MICROTECHNOLOGY AND MEMS

H. Ukita

Micromechanical Photonics

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Micromechanical Photonics

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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 micro-cantilever 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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Lakeside Biwako
February 2006 Hiroo Ukita

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1

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.

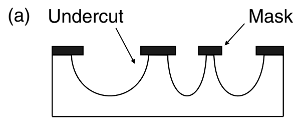

Fig. 1.1. Isotropic (**a**) and anisotropic (**b**) etchings for bulk micromachining

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.

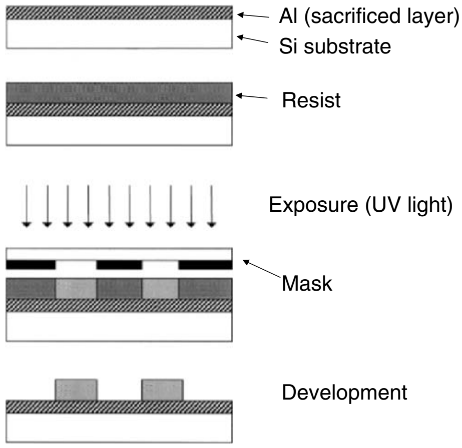

Fig. 1.2. Basic process of photolithography using a negative resist

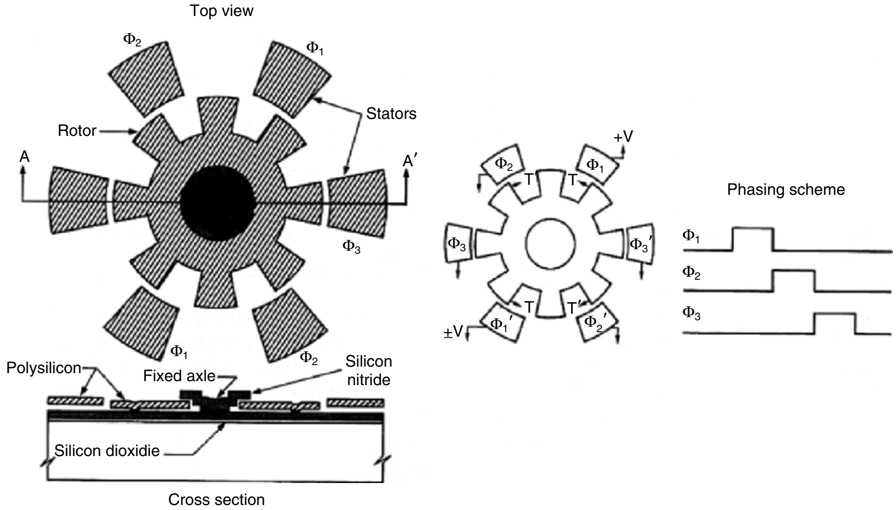

Fig. 1.3. Top view, cross-section, and the phasing scheme of a micromotor fabricated by surface micromachining [1.2] ©1988 IEEE

In the case of thick microstructures, SU-8 resists are widely used [1.23]. Physical properties of SU-8 can be found at http://aveclafaux.freeservers.com/SU-8.html. To view typical SU-8 applications, visit http://www.mimotec.ch/.

As an example of optical MEMS, the process for fabricating optical pressure rotors having anisotropic geometry on the side is shown in Fig. 1.4. First, the SiO_2 layer is deposited on a GaAs substrate, and then the SiO_2 is etched down to the GaAs substrate by reactive ion beam etching (not by UV light). The substrate is then immersed in a wet-etching solution to dissolve the GaAs

