Micromechanical Photonics

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Recent remarkable development of microsystems dates back to the 1983 when Professor R. 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 micro-motor, and pointed out the necessity of friction-less, contact sticking-less 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, which rotated at 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 technology fusion. In addition, new devices are appearing, such as optical MEMS including optical sensors, optical switches, optical scanners, optical heads, near-field probes, optical rotors and mixers, actuators, 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).

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 to not only to a reduction in size but also 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 through not only theoretical and experimental results, but also by describing various products and their fields of application. Chapter 1 begins with an overview 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 results obtained experimentally, finally showing the variety of applications. Chapter 4 deals with the design and fabrication of an optical rotor; and evaluates the increase in its mixing performance of micro-liquids for future fluidic applications such as micro-total analysis systems (μ-TAS). In chapter 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.

4. Optical Mixer

4.1 Introduction

4.2 Theoretical Analysis I - Optical Torque -

4.3 Theoretical Analysis II - Fluid Dynamics -

4.4 Fabrication

4.5 Evaluation

4.6 Future Applications

5. Near Field

5.1 Introduction

5.2 Theoretical Analysis

5.3 Experimental Analysis

5.4 Future Applications

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 micro-electromechanical systems (optical MEMS) including an integrated optical sensor, an integrated optical switch, an integrated optical head, an optical rotor, a micro-total analysis system (μ-TAS); micromechanical photonics devices including a very short external cavity tunable laser diode with a microcantilever, a resonant sensor, an optical encoder and a blood flow sensor; nano-electromechanical 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 laser diode 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, micro-servo mechanisms [1.8, 1.9] for optical and magnetic recording, and micro-total analysis systems (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 laser diode, the moving external cavity mirror has been integrated with a surface-emitting laser diode. [1.16] A moving cantilever has been integrated with edge-emitting laser diodes 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 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 sacrificial layers that are etched away to leave etch-resistant layers. The fabrication methods of microstructures with optical elements are reviewed in references [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.

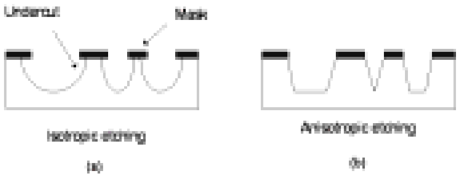
Silicon (Si) has been the most commonly used in micromachining, and its good electrical and mechanical properties have resulted in many commercially available sensors and actuators. A diaphragm is fabricated by bulk micromachining such as selective wet etching. Free-space microoptical systems can be 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] The advantage of the SOI technology is its simplicity and small number of process steps.

Group III-V compounds, such as gallium arsenide (GaAs) and indium phosphide (InP), are attractive candidates for monolithic integration of optical and mechanical structures. [1.14, 1.15] Concrete examples are given below.

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. 1.1 (a). On the other hand, in anisotropic etching, etching proceeds at different rates depending on the crystal orientation, which leads to a precise features, shown Fig. 1.1 (b). 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.

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

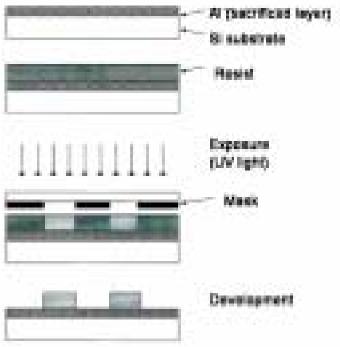


To fabricate structures by surface micromachining, a sacrificial film is first deposited and patterned on the wafer. The film to be formed into the desired microstructure is next deposited and patterned, and the sacrificial layer is then etched away, undercutting the microstructure and leaving it freely suspended. There are two kinds of surface micromachining: photolithography for a thickness less than 100 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

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



process steps shown in Fig. 1.2 include 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.

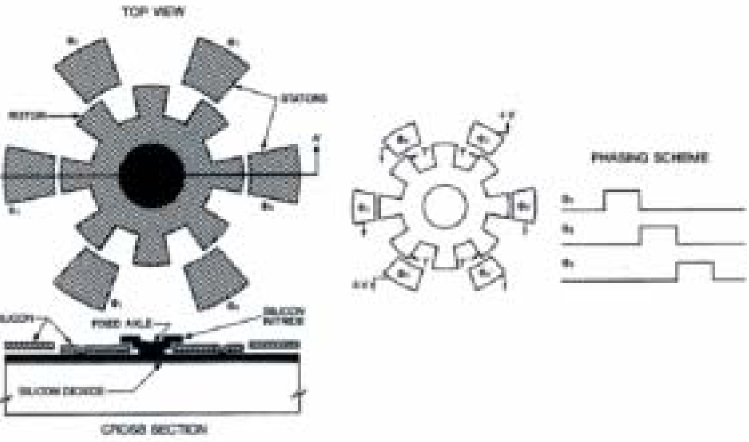


Fig. 1.3. Top view, cross section and the phasing scheme of a micromotor fabricated by surface micromachining [1.1]

The micromotor [1.1] 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 rotor 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. of the Massachusetts

Institute of Technology fabricated a micromotor with a higher speed of 15000 rpm. [1.22] Recently, commercially used MEMS such as pressure sensors, accelerometers, microphones and gyros are fabricated by the successive photolithography.

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 SiO_2 microrotors having anisotropic geometry on the side is shown in Fig. 1.4. First, the SiO_2 layer is deposited on a gallium arsenide (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 layer. The resulting microrotors are washed and dispersed in water. Typical optical pressure rotors are about 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.

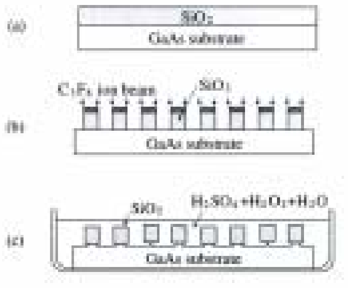


Fig. 1.4. Fabrication sequence, by photolithography, of a SiO_2 microrotor. (a) Deposition of SiO_2 layer by RF sputtering. (b) Etching of SiO_2 layer by reactive ion-beam etching. (c) Separation of SiO_2 by dissolution of the substrate

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).

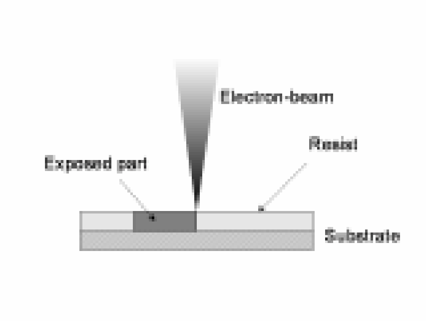


Fig. 1.5. Electron beam lithography (EBL) in which focused high-energy electrons are irradiated to the electron-sensitive resist

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 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 micromolding 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.

