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微机械光子学

Micromechanical Photonics

H.Ukita

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Micromechanical Photonics

●The purpose of this book is to give the engineering student and the practical engineer a systematic introduction to optical MEMS (Micro electro mechanical systems) and micromechanical photonics through not only theoretical and experimental results, but also by describing various products and their fields of application.

●The book describes extremely-short-external-cavity laser diodes tunable laser diodes, a resonant sensor and an integrated optical head. It then addresses optical tweezers, the new technology employed to manipulate various types of objects in a variety of research and industrial fields. Coverage progresses through topics on the design and fabrication of an optical rotor and evaluation of mixing performances of micro-liquids for future fluidic applications.

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内 容 简 介

光学 MEMS 是 MEMS 中的热门领域，也是 MEMS 的重要发展方向之一。本书系统论述了光学 MEMS 和微机械光子学，书中阐述了此领域的理论及实验结果，并且介绍了多种器件及其应用。内容涉及激光二极管、共振传感器、光镊子等多种器件，最后，对微机械光子学的未来发展做了展望。

本书内容丰富，系统阐述了光学 MEMS，可供从事此领域的学生及工程技术人员参考。

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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

The recent remarkable development of microsystems dates back to 1983 when Richard P. Feynman of California University delivered a speech to a large audience of scientists and engineers at the Jet Propulsion Laboratory. He presented the concept of sacrificed etching to fabricate a silicon micromotor, and pointed out the need for a friction-less, contact sticking-free structure, due to the relative increase of the surface effect in such microsystems and devices. A micromotor fabricated by Fan *et al.* in 1988 caused a tremendous sensation and opened the way for Micro-Electro-Mechanical-System (MEMS) technology. The diameter of the rotor was 120 μm, its rotational speed was 500 rpm, and the gap between the rotor and the stator was 2 μm. Today, many successful examples of MEMS products can be found: MEMS such as accelerometers, pressure sensors, microphones and gyros are used commercially, and various branches of industry are already including MEMS components in their new products.

Furthermore, optical MEMS, or micromechanical photonics, are evolving in interdisciplinary research and engineering fields to merge independently developed technologies based on optics, mechanics, electronics and physical/chemical sciences. Manufacturing technologies such as semiconductor lasers, surface-micromachining and bulk-micromachining are promoting this fusion of technologies. In addition, new devices such as optical MEMS including optical sensors, optical switches, optical scanners, optical heads, near-field probes, optical rotors and mixers, actuators, and microsystems for diagnosis and treatments, and new conceptual frameworks such as micromechanical photonics including an optical encoder, a tunable laser diode with a microcantilever and Nano-Electro-Mechanical-Systems (NEMS) are appearing.

Rapidly emerging interdisciplinary science and technology are expected to provide new capabilities in sensing, actuation, and control. Advances such as MEMS, optical MEMS, micromechanical photonics and microfluidics have led not only to a reduction in size but also be the merging of computation, communication and power with sensing, actuation and control to provide new functions. By integrating smart optoelectronics and antennas for remote control with a microstructure, the ability of microsystems to interpret and control its environment will be drastically improved. Much further work, however, is required to develop this new field to the stage of commercial production.

The purpose of this book is to give the engineering student and the practical engineer a systematic introduction to optical MEMS and micromechanical photonics not only through theoretical and experimental results, but also by describing various products and their fields of application. Chapter 1 begins with an overview spanning topics from optical MEMS to micromechanical photonics and the diversity of products using them at present and in the near future. Chapter 2 demonstrates extremely short-external-cavity laser diodes, tunable laser diodes, a resonant sensor and an integrated optical head. The chapter deals with laser diodes closely aligned with a microstructure including a diaphragm, a microcantilever and a slider. Chapter 3 addresses optical tweezers. This new technology is employed to manipulate various types of objects in a variety of research and industrial fields. The section first analyzes the trapping efficiency by geometrical optics and then compares the theory with the results obtained experimentally, finally presenting a variety of applications. Chapter 4 deals with the design and fabrication of an optical rotor and evaluates its improved mixing of micro-liquids for future fluidic applications such as micrototal analysis systems (μ-TAS). In Chap. 5, the fundamentals and applications of the near field are described for the future development of micromechanical photonics. This technology enables us to observe, read/write and fabricate beyond the wavelength resolution by accessing and controlling the near field. The chapter deals with near-field features, theoretical analyses, experimental analyses and applications mainly related to optical recording.