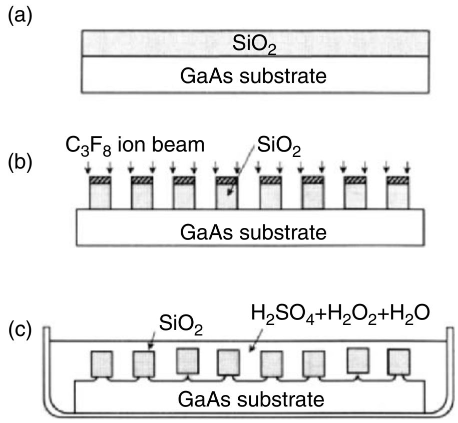

Fig. 1.4. Fabrication sequence, by photolithography, of an SiO_2 optical rotor (see Fig. 1.26). Deposition of SiO_2 layer by RF sputtering (**a**), etching of SiO_2 layer by reactive ion-beam etching (**b**), and stripping of SiO_2 by dissolution of the substrate (**c**)

layer. The resulting microrotors are washed and dispersed in water. Typical optical rotors are 20 μm in diameter and 10 μm thick, and are made of SiO_2 or polyimide or SU-8, which are transparent at the laser wavelength of 1.06 μm.

Electron Beam Lithography

In electron beam lithography (EBL), focused high-energy electrons with wavelengths less than that of UV light are irradiated onto electron-sensitive resist, as shown in Fig. 1.5. High-resolution patterning can be accomplished by scanning the e-beam two-dimensionally on the resist. Numerous commercial resists have been produced. EBL exhibits the following characteristics:

1. high-resolution patterning (less than 0.1 μm)
2. Easy and precise deflection by electrostatic or magnetic field
3. No need for mask process
4. Low throughput due to direct e-beam writing
5. Low aspect ratio (less than 1 μm thick).

1.2.2 Three-Dimensional Micromachining

LIGA

A surface-micromachined device has a thickness less than 100 μm. However, many micromechanical devices, particularly microactuators, require a thickness of few hundreds micrometers. Microstructures with a very large aspect

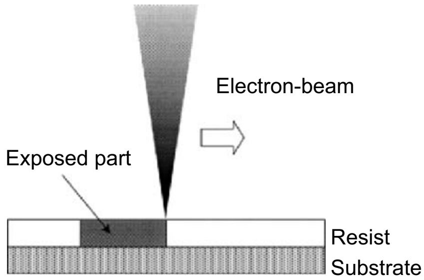

Fig. 1.5. Electron beam lithography (EBL) in which focused high-energy electrons are irradiated to the electron-sensitive resist

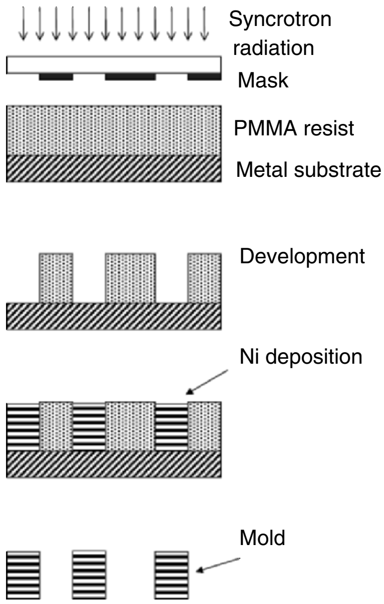

Fig. 1.6. Lithographie galvanoformung abformung (LIGA) involves X-ray lithography and electrodeposition processes

ratio (thickness-to-width ratio) can be fabricated by Lithographie galvanoformung abformung (LIGA), illustrated in Fig. 1.6. LIGA involves X-ray lithography, electrodeposition and molding process [1.24]. The aspect ratio that can be achieved using LIGA exceeds 300. LIGA exhibits the following characteristics:

1. high resolution
2. high aspect ratio
3. high throughput by mask and molding process
4. complicated mask production process.