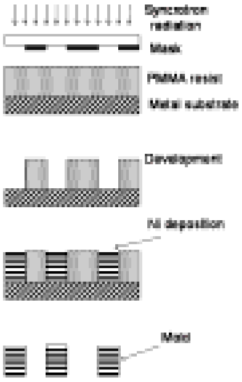


Fig. 1.6. Lithographie Galvanoformung Abformung (LIGA) involves X-ray lithography and electrodeposition proceses

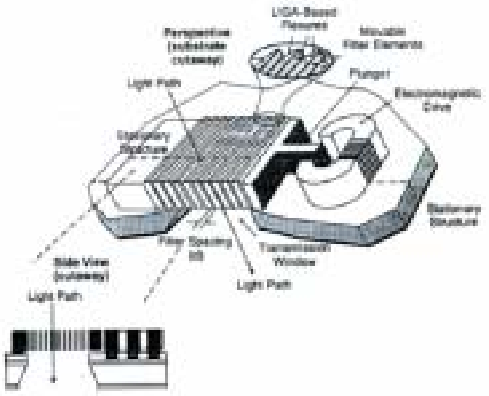


Fig. 1.7. LIGA-based tunable IR filter showing vertical parallel plate filter structure and linear magnetic drive actuator [1.25]

Figure 1.7 shows a 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-Dmicrostructures will be fabricated by the LIGA process. [1.26]

Fig. 1.8 Mechanism of photo-polymerization using a focused laser beam [1.27]

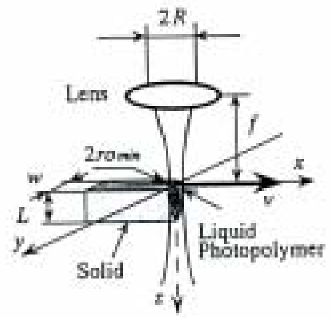
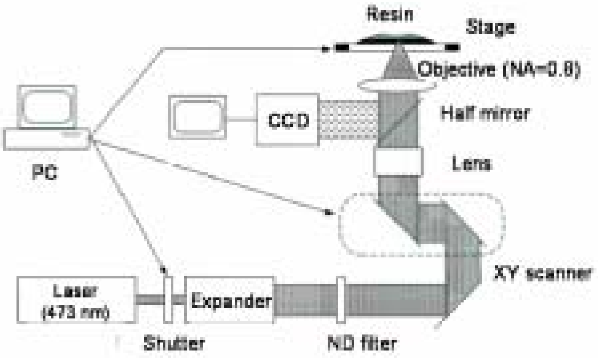


Fig. 1.9. 3-D microfabrication with photopolymerization using scanning focused laser beam

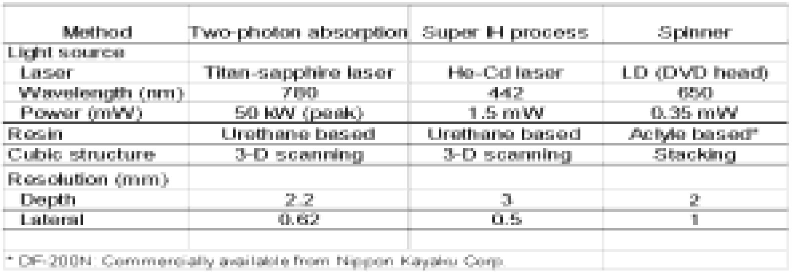


Photoforming

Complicated 3-D microstructures have been fabricated by stacking preshaped layers made by solidifying a thin resin layer with ultraviolet (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.

Table 1.1. Comparison of proposed photoforming methods with high resolution

Photoforming exhibits the following characteristics.



Method	Two-photon absorption	Super IH process	Spinner
Light source			
Laser	Titan-sapphire laser	He-Cd laser	LD (DVD head)
Wavelength (nm)	780	442	650
Power (mW)	50 kW (peak)	1.5 mW	0.35 mW
Resin	Urethane based	Urethane based	Aclyle based*
Cubic structure	3-D scanning	3-D scanning	Stacking
Resolution (mm)			
Depth	2.2	3	2
Lateral	0.62	0.5	1

* OF-200N: Commercially available from Nippon Kayaku Corp.

1. Complicated microstructures can be fabricated.
2. Light beam can be deflected easily by scanning mirrors.
3. No need for mask process.
4. Low throughput due to direct laser beam writing.

We also can directly fabricate a microstructure by scanning the light 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 14 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.

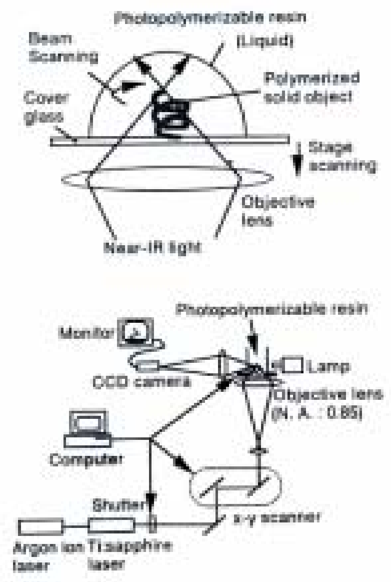


Fig. 1.10. Photo-polymerization stimulated by two-photon-absorption using Ti:sapphire laser and SCR-500 resin [1.29]

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 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 μm 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 costs 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. [1.31] 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 microoptical devices and optical MEMS including a sol-gel cantilever with a microlens on the top.

1.2.3 Monolithic Integration - Micromachining for a Laser Diode -

Monolithic integration of micromechanics is possible not only on a silicon substrate but also on a laser diode (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 GaAs and InP semiconductor laser diodes.

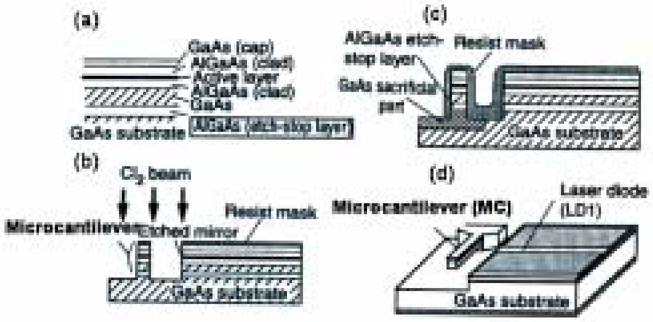


Fig. 1.11. Steps in the fabrication of a GaAs / AlGaAs resonant microcantilever (MC) integrated with a laser diode (LD)

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 a laser diode 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 mirror facets for LDs. (c) A wet-etch window is made with a photoresist, and themicrocantilever is undercut by selective etching to leave it freely suspended.

These processes are compatible with laser fabrication, so a MC structure can be fabricated at the same time as a 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 above 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.

