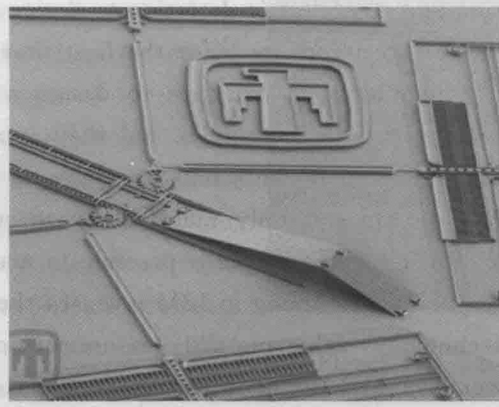

Figure 1.7 The scanning electron microscopy image of the micromirror of MEMS

Draper Laboratory introduced the double-frame bulk silicon micromechanical vibrating gyroscope sample driven by plate capacitor in 1988. It was the first silicon micromechanical gyroscope, and the plane dimension was 300 μm × 600 μm[7]. In 1993, ADI Corporation in America achieved the commercialization of MEMS acceleration sensors. In the next 10 years, the company introduced a series of acceleration sensors, which have been widely used in the field of automotive electronics and aerospace. In 1988, Greenwood J C published his research findings[8], making substantial content and theoretical analysis of resonant silicon micro-mechanical pressure sensor designed by himself in 1984. The design was then used by Druck Corporation and achieved industrialization by marketing in 1990s. As shown in Figure 1.8, it used a butterfly structure. When applying tested pressure to the back of the silicon diaphragm, the diaphragm is deformed, resulting in strain in the wedge part of butterfly resonant beam. Thus the natural frequency of the resonant beam changes, and the pressure can be calculated by testing its change value. The sensor, using the bulk silicon technology, could be used to measure the flying height of the aircraft and was widely used.

In 2002, University of California, Berkeley invented the resonant silicon micromechanical gyroscope[9-10], making the performance of the gyro further improved. At present, MEMS has formed the industrialization, and its products include acceleration sensors, gyroscopes, inkjet print heads, pressure sensors and so on, and its application fields refer to aerospace, automotive electronics, the game industry, mobile phones and so on.