Invited Paper

Micromachined Free-Space Integrated Optics

M. C. Wu, L. Y. Lin, and S. S. Lee

UCLA, Electrical Engineering Department
405 Hilgard Avenue
Los Angeles, CA 90024-1594

ABSTRACT

We report a novel surface-micromachined *micro-optical bench* (MOB) technology which enables us to monolithically integrate "flipped-up" *free-space optical elements* with *micro-positioners* and *micro-actuators*. This technology allows complete optical systems be implemented on a single Si chip using IC-like microfabrication processes. We have, for the first time, successfully fabricated micro-Fresnel lenses, mirrors, beam-splitters, gratings, and precision optical mounts, as well as rotational stages and other micro-positioners. Self-aligned hybrid integration with edge-emitting lasers and vertical cavity surface-emitting lasers (VCSEL) are also demonstrated for the first time. The MOB technology could significantly reduce the size, weight, and cost of most optical systems, and has a significant impact on optical switching, optical data storage, optoelectronic packaging.

Keywords: integrated optics, micro-opto-mechanical systems, micro-optical bench, free-space integrated optics

1. INTRODUCTION

Integrated optics has been an active research area since it was proposed in 1969 [1] To date, most of the research efforts focus on guided-wave approach [2,3]. On the other hand, free-space optics offers many unique advantages that cannot be achieved in guided-wave devices. For example, free-space optics allow us to implement three-dimensional optical interconnect that could significantly improve the communication bottlenecks in VLSI systems [4]. Much higher spatial bandwidth (diffraction limit) can be achieved. It is also

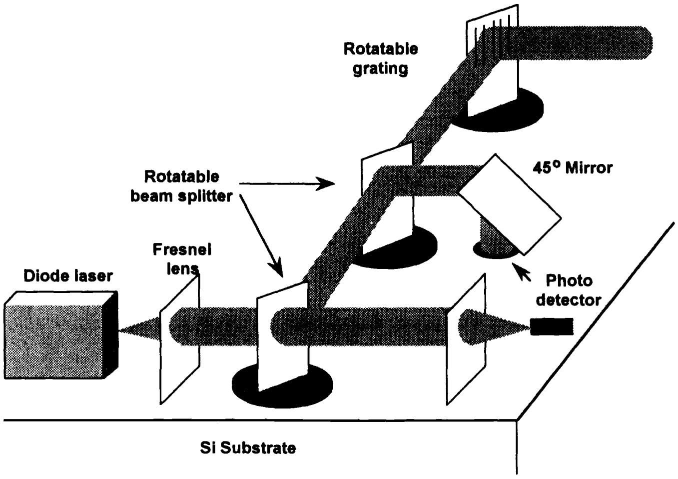


Figure 1. The schematic diagram illustrating the micromachined free-space integrated optics on a single Si chip.

0-8194-1615-0/94/$6.00

possible to perform sophisticated optical information processing such as Fourier transform in free space using lenses [5]. However, most of the present free-space optical systems consist of bulk optical elements or multiple-plane micro-lens arrays that cannot be integrated on a single chip [6,7].

Micromachining of silicon substrate has been applied to miniature optical bench and integrated optics since 1970's [8]. Silicon V-grooves in (100) wafer can now be found in many products for aligning optical fibers. Torsional mirrors [9] have evolved to digital micromirror devices [10] for projection displays. Micromachining allows inexpensive and reproducible batch processing of optical components. However, to date, most of the micro-mechanical optical components and systems are designed for surface-normal optical access because the microfabricated optical elements are confined to the surface of the substrate. Examples are the digital micromirrors [10] and microfabricated optical choppers [11]. Since external optics is needed for optical systems using such components, monolithic integration of the complete optical system on a single chip is not possible.

Monolithic integration of the whole optical system, or *micro-optical system*, can drastically reduce its size, weight and cost. Furthermore, the expensive packaging process of individual optical components can be totally eliminated. One key component for monolithic micro-optical system is out-of-plane optical elements, i.e., optical elements not confined to the surface of the substrate. In particular, vertical optical elements standing perpendicular to the substrate allow multiple elements be cascaded along the optical axis on the same substrate. The LIGA process can produce tall structures with height of several hundred micrometers [12] and can be applied to the fabrication of such optical elements, however, X-ray lithography is required. Recently, a micro-hinge technology is proposed which allows three-dimensional structures be assembled from thin plates on the surface of the substrate [13]. It is based on surface-micromachining and is compatible with most micro-actuator fabrication processes.