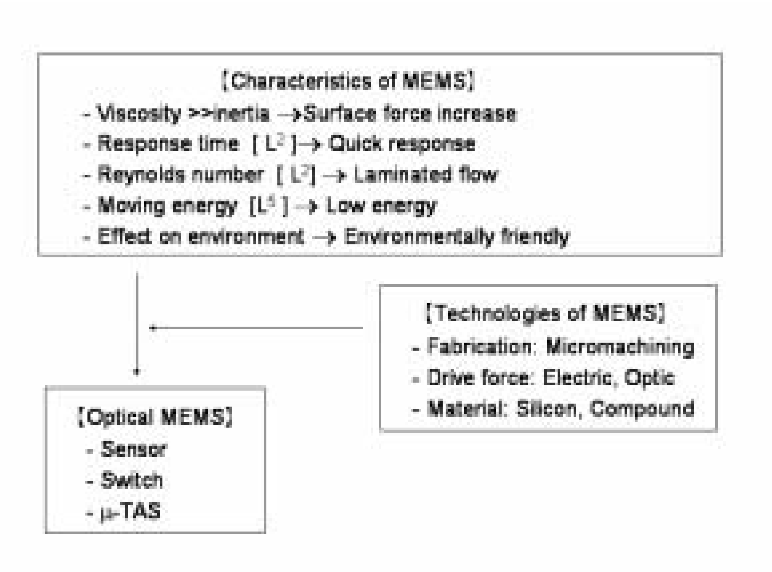


Fig. 1.12. General characteristics of scaling laws: the merits of miniaturization

Feynman presented the concept of sacrificial etching to fabricate a silicon micromotor twenty years ago. [1.32] At the same time, he pointed out the necessity of friction-free 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 render 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 / drag force], i.e., [L^3/L] = [L^2], which leads to fast response. The Reynolds number is proportional to [inertial force / viscous force], i.e., [L^4/L^2] = [L^2], which leads to laminar flow. Moving energy is proportional to [mass x velocity^2], i.e., [L^3 x 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 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 digital micromirror device, [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]

Fig. 1.13. An on-chip Mach-Zehnder interferometer produced by anisotropic etching on (100) silicon [1.36]

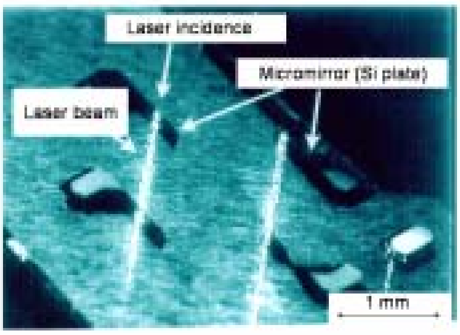
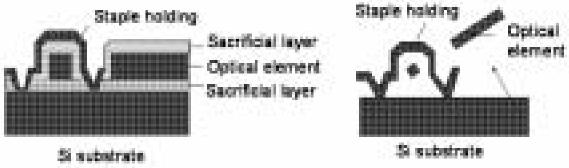


Fig. 1.14. Free-space microoptical elements held by 3-D alignment structures on a silicon substrate, fabricated using a surface-micromachining technique. Optical elements were first fabricated by planar process and then folded into three-dimensional structures [1.37]



Free-space microoptical 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 et al. [1.36] Micromirrors are reported several μms thick and 200 μm high.

Free-space microoptical 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 three-dimensional 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 three-dimensional micro-Fresnel lens (b). [1.38] A Fresnel lens stands in front of an edge-emitting laser diode to collimate its light beam.

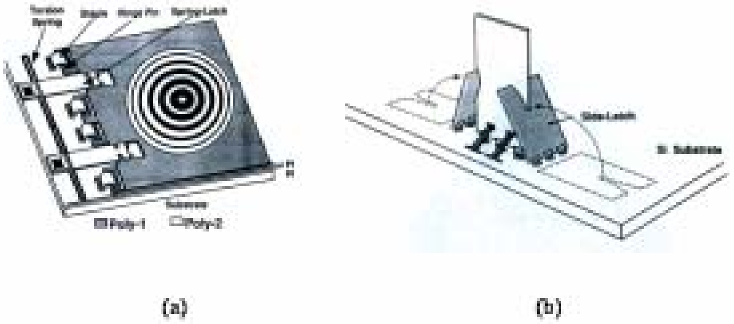


Fig. 1.15. Schematic of the out-of-plane micro-Fresnel lens fabricated on a hinged polysilicon plate (a), and the assembly process for the three-dimensional micro-Fresnel lens (b) [1.38]

To achieve on-chip alignment of hybrid-integrated components such as a laser diode and a microoptical element, a micro-XYZ stage consisting of a pair of parallel 45^0 mirrors has been demonstrated to match the optical axis of the laser diode with that of the microoptical element. [1.38] Both the micro-XYZ stage and the free-space microoptical elements are fabricated by the micro-hinge technique to achieve high-performance single-chip microoptical 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 x 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]

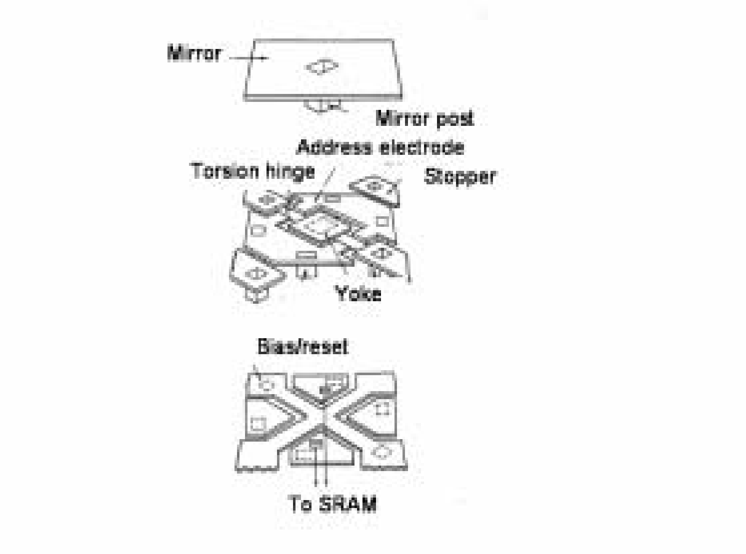


Fig. 1.16. Digital micromirror device (DMD) developed by Texas Instruments. A DMD structure, with a mirror connected to a yoke by two torsion hinges, is fabricated by a CMOS-like process [1.5]

The surface micromachining process to fabricate DMD is shown in Fig. 1.17. The illustrations are after sacrifical 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.

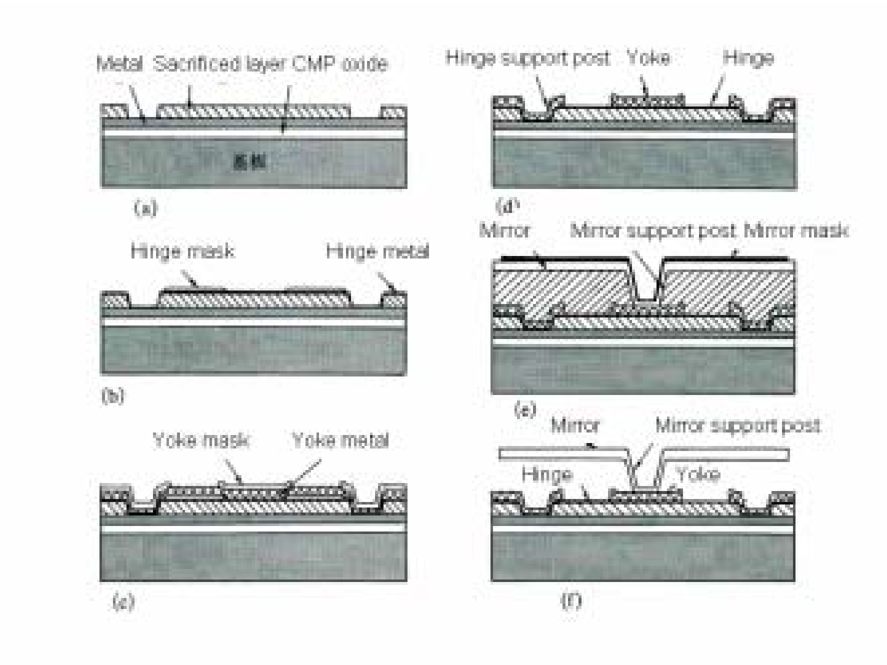


Fig. 1.17. Fabrication process of a digital mirror device (DMD) structure consisting of a mirror connected by two torsion hinges [1.5]