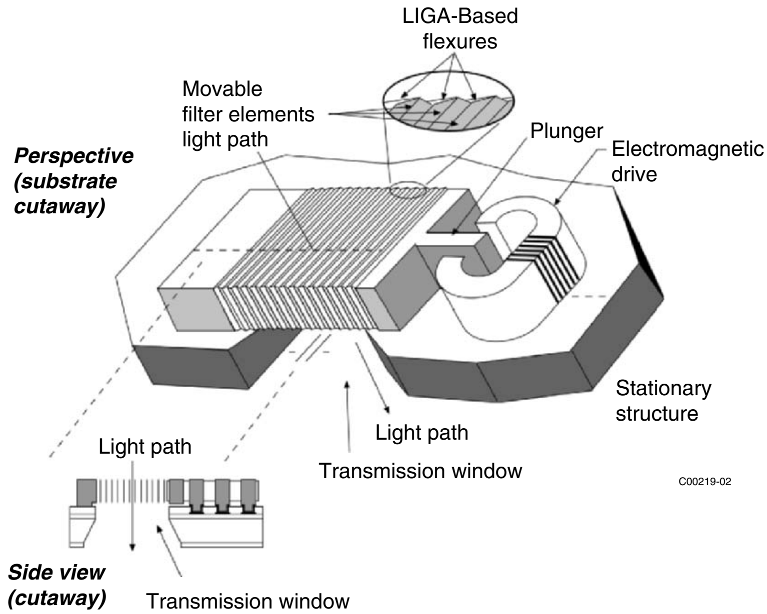

Fig. 1.7. LIGA-based tunable IR filter showing vertical parallel plate filter structure and linear magnetic drive actuator [1.25]. Courtesy of J. Allen Cox, Honeywell, USA

Figure 1.7 shows an LIGA-based tunable infrared (IR) filter [1.25]. Gratings with free-standing nickel walls as high as 50 µm with periods on the order of 10 µm were fabricated by LIGA. The linear actuator utilizes a permalloy electromagnet with an air gap because of the large power (0.1 mN) necessary to adjust the spacing of the grating. Furthermore, simple 3-D microstructures will be fabricated by the LIGA process [1.26].

Photoforming

Complicated 3-D microstructures have been fabricated by stacking preshaped layers made by solidifying a thin resin layer with UV light [1.27, 1.28]. There are two solidification methods: a free surface and a fixed surface solidification. In the case of the free surface, solidification occurs at the resin/air interface, leading to perturbation on the surface. On the other hand, in the case of the fixed surface, solidification occurs at the stable window/resin interface, leading to smoother structures. Photoforming exhibits the following characteristics:

1. complicated microstructures can be fabricated
2. laser beam can be deflected easily by scanning mirrors
3. no need for mask process
4. low throughput due to direct laser beam writing.

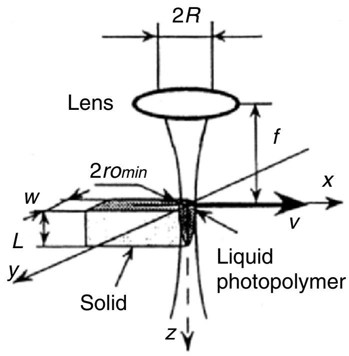

Fig. 1.8. Mechanism of photopolymerization using a focused laser beam. Reprinted from [1.27] with permission by K. Yamaguchi

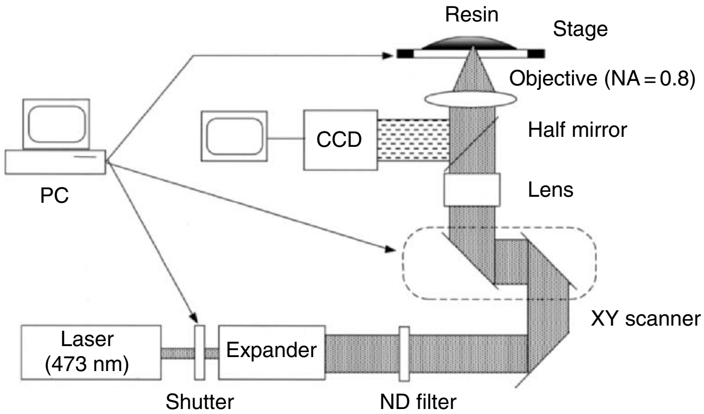

Fig. 1.9. 3-D microfabrication with photopolymerization using scanning focused laser beam