This work was created in conjunction with many coworkers at NTT and professors and graduate students in Ritsumeikan University. I would like to thank many friends at NTT Laboratories: T. Toshima, K. Itao, and K. kogure for their helpful discussions; Y. Uenishi, Y. Katagiri, E. Higurashi for their long-term co-operation; H. Nakata for bonding an LD–PD on a slider; Y. Sugiyama and S. Fujimori for the fabrication of phase-change recording media; R. Sawada, H. Shimokawa, O. Oguchi, and Y. Suzuki for the preparation of experimental devices; T. Maruno and Y. Hibino for their help with the fabrication of a PLC grating sample; K. Kurumada, N. Tuzuki, and J. Nakano for the preparation of InP laser diodes; and T. Ohokubo and N. Tamaru for their help with the experiments.

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I would like to thank J. Tominaga of the National Institute of Advanced Industrial Science and Technology for preparation and discussion of the super-RENS optical disk, and S. Hiura and K. Yamano of Denken Engineering Co. for the trial manufacture of a micro-photoforming apparatus, and K. Horio of Moritex Co. for the trial manufacture of a micro-energy-conversion apparatus.

I would also like to thank Dr. Claus E. Ascheron and Ms. Adelheid Duhm for supporting our book project.

Finally, I wish to thank my wife Misako for her continuous support. I would like to offer her this book as a gift for our 30th wedding anniversary.

Lakeside Biwako
February 2006

Hiroo Ukita

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From Optical MEMS to Micromechanical Photonics

Micromechanical photonics is evolving in interdisciplinary research and engineering fields and merging independently developed technologies based on optics, mechanics, electronics, and physical/chemical sciences. Manufacturing technologies such as those of semiconductor lasers, surface micromachining and bulk micromachining are promoting technology fusion.

This chapter presents an overview of the emerging technologies that feature new conceptual frameworks such as optical microelectromechanical systems (optical MEMS) including an integrated optical sensor, an integrated optical switch, an integrated optical head, an optical rotor, and a micrototal analysis system (μ-TAS); micromechanical photonics devices including an extremely short-external-cavity tunable laser diode (LD) with a microcantilever, a resonant sensor, an optical encoder and a blood flow sensor; nanoelectromechanical systems (NEMS) and system networks.

1.1 Micromechanical Photonics – An Emerging Technology

We have made substantial progress in individual areas of optics, mechanics, electronics and physical/chemical sciences, but it is insufficient to apply individual technologies and sciences to solve today's complicated technical problems. The start of semiconductor LD room temperature continuous oscillation in 1970 and micromachining technology [1.1, 1.2] based on photolithography and selective etching in the late 1980s resulted in the birth of optical MEMS [1.3]/micromechanical photonics [1.4] that combines/integrates electrical, mechanical, thermal, and sometimes chemical components through optics in the early 1990s.

Various kinds of optical MEMS have been developed for the fields of information, communication, and medical treatment. They include a digital micromirror device (DMD) [1.5] for both large projection display and color printing, optical switches [1.6, 1.7] for communication, microservo mechanisms

[1.8, 1.9] for optical and magnetic recording, and μ-TAS [1.10] for medical treatment.

Advanced lithography has been applied not only to silicon (Si) but also to thin film materials, including dielectric [1.11], polyimide [1.12], and metal [1.13] to offer unprecedented capabilities in extending the functionality and miniaturization of electro-optical devices and systems. Group III–V compounds, which include gallium arsenide (GaAs) [1.14] and indium phosphide (InP) [1.15], are attractive for integrating optical and mechanical structures to eliminate the need for optical alignment. In a tunable LD, the moving external cavity mirror has been integrated with a surface-emitting LD [1.16]. A moving cantilever has been integrated with edge-emitting LDs and a photodiode in a resonant sensor [1.17]. Monolithic integration technologies are expanding the field of micromechanical photonics.