Fig. 1.18. Optical layout of a projector using a DMD

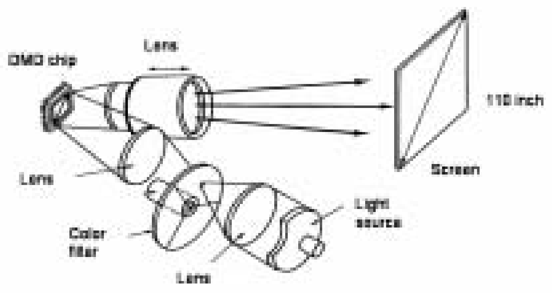


Figure 1.18 shows the optical layout of a large-screen projection display using a DMD. The DMD is a micromechanical reflective spatial light modulator consisting of an array of aluminum micromirrors. A color filter wheel divided into three

colors, red, blue, and green, is used for color presentation. A 768 x 576 pixel DMD was tested and a contrast ratio of 100 was reported.

Optical switch

Optical MEMS has become a household word thanks to the enormous interest in fiber-optic switching technology. Analog and digital switches, tunable filters, attenuators, polarization controllers, and modulators are some of the devices required in optical communication. Micromirror-based all-optical switches are thought to be the only actual solution to wavelength division multiplexing because they are independent of wavelength. Miniaturized optical switches can be changed to select different optical paths by adjusting the mirror tilt (without optic to electric transformation).

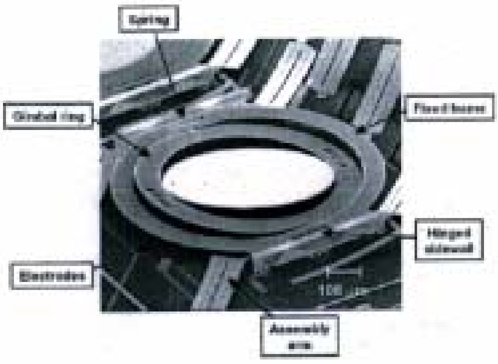


Fig. 19. Surface-micromachined beam-steering micromirror [1.7]

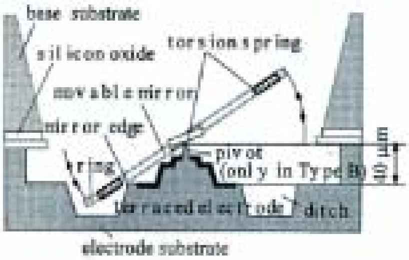


Fig. 1.20. Single-crystalline mirror actuated by electrostatic force applied via terraced electrodes [1.40, 1.41]

The micromirrors were fabricated based on the surface micromachining of polysilicon thin films (Fig. 1.19) [1.6, 1.7] in the first stage. Miniaturization methods enable the creation of arrays of tiny, high-capacity optical switches, such as those for switching 256 input light beams to 256 output fibers developed at Lucent Technologies. [1.7] An optical switch of 1152 x 1152 optical cross-connects was fabricated by Nortel. Free-space switching with a MEMS micromirror array between two stacked planar lightwave circuits (PLCs) is used to construct a wavelength-selective switch. [1.39]

Recently, bulk micromachining of crystalline silicon has been revived (Fig. 1.20) [1.40, 1.41] because the conventional mirror surface (polysilicon) fabricated by surface micromachining is thin (1 μm) and deformable due to the presence of both residual stress and a metal film coating. [1.42] The use of silicon-on-insulator (SOI) substrates together with deep reactive ion etching (DRIE) is now an established technology for fabricating high-performance optical switches because of the flatness of the mirror. [1.43]

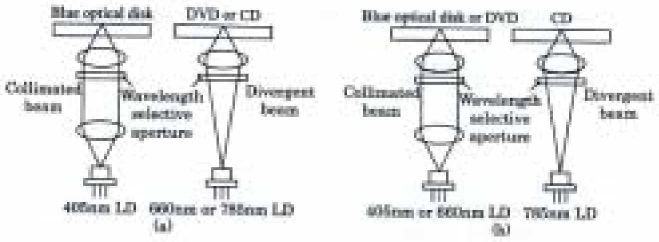


Fig. 1.21. Blue Ray / DVD / CD compatible optical head technology. The compatibility principle is based on spherical aberration correction and objective NA control for each disk [1.45]

Optical heads

Various optical disk systems with a Blue ray / DVD / CD compatible optical head, a free-space integrated optical head, and an electrostatic torsion mirror for tracking have been investigated for the advanced digital versatile disk (DVD) [1.44]. Flying optical heads with various small-aperture probes are proposed for next-generation near-field recording.

Three kinds of light wavelength λ and objective lens NA are used for the optical heads for a Blue ray, a DVD and a CD: (λ, NA) = (405 nm, 0.8), (650 nm, 0.6), and (785 nm, 0.5), respectively. Compatibility of heads with different wavelengths and different NAs, is needed (Fig. 1.21). [1.45] The compatibility principle is based on spherical aberration correction and objective NA control for each disk. Optical MEMS technologies are applied to control NA (aperture) depending on the wavelength, [1.45] to integrate optical components (Fig. 1.22), [1.20] and to track the optical disk groove. [1.9] Rotable microstages are implemented by a suspended polysilicon plate similar to that of a micromotor.

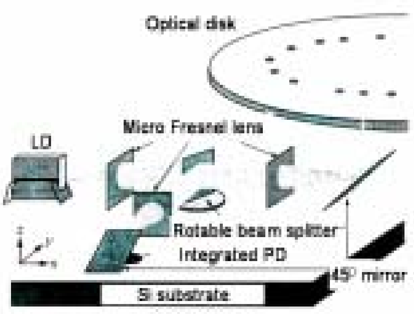


Fig. 1.22. A free-space optical pickup head integrated by surface micromachining [1.21]

In order to realize an ultrahigh-density optical disk, a tiny-aperture probe is needed. However, the optical transmittance decreases rapidly as the aperture diameter decreases below 100 nm. To increase the transmittance, a bow-tie probe with an actuator driven by electrostatic force was successfully fabricated (Fig.

1.23). [1.46] The on-chip actuator provides not only a narrow gap to enhance the intensity of the near field but also precision alignment of the optical components.