We also can directly fabricate a microstructure by scanning the laser beam in the resin. Figure 1.8 shows the mechanism of photopolymerization using a focused laser beam. Figure 1.9 shows the block diagram of such a point-by-point photoforming method. A focused blue laser beam (wavelength of 473 nm, output power of 10 mW) is used to solidify the resin. The scanning of the blue laser beam is controlled by adjusting mirrors according to the slice data of the microstructure. In this case, a 3-D structure is fabricated by scanning the focused spot in three dimensions inside the resin, rather than by using a layer-by-layer process. Although the spot diameter is small at the focal plane, the depth of focus is large, which leads to inferior resolution at depth.

In order to improve 3-D resolution, several photoforming methods have been proposed, as listed in Table 1.1. Photopolymerization stimulated by two-photon absorption was demonstrated using a Ti:sapphire laser and urethane-based resin (SCR-500), as shown in Fig. 1.10 [1.29]. Since the two-photon

Table 1.1. Comparison of proposed photoforming methods with high resolution

method	two-photon absorption	super IH process	spinner
light source			
laser	titan-sapphire laser	He–Cd laser	laser diode
wavelength (nm)	780	442	650
power	50 kW (peak)	1.5 mW	0.35 mW
resin	urethane based (SCR-500)	urethane based (Threshold)	aclyle based (DF-200N)[a]
cubic structure	3-D scanning	3-D scanning	stacking
resolution (μm)			
depth	2.2	3.0	2.0
lateral	0.62	0.5	1.0

[a] Commercially available from Nippon Kayaku Corp.

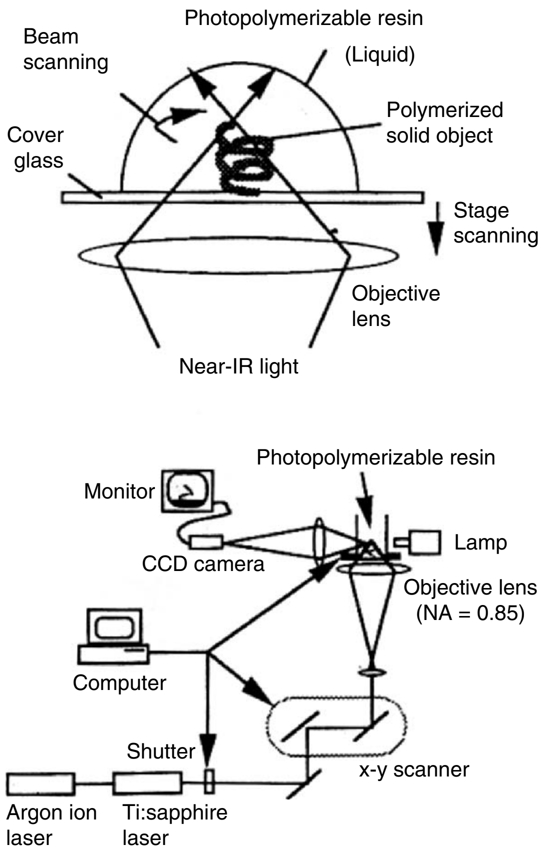

Fig. 1.10. Photopolymerization stimulated by two-photon-absorption using Ti:sapphire laser and SCR-500 resin. Reprinted from [1.29] with permission by S. Kawata, Osaka University, Japan

absorption rate is proportional to the square of the incident light intensity, a 3-D structure is fabricated by scanning the focused spot of a near-infrared-wavelength beam in three dimensions inside the resin. The lateral and depth resolutions are said to 0.62 and 2.2 μm, respectively. After that, they also succeeded in fabricating a micrometer sized cow with a resolution of 140 nm [1.30].