Novel probing technologies such as the scanning tunneling microscope (STM) and optical tweezers have advanced our knowledge of surface science [1.18, 1.19] and technology, which are important in microscale and nanoscale mechanisms. Today's science and technology requires the focusing of multidisciplinary teams from engineering, physics, chemistry, and life sciences in both universities and industry. In this chapter, I first review fabrication methods of microstructures, then summarize some of the highlights in these attractive research fields, and then discuss the outlook for the future.

1.2 Fabrication Methods

There are common steps in fabricating optical MEMS/micromechanical devices: deposition, sputtering and etching, bulk micromachining including anisotropic etching and etch stop, and surface micromachining characterized by sacrificed layers that are etched away to leave etch-resistant layers. The fabrication methods of microstructures with optical elements are reviewed in [1.1, 1.2]. Miniaturization requires high aspect ratios and new materials. Reactive ion beam etching (RIBE) precisely defines the features and the spacing in deposited thin film and is of great importance in making high-aspect-ratio microstructures.

Si has been the most commonly used in micromachining, and its good electrical and mechanical properties have resulted in many commercially available sensors and actuators. A diaphragm is fabricated by bulk micromachining such as selective wet etching. Free-space micro-optical systems can be fabricated by surface micromachining; this is very promising and will greatly enrich the variety of integrated optical devices [1.20]. One choice is the silicon-on-insulator (SOI) technology [1.21]. Advantages of the SOI technology are its simplicity and small number of process steps.

Group III–V compounds, such as GaAs and InP, are attractive candidates for monolithic integration of optical and mechanical structures [1.14, 1.15]. Concrete examples are given later.

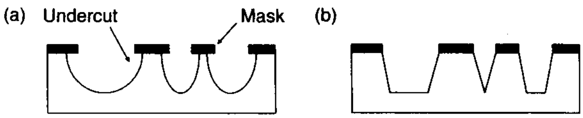

Fig. 1.1. Isotropic (**a**) and anisotropic (**b**) etchings for bulk micromachining

1.2.1 Bulk and Surface Micromachining

To fabricate structures by bulk micromachining, two etching methods can be used, isotropic and anisotropic etchings. In isotropic etching, etching proceeds at the same rate in all directions, which leads to the isotropic undercut shown in Fig. 1.1a. On the other hand, in anisotropic etching, etching proceeds at different rates depending on the crystal orientation, which leads to precise features, shown in Fig. 1.1b. Silicon V-grooves are fabricated by anisotropic etching of a (100) silicon substrate and are widely used in optical MEMS. The V-grooves are also used in packing of fiber and optoelectronic components.

To fabricate structures by surface micromachining, a sacrificed film is first deposited and patterned on the wafer. The film to be formed into the desired microstructure is next deposited and patterned, and the sacrificed layer is then etched away, undercutting the microstructure and leaving it freely suspended. There are two kinds of surface micromachining: photolithography for a thickness less than several 10 μm, and electron beam lithography for a thickness of less than 1 μm.

Photolithography

Photolithography is most widely used for the fabrication of a microstructure. The process steps shown in Fig. 1.2 include ultraviolet (UV) light exposure, development, etching, and resist stripping. This essentially 2-D process has the following characteristics:

1. difficulty in fabricating features smaller than the exposure light wavelength
2. high throughput by a mask process
3. relatively high aspect ratio.

The electrostatic micromotor [1.2] shown in Fig. 1.3, fabricated by Fan et al. of California University in 1988, caused a tremendous sensation and paved the way for the development of MEMS technology. The diameter of the microrotor was 120 μm and the gap between the rotor and the stator was 2 μm. Both were made of polysilicon thin films. When pulse voltages are applied to stator poles with different phases, an electrostatic torque arises between the rotor and the stator, which leads to the rotation rate of 500 rpm. Two years later, Mehregany et al. [1.22] of the Massachusetts Institute of Technology fabricated a micromotor with a higher speed of 15000 rpm. Recently, commercially used MEMS such as pressure sensors, accelerometers, and gyros are fabricated by the successive photolithography.