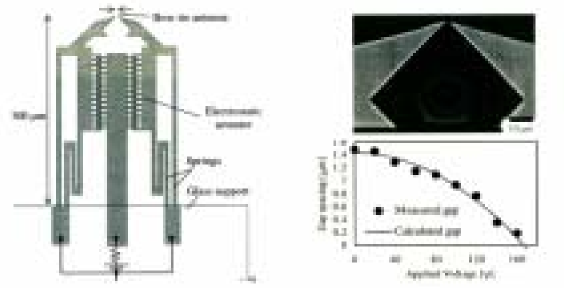


Fig. 1.23. A bow-tie probe with an actuator driven by electrostatic force is fabricated to provide a narrow gap that enhances the intensity of the near field [1.46]

μ-TAS / bio MEMS

Chip-scale technologies are diversifying into the field of microfluidics, such as a sample analysis system for physiological monitoring, sample preparation and screening, and a biomedical treatment application for a new surgical tool and drug delivery. [1.47]

A micro-total analysis system (μ-TAS) [1.48] is expected to reduce inspection time or the amount of reagent needed. The system shown in Fig. 1.24 comprises inlets for the sample and reagent loading, microchannels with a mixing chamber, an analysis chamber, and outlets for sample wastes.

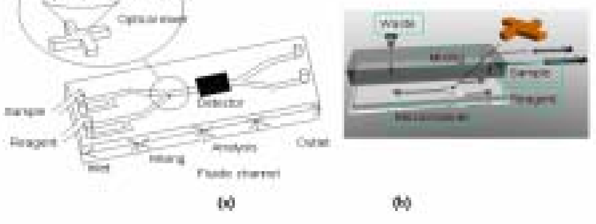


Fig. 24. Conceptual drawing of the future micro-total analysis system (μ-TAS)

In a microchannel, mixing is performed mainly by diffusion owing to the small Reynolds number. To promote a diffusion effect by interweaving two fluids, micro-mixing devices such as micronozzle arrays to increase the contact area, and intersecting channels [1.49] to induce chaotic behavior of a flow have been fabricated. An optically driven micromixer [1.50] has been proposed to stir a liquid directly, which is described in detail in Chap. 4. Highly sensitive detection methods [1.51] and high-performance micropumps [1.52] are also important because of the reaction between small liquids, as well as to drive liquids in microchannels.

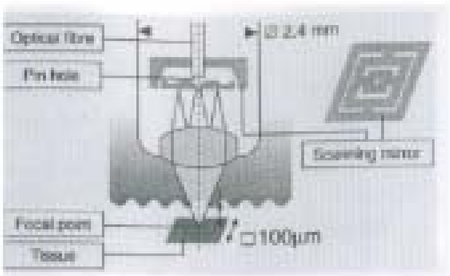


Fig. 1.25. Micro-confocal optical scanning microscope fabricated for minimally invasive medical diagnosis and treatment (m-COSM) [1.53]

Optical inspection of a human body is also a useful method for minimally invasive diagnosis and treatment. Figure 1.25 shows the micro-confocal optical scanning microscope (mCOSM). [1.53] The probe, 2.4 mm in diameter, consists of a 2-D electrostatic scanner which is placed in front of the end of the optical fiber. Light reflected by the tissue is collected by the same objective lens and reflected back into the same optical fiber. The field of view is 100 μm x 100 μm and the resolution is 1 μm with an image feed speed of 4 frames / s.

1.3.3 Kinetic Energy of Light

Light is conventionally applied in optical data storage, for example, a CD and a DVD, in an optoelectronic information apparatus such as displays and printers, in optical communication devices such as optical fibers and laser diodes, and in optical measurements, for example, using various kinds of sensors. In these applications, we have utilized the electromagnetic aspect of light. On the other hand, in optical MEMS and in micromechanical photonics applications, the kinetic energy aspect of light becomes important.

Powering of miniaturized equipments or systems by a light beam has recently been rediscovered, and many kinds of transduction from light energy to kinetic energy have been developed. The photoelectric effect was used to make a photostrictional actuator driven by light-induced conformational change of a polymer, semiconductor or ceramic. The photothermal effect was used to make a tiny resonator [1.14], a micropump, a microgripper [1.54] and a waveguide switch [1.55]. A photoformed gripper, designed for handling micro-objects in a narrow space, is actuated by the volume change of fluid upon applying laser power. This photothermal energy should be useful as a driving force of miniaturized systems because of its high power density and good energy transfer efficiency. A photo-electrochemical effect was studied for the development of a storage battery. [1.56]

A photovoltaic microdevice to cover the surface of a miniaturized system was developed for amorphous silicon thin films triple-stacked and series-connected to obtain a high voltage of 200 V. [1.57] A microdevice to transfer energy via light to a microwave by combining piezoelectric force and an antenna has been reported. [1.58]

1.3.4 Micro Mechanical Control by Optical Pressure

Ashkin et al. demonstrated optical trapping in 1970. A great deal of theoretical and experimental knowledge and technology in this field has been accumulated.

Today, such technology is used in various scientific and engineering fields to manipulate [1.59], align [1.60] and switch [1.61] many kinds of micro-objects. Optical tweezers is described in detail in chapter 3.

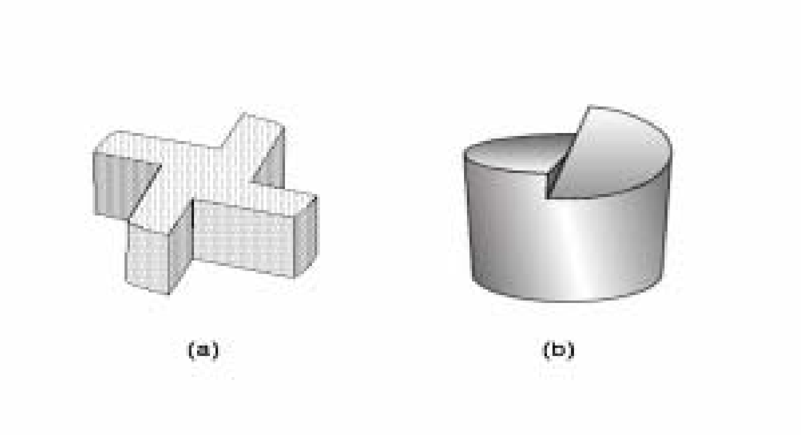


Fig. 26. Two kinds of optical rotors: (a) a rotationally but not bilaterally symmetric rotor which uses optical torque exerted on its side surfaces, and (b) a cylindrical optical rotor which has slopes for rotation on its upper surfaces

Using a laser beam the rotation of artificial micro-objects fabricated by micromachining was demonstrated. Figure 1.26 shows two kinds of optical rotors: (a) a rotationally but not bilaterally symmetric structured rotor to which optical torque is exerted on its side surfaces [1.62] and (b) a cylindrical optical rotor which has slopes for trapping and rotating on its upper surfaces. [1.63] The rotation mechanism has been shown both experimentally and theoretically.

The use of optical rotors is expected to solve the problems of a micro-electro mechanical motor, i.e., short lifetime due to friction and the requirement of electrical wires for the power supply. Applications of directional high-speed optical rotation may include an optical motor and a microgear for micromachines [1.64, 1.65] and a micromixer [1.66] for miniaturized total analysis systems. These optical-rotor-related technologies could have a significant effect on developments in optical MEMS and micromechanical photonic systems. Optical rotation is described in detail in Chap. 4.