Replication

Replication from a mold is important technology for realizing lower cost and mass production. For optical MEMS applications, the use of sol–gels which become glass-like material upon curing is foreseen. ORMOCER US-S4 is such a material. It is optically transparent over the wavelength from 400 to 1600 nm and has a refractive index of 1.52 at 588 nm. Obi et al. replicated many sol–gel micro-optical devices and optical MEMS including a sol–gel cantilever with a microlens on the top [1.31].

1.2.3 Monolithic Integration – Micromachining for an LD

Monolithic integration of micromechanics is possible not only on a Si substrate but also on a semiconductor LD substrate of GaAs [1.14] or InP [1.15]. A smooth etched surface and a deep vertical sidewall are necessary for good lasing characteristics of LDs.

For fabricating a resonant microcantilever (MC), for example, there are three micromachining steps (Fig. 1.11). (a) An etch-stop layer of AlGaAs is formed in an LD structure prepared by metalorganic vapor phase epitaxy (MOVPE). (b) The microstructure shape is precisely defined by a reactive dry-etching technique, which simultaneously forms the vertical etched

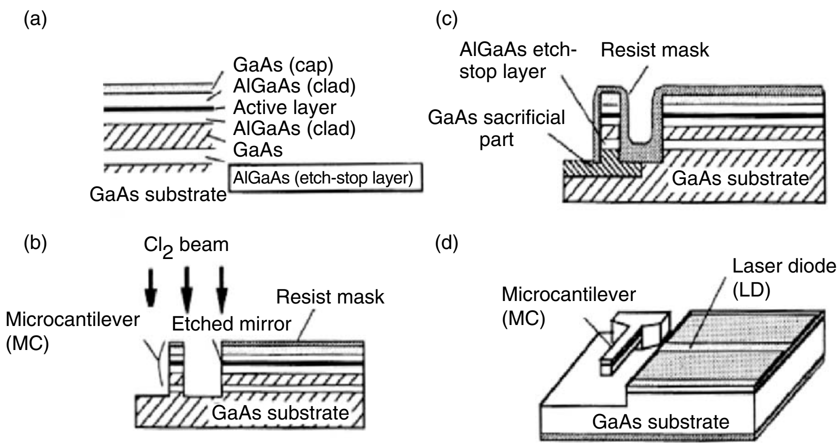

Fig. 1.11. Steps in the fabrication of a GaAs/AlGaAs resonant microcantilever (MC) integrated with a laser diode (LD)

mirror facets for LDs. (c) A wet-etching window is made with a resist, and the microcantilever is undercut by selective etching to leave it freely suspended.

These processes are compatible with laser fabrication, so an MC structure can be fabricated at the same time as an LD structure. Furthermore, because a single-crystal epitaxial layer has little residual stress, precise microstructures can be obtained without significant deformation.

Combined use of the above micromachining processes will be useful in the future. However, processing of electronics and MEMS must be compatible and should be held down to low costs. In many actual microsystems, microassembly, bonding, and packing techniques will also play important roles. Moreover, to apply the merit of the mask process to the MEMS with an arrayed structure, it is imperative to increase the yield rate.

1.3 Miniaturized Systems with Microoptics and Micromechanics

1.3.1 Important Aspects for Miniaturization

We see that the miniaturization techniques described earlier will provide many new optical MEMS that will environmentally friendly due to their smallness, reliable due to the integration process, and low in cost owing to mass production. However, new problems arise as a result of the miniaturization. Understanding the scaling laws and the important aspects of miniaturization will help readers in choosing the appropriate actuator mechanism and power source.

Feynman presented the concept of sacrificed etching to fabricate a silicon micromotor 20 years ago [1.32]. At the same time, he pointed out the necessity of friction-less and contact sticking-free structure for the MEMS because of the relative increase of the surface effect in such microdevices.

Figure 1.12 shows the general characteristics of scaling laws. As the object size $[L]$ decreases, the ratio of surface area $[L^2]$ to volume $[L^3]$ increases. Weight depends on volume, while drag force depends on surface area, which renders surface forces highly important in microstructures. Faster evaporation associated with larger surface-to-volume ratios has important consequences in analytical equipment such as μ-TAS.