1.4 Integrated Systems with Laser Diodes and Micromechanics

In micromechanical photonics applications using laser diodes of group III-V compounds are predominant for monolithic integration of microstructures. They include a GaAs-based integrated tunable laser, [1.16, 1.67] a resonant sensor, [1.17] an optical encoder, [1.68] an optical head, [1.69] and an InP-based free-standing microstructure, [1.15] a portable blood flow sensor, [1.70] which can be used to provide supersmall, cost-effective microdevices.

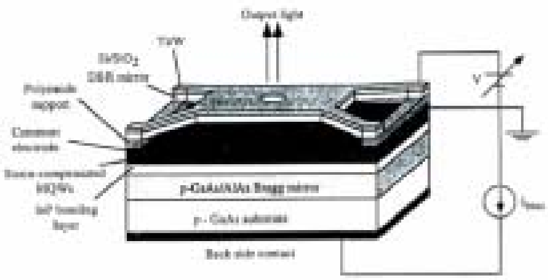


Fig. 1.27. A surface-emitting laser diode with a thin film mirror. A laser driver supplies current for light emission, and the bias applied moves the thin film mirror in the adjustment of the output wavelength [1.16]

1.4.1 Tunable Laser Diode

Tunable laser diodes are desirable for use in wavelength division multiplexing communications, multi-wavelength optical data storage, sensing systems, and a variety of scientific instrumentations. A surface-emitting laser diode or an LED with microstructure, as shown in Fig.1.27, can be used for micromechanically tuned devices. [1.16] By varying the external cavity length, the laser wavelength can be easily changed.

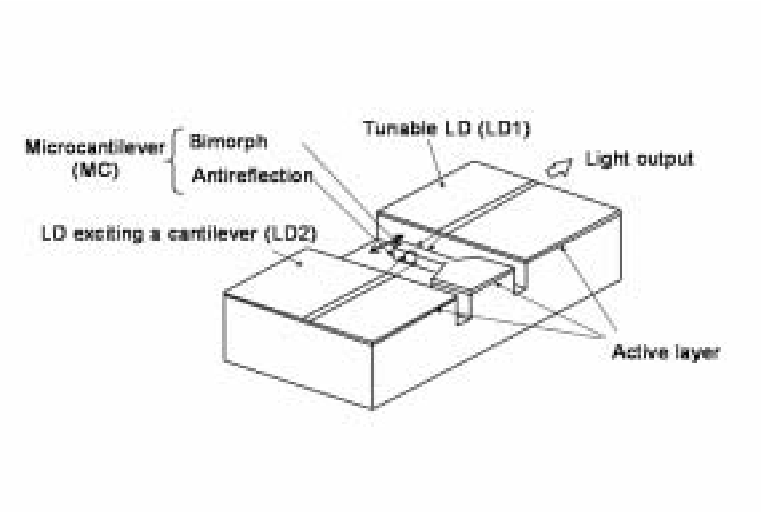


Fig. 1.28. Edge-emitting laser diodes with a microcantilever (MC). The microcantilever is driven photothermally by one laser diode (LD2) to adjust the output wavelength from the other laser diode (LD1)

Edge-emitting laser diodes that have an ultrashort external-cavity length are also applicable as tunable lasers, [1.67] as shown in Fig.1.28. The wavelength shift varies every λ/2. The tuning span was 30 nm around 1300 nm, which was measured using a laser diode (LD) on a slider with an antireflection coating (ARC) [1.71] on the LD facet facing the external mirror. To increase the monolithically integrated cantilever displacement driven by the temperature rise induced upon applying the laser diode, an antireflection-coated metal-dielectric bimorph structure was designed. [1.72]

1.4.2 Resonant Sensor

A resonant sensor is a device that changes its mechanical resonant frequency as a function of a physical or chemical parameter such as stress or massloading. A microcantilever, laser diodes, and a photodiode have been fabricated on the surface of a GaAs substrate, as shown in Fig. 1.29. Possible applications are resonant frequency change detection sensors such as accelerometers, and mechanical filters such as those for synchronizing signal detection, which are described in Sect. 2.4.2. [1.14]

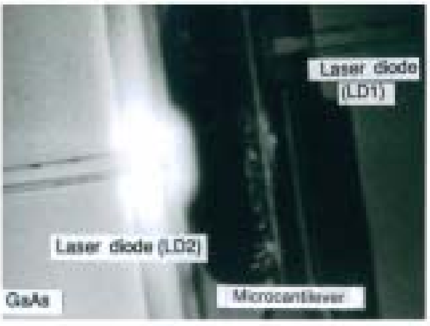


Fig. 1.29. Photograph of central part of a resonant sensor

1.4.3 Optical Encoder

Elimination of bulky optical components, including a beamsplitter, a reflection mirror, a photodiode, and a collimating lens, will lead to adjustment-free, cost-effective small optical devices. A supersmall optical encoder consisting of a photodiode, a U-shaped laser diode and microlenses, as shown in Fig. 1.30 and Fig. 1.31, [1.68] was proposed. It has been evaluated to measure the relative displacement between a scale grating and the encoder itself with a resolution of 0.01 μm.

Fig. 1.30. Schematic drawing of an optical encoder consisting of a photodiode, a U-shaped laser diode and micro-lenses [1.68]

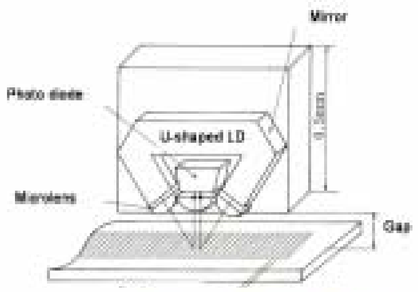
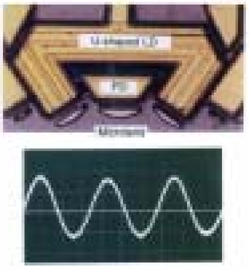


Fig. 1.31. Photograph of the optical encoder



When the encoder moves a distance x relative to the grating, the phase shift of the light refracted at the grating of pitch Λ is +2πx / Λ for one etched mirror and -2πx/ Λ for the other etched mirror. The intensity of interference caused by the refracted lights is expressed as a function of period 4πx / Λ.

1.4.4 Integrated Flying Optical Head

Figure 1.32 shows a flying optical head with an integrated laser diode. [1.69] The flying optical head consists of a monolithically integrated laser diode and a photodiode attached to the slider. Autofocusing is accomplished by means of an air bearing, which maintains a spacing of 2 μm and eliminates the need for a focusing servo system.

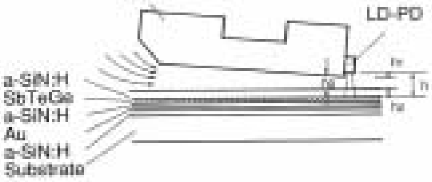
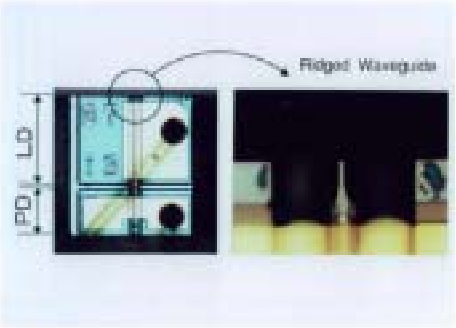


Fig. 1.32. A flying optical head with an integrated laser diode. The optical head consists of a monolithically integrated laser diode and a photodiode attached to the slider

Fig. 1.33. Photograph of a laser diode (LD) integrated with a photodiode (PD). To reduce the beam width parallel to the junction plane, a taper-ridged waveguide is fabricated on the edge of the diode cavity by reactive ion beam etching (RIBE)



The sensing part of the head is a laser diode integrated with a photodiode, as shown in Fig. 1.33. To reduce the light beam width parallel to the junction plane, a taper-ridged waveguide was fabricated on the edge of the diode cavity by reactive ion beam etching (RIBE). The ridged waveguide is 1.3 μm wide and the groove is 3 μm deep, which is deeper than the active layer. The full widths at half-maximum of the near-field pattern perpendicular and parallel to the junction plane are 0.65 and 0.85 μm, respectively, at the facet and less than 1 μm at the recording medium.

A laser diode used in an optical head forms a composite cavity with a recording medium. Light output of the laser diode is either a strong stimulated emission corresponding to the high-reflectivity part of the non-mark or a weak spontaneous emission corresponding to the low-reflectivity part of the mark. That is, the laser is switched according to the light fed back from the recording medium.

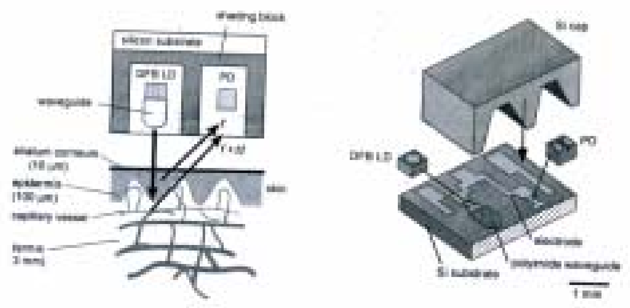


Fig. 1.34. The hybrid integrated structure of the blood flow sensor optical system consists of an InGaAsP-InP distributed feedback laser diode (DFB-LD), a photodiode (PD) and a polyimide waveguide on a silicon substrate [1.70]

1.4.5 Blood Flow Sensor

A very small and lightweight blood flow sensor was constructed using surface mounting techniques, as shown in Fig. 1.34. [1.70] The hybrid integrated structure of the optical system incorporates an edge-emitting InGaAsP-InP distributed feedback laser diode (DFB LD) with a wavelength of 1.3 µm, a photodiode (PD) and a polyimide waveguide on a silicon substrate.

Figure 1.34 (a) shows the velocity measurement principle. The DFB LD in Fig. 1.34 (b) illuminates the human skin and the lights scattered by the flowing blood and by the stationary tissue interfere on the PD. The beat frequency between the two depends on the average velocity of the blood flow. This integrated flow sensor can be positioned directly on a finger and permits real-time monitoring of the blood flow.

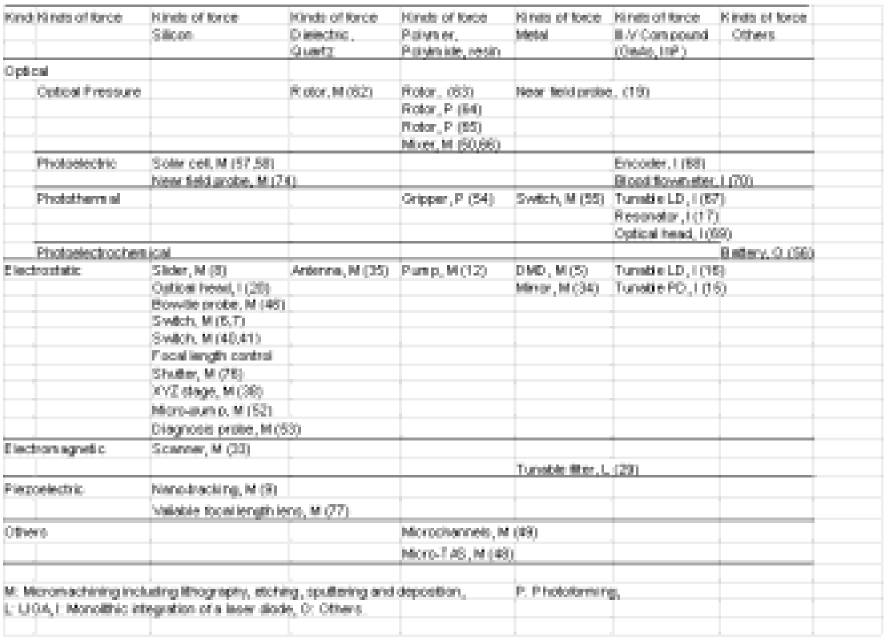
1.5 Future Outlook of Optical MEMS and Micromechanical Photonics

One advantage of the optical method in microdevices is that it is not affected by electromagnetic interference. This is particularly critical for highly integrated devices. Other advantages are its remote control and friction-free characteristics, which are of great value in optical tweezers and optical rotors. An earlier disadvantage was that the optical technique required lenses and fiber systems to guide the light to a photodiode or a moving mechanism, but recent micromachining technology has made it easy to eliminate these lenses and fiber systems, leading to the easy integration of optics, mechanics and electronics. In this session we present current and potential applications of the optical MEMS and micromechanical photonics.

Various kinds of optical MEMS / micromechanical photonics devices have been fabricated on silicon substrates, polymers, and III-V compounds. They include a micro-grating / mirror with a rotating stage for optical interconnects, a micromirror scanner for displays and printers, a micromirror switch / tunable laser diode for wavelength division multiplexing systems, information and communication apparatus, and sophisticated positioning systems at submicrometer and nanometer levels. Other applications may be in medical instruments such as micropumps for disposable drug delivery systems, [1.52] medical microsystems for minimally invasive diagnosis and treatment [1.53] and μ-TAS. [1.48]

Researchers have been using various types of controlling / driving methods: for example, optical, electrostatic, electromagnetic, and piezoelectric methods, as shown in Table 1.2. Optical force is classified into optical pressure, photoelectric, photothermal, and photo-electrochemical effects. Table 1.2 shows already proposed or commercialized optical MEMS / micromechanical photonics devices and systems classified according to the driving method and materials used. Refer to the fabrication method and reference number given after each device / system. In the table, we can see not only conventional sensors and actuators but also the recently developed tunable LDs, optical switches, scanners, mirrors, optical heads, near-field probes, control devices with nanometer precision, and medical microsystems for diagnosis and treatment.

Table 1.2. Optical micro-electromechanical systems (optical MEMS) and micromechanical photonics devices. Waveguides and optoelectronics devices without mechanical structures are not shown.