Response time is proportional to [mass/frictional force], i.e., $[L^3/L^2] = [L]$, which leads to fast response. The Reynolds number is proportional to [inertia force/viscous drag force], i.e., $[L^4/L^2] = [L^2]$, which leads to laminar flow. Moving energy is proportional to [mass × velocity^2], i.e., $[L^3 \times L^2] = [L^5]$, which leads to low energy consumption.

Almost all micromotors and microactuators have been built based on electrostatic actuation, nevertheless, electrostatic force is proportional to $[L^2]$, but electromagnetic force is proportional to $[L^4]$. This is because the plate for

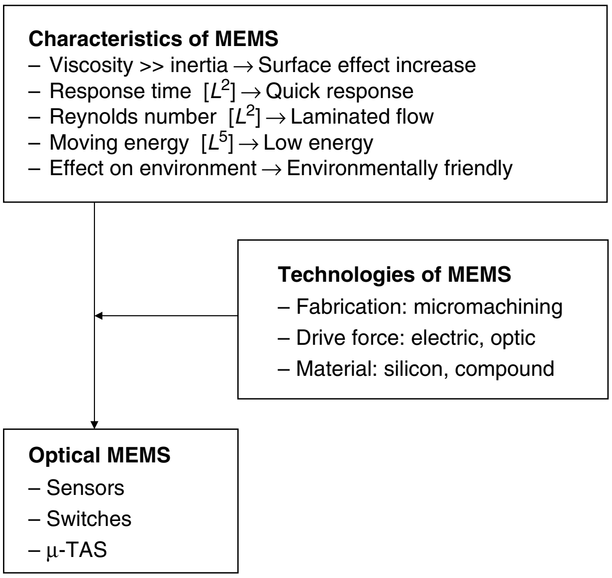

Fig. 1.12. General characteristics of scaling laws: the merits of miniaturization

generating electrostatic force is easier to fabricate in a limited space than the inductance coil that generates the magnetic field for actuation. Actually, to drive thick and heavy MEMS [1.25], electromagnetic force is used because the electrostatic driving force is too weak.

We deal mostly with micrometer-sized devices. In the micrometer regime, conventional macrotheories concerning electrical, mechanical, fluidic, optical, and thermal devices require corrections. Specific properties of the thin film material differ from those of bulk. Shape change due to thermal stress or fast movement occurs in the micromirror fabricated by surface micromachining, which degrades the optical quality of the laser beam.

1.3.2 Light Processing by Micromechanics

Since light can be controlled by applying relatively low energy, the electrostatic microstructures such as moving mirrors or moving gratings have been fabricated on the same wafer. Applications of moving mirrors in micro positioning have begun to appear recently, and many kinds of digital light switches have been demonstrated. These include a DMD [1.5], an optical scanner [1.33], a tunable IR filter [1.25], and a comb-drive nickel micromirror [1.34]. A nickel micromirror driven by a comb-drive actuator was fabricated by nickel surface micromachining. The micromirror was 19 μm high and 50 μm wide and the facet reflectivity was estimated to be 63%. A microstrip antenna was fabricated on a fused quartz structure that could be rotated to adjust spatial scanning of the emitted microwave beam [1.35].

Free-space Micro-optical Bench and Sensors

Vertical micromirrors can be fabricated by anisotropic etching on (100) silicon just like the V-groove described in Sect. 1.2.1. The (111) planes are perpendicular to the Si surface and atomically smooth. Therefore, high-aspect-ratio mirrors can be formed. Figure 1.13 shows an on-chip Mach-Zehnder interferometer produced by Uenishi [1.36]. Micromirrors are reported several μms thick and 200 μm high.