Kind	Kinds of force	Kinds of force Silicon	Kinds of force Dielectric, Quartz	Kinds of force Polymer, Polyimide, resin	Kinds of force Metal	Kinds of force III-V Compound (GaAs, InP)	Kinds of force Others
Optical							
	Optical Pressure		Rotor, M (62)	Rotor, (63)	Near field probe, (19)		
				Rotor, P (64)			
				Rotor, P (65)			
				Mixer, M (50,66)			
	Photoelectric	Solar cell, M (57,58)				Encoder, I (68)	
		Near field probe, M (74)				Blood flowmeter, I (70)	
	Photothermal			Gripper, P (54)	Switch, M (55)	Tunable LD, I (67)	
						Resonator, I (17)	
						Optical head, I (69)	
	Photoelectrochemical						Battery, O (56)
Electrostatic		Slider, M (8)	Antenna, M (35)	Pump, M (12)	DMD, M (5)	Tunable LD, I (18)	
		Optical head, I (20)			Mirror, M (34)	Tunable PD, I (16)	
		Bowtie probe, M (46)					
		Switch, M (6,7)					
		Switch, M (40,41)					
		Focal length control					
		Shutter, M (78)					
		XYZ stage, M (38)					
		Micro-pump, M (52)					
		Diagnosis probe, M (53)					
Electromagnetic		Scanner, M (33)					
					Tunable filter, L (29)		
Piezoelectric		Nano-tracking, M (9)					
		Variable focal length lens, M (77)					
Others				Microchannels, M (49)			
				Micro-TAS, M (48)			

M: Micromachining including lithography, etching, sputtering and deposition, P: Photoforming,
L: LIGA, I: Monolithic integration of a laser diode, O: Others

The reduction of friction force and the adoption of contact sticking-free mechanisms are important in microscale operation. Therefore, microstructures without contact, for example, a micromirror suspended by two torsion hinges, [1.5] a cantilever, [1.17] a deformable membrane, [1.16] and a flying slider [1.69] are preferably used to prevent friction and sticking.

Figure 1.35 shows the direction of development in these technical fields. The horizontal axis shows miniaturization (size) and the vertical axis shows the number of functions that characterize the optical MEMS / micromechanical photonics devices. To evaluate the number of functions, we firstly considered how optics, mechanics, and electronics are combined: 1: simple assembly, 2: hybrid, 3: monolithic. Secondly, in how many directions can the device / system move: 1: 1D, 2: 2D, 3: 3D. Finally, what kind of functions does the device / system have: measurement, feedback control, recognition, and remote power supply. We gave a point for each function. The maximum number of points becomes 3+3+5 = 11. Many kinds of proposed optical MEMS and micromechanical photonics devices are seen, and the fabrication of molecular devices is the final goal in the figure.

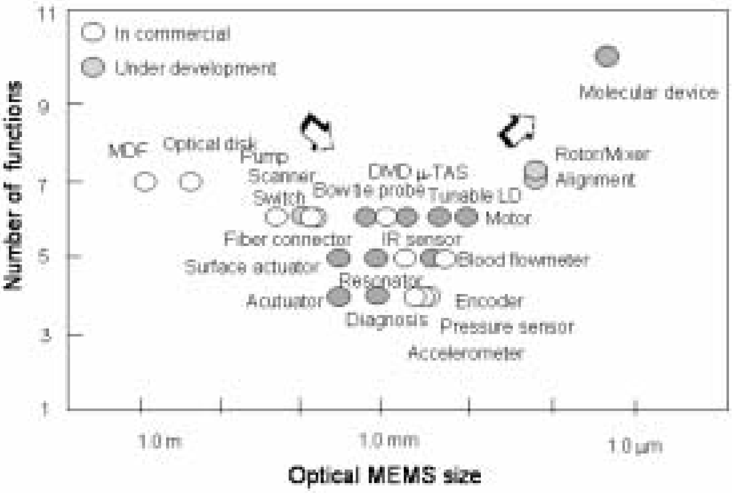


Fig. 1.35. Proposed and commercialized devices / systems fabricated using optical MEMS and micromechanical photonics. The horizontal axis is size and the vertical axis is the number of functions

It is apparent from the figure that there are two development directions owing to miniaturization. Firstly, as the device / system size decreases, the number of function decreases, for example, from a MDF (exchanger: main distributing frame) to an optical disk system to optical interconnection to an actuator and to a sensor. It is a natural direction and has led to the commercialization of many products (white circles), as seen in the figure. Secondly, as the device / system size decreases the number of functions increases, for example, from a sensor to an optical resonator to an electrostatic motor to an optical motor and to a molecular device. It is an ideal and a research-oriented direction, in which many devices are under development (black circles), as seen in the same figure.

Much work is needed to reach the final goal. Good mechanical properties, high speed, and strong power are foreseen for microdevices. Microassembly, packing, and wiring techniques must be improved. Tribology on the microscale must be studied to realize smooth motion.

In the following chapters, we highlight key technologies in the development of future optical MEMS / micromechanical photonics devices and describe not only theoretical and experimental results but also their fields of application. The next chapter deals with laser diodes closely aligned with a microstructure such as a diaphragm, a microcantilever and a slider. As examples, we examine extremely short external-cavity laser diodes such as a tunable laser diode, a resonant sensor and an integrated optical head. Chap. 3 addresses optical tweezers. The new technology is employed to manipulate various types of objects in a variety of research and industrial fields. Chap. 4 deals with the design and fabrication of an optical rotor and the evaluation of the mixing performance of microliquids for a future fluidic applications such as micro-total analysis systems (μ-TAS). In Chap. 5, the fundamentals and applications of the near field induced on an object surface are described for the future development of micromechanical photonics. This technology enables us to carry out observing, reading / writing and fabrication beyond the wavelength resolution by accessing and controlling the near field.

Problems

Q1.1: Compare the methods of fabricating optical MEMS / micromechanical photonics devices.

A1.1: There are several aspects in comparing the fabrication methods for microstructures: productivity, thickness, shape, and material used. Photolithography and LIGA will be used for mass production, but photoforming will be used for small-scale production and also for fabricating a complicated 3D structure. An EBL, which has high resolution and does not require masks, will be used for fabricating microstructures less than 1 μm thick. Photolithography will be used for fabricating microstructures less than several 10 μm, and LIGA less than several 100 μm. The latter two require the use of masks for the etching. Group III-V compound materials are used to integrate a laser diode and a photodiode.

Q1.2: Explain the working mechanism of a sacrificial layer in the fabrication of microdevices.

A1.2: A sacrificial layer is the layer that is etched away, whereby the microstructure is undercut, leaving it freely suspended (See Sect. 1.2.1).

Q1.3: Explain the problems to be solved for a miniaturized device.

A1.3: Friction-free and contact sticking-free structures are needed for an optical MEMS because of the increase of the surface effect. Refer to the scaling law (See Sect. 1.3.1).

Q1.4: Estimate the reduction of torque required to tilt a micromirror with a 50% reduction of the dimensions (the mirror is a x b in area and t thick).

A1.4: The moment of inertia of the mirror is $I_1 = \rho ab^3t / 12$. I_2 with a 50% reduction in the dimensions is $I_2 = \rho\ (0.5a)\ (0.5b)^3\ (0.5t) / 12 = (0.5)^5\ I_1 = 3.1\%$.

Q1.5: Why does response time become fast in a microsystem?

A1.5: Response time is proportional to [mass / drag force], i.e., $[L^3/L] = [L^2]$, which leads to faster response as L decreases.

Q1.6: Compare the methods of driving micromechanical photonics devices.

A1.6: See Sect. 1.5.

Q1.7: Predict the future technical trend of micromechanical photonics.

A1.7: There will be two development directions when device / system size decreases: the number of functions will decrease (natural direction), and the number of functions will increase (research-oriented direction). See Sect. 1.5.

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