Free-space micro-optical elements held by 3-D alignment structures on a silicon substrate have been demonstrated using a surface-micromachining technique in which the optical elements are first fabricated by a planar process and then the optical elements are folded, into 3-D structures, as shown in Fig. 1.14 [1.37]. Figure 1.15 shows the schematic of the out-of-plane micro-Fresnel lens fabricated on a hinged polysilicon plate (a), and the assembly process for the 3-D micro-Fresnel lens (b) [1.38]. A Fresnel lens stands in front of an edge-emitting LD to collimate its light beam.

To achieve on-chip alignment of hybrid-integrated components such as an LD and a micro-optical element, a micro-XYZ stage consisting of a pair of

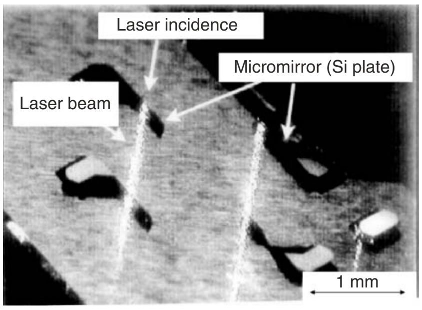

Fig. 1.13. An on-chip Mach-Zehnder interferometer produced by anisotropic etching on (100) silicon [1.36]. Courtesy of Y. Uenishi, NTT, Japan

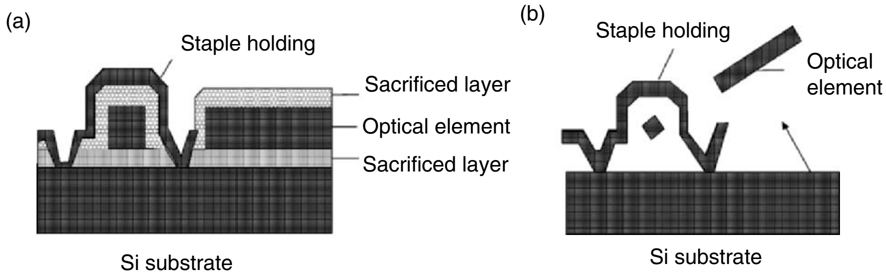

Fig. 1.14. Free-space micro optical elements held by 3-D alignment structures on a silicon substrate, fabricated using a surface-micromachining technique. Optical elements were first fabricated by planar process and then folded into 3-D structures [1.37]

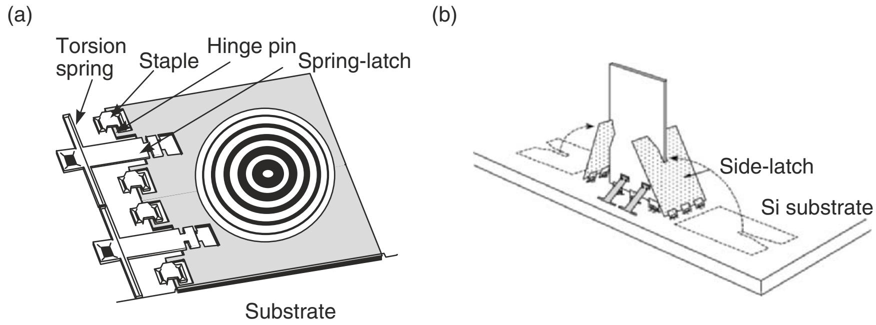

Fig. 1.15. Schematic of the out-of-plane micro-Fresnel lens fabricated on a hinged polysilicon plate (**a**), and the assembly process for the 3-D micro-Fresnel lens (**b**) [1.38]. Courtesy of Ming Wu, University of California, USA

parallel 45° mirrors has been demonstrated to match the optical axis of the LD with that of the micro-optical element [1.38]. Both the micro-XYZ stage and the free-space micro-optical elements are fabricated by the microhinge technique to achieve high-performance single-chip micro-optical systems.

Digital Micromirror Device (DMD)

A digital micromirror device (DMD) was developed by Texas Instruments in 1987. A standard DMD microchip has a 2-D array of 0.4×10^6 switching micromirrors. Figure 1.16 shows a DMD structure consisting of a mirror that is connected to a yoke through two torsion hinges fabricated by a CMOS-like process. Each light switch has an aluminum mirror that can be rotated ± 10 degrees by electrostatic force depending on the state of the underlying CMOS circuit [1.5].

The surface micromachining process to fabricate DMD is shown in Fig. 1.17. The illustrations are after sacrificial layer patterning (a), after oxide hinge mask pattering (b), after yoke oxide patterning (c), after yoke/hinge etching and oxide stripping (d), after mirror oxide patterning (e), and the completed device (f). "CMP" in (a) means "chemomechanically polished" to provide a flat surface.

Figure 1.18 shows the optical layout of a large-screen projection display using a DMD. The DMD is a micromechanical reflective spatial light modulator consisting of an array of aluminum micromirrors. A color filter wheel divided into three colors; red, blue, and green, is used for color presentation. A 768×576 pixel DMD was tested and a contrast ratio of 100 was reported.

Optical Switch

Analog and digital switches, tunable filters, attenuators, polarization controllers, and modulators are some of the devices required in optical

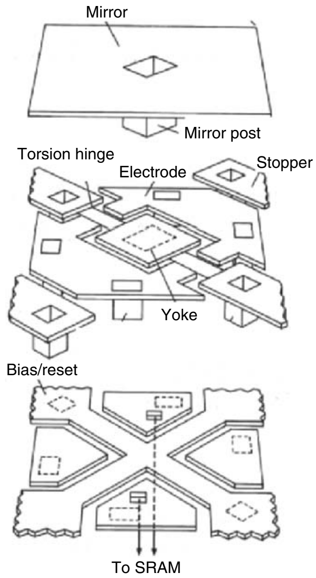

Fig. 1.16. Digital micromirror device (DMD) developed by Texas Instruments. A DMD structure, with a mirror connected to a yoke by two torsion hinges, is fabricated by a CMOS-like process [1.5] Courtesy of Larry J. Hornbeck, Texas Instruments, USA ©1993 IEEE

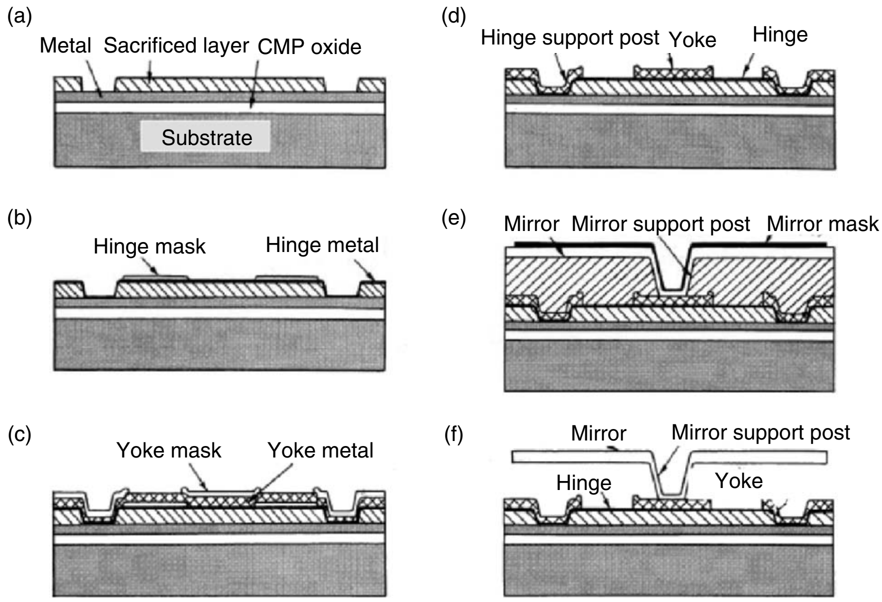

Fig. 1.17. Fabrication process of a digital mirror device (DMD) structure consisting of a mirror connected by two torsion hinges [1.5] ©1998 IEEE