Three-dimensional micro-optics fabricated by surface-micromachining opens a new area for integrated optics in free-space. Using this new technology, integrable micro-optical elements can be made to stand perpendicular to the substrate. Thus multiple free-space optical elements along the optical path can be made on the same substrate. This allows sophisticated optical system with a large number of optical elements to be integrated monolithically on a single Si chip. The substrate serves as a "*micro-optical bench*", and lenses, mirrors and other components are pre-aligned by photolithography and then constructed by microfabrication, as illustrated in Fig. 1. A micro-Fresnel lens standing perpendicular to the substrate has been successfully

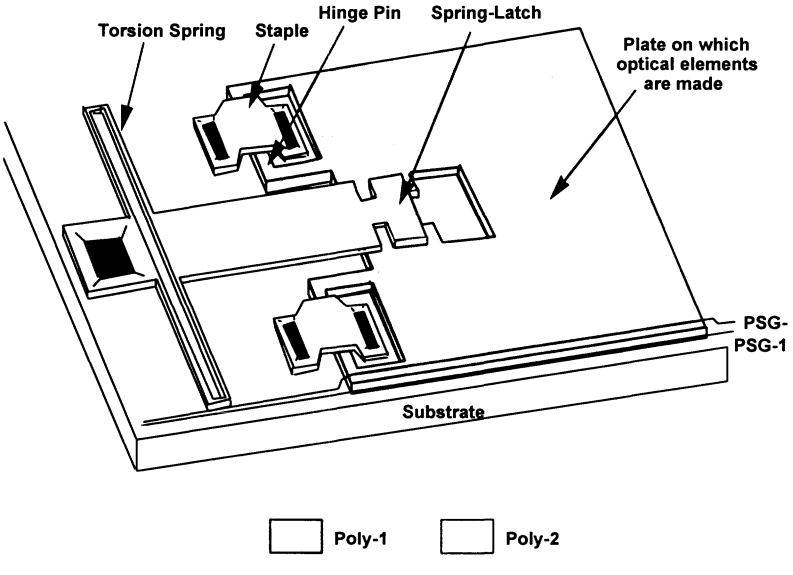


Figure 2. The schematic structure of the surface-micromachined micro-optical element before assembly.

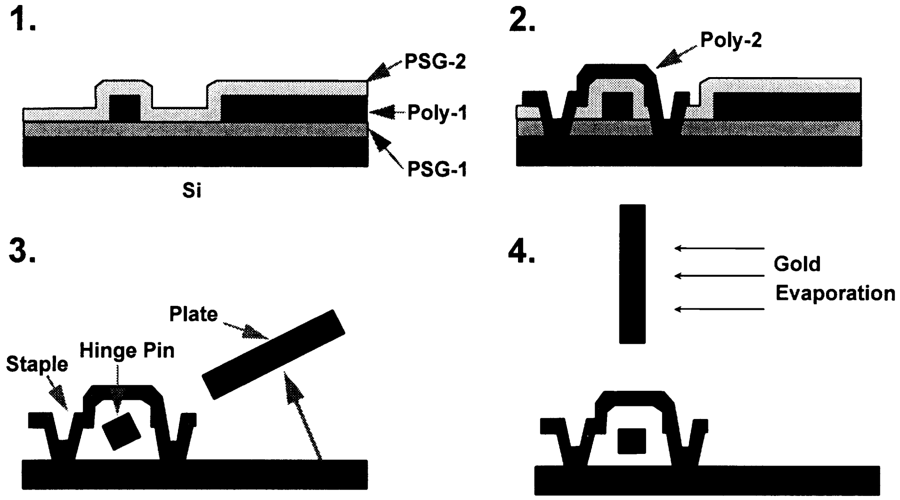


Figure 3. The microfabrication processes for the vertical free-space micro-optical components.

fabricated [14]. The lens has a diameter of 650 μm, an optical axis of 1 mm above the Si substrate, and a focal length of 1 mm. The lens plate has a height of 1.4 mm. Excellent optical collimating ability has been achieved. The micro-Fresnel lens is fixed by micro-hinges and supported by micro-spring latches. Other vertical optical components including micro-mirrors, gratings, beam splitters, and lens mount have also been demonstrated [15]. This microfabrication is compatible with micro-actuators, and integrating of the vertical mirror with a rotational stage is demonstrated [15]. This technology also has a large impact on the packaging of active optoelectronic devices [16-18]. The three-dimensional flipped-up plates are used as self-aligned structures for hybrid integration with vertical cavity surface-emitting laser (VCSEL) arrays [17] and edge-emitting lasers [18], and has applications in free-space optical interconnect [19]. A three-dimensional corner cube reflector was also demonstrated [20].

2. FABRICATION

The three-dimensional micro-optical system is constructed on Si substrate by surface micromachining technique. The schematic structure is shown in Fig. 2. Optical elements such as lenses and mirrors are made on polysilicon plates. These plates are free to rotate around the bottom micro-hinges. The angle between the optics plate and the substrate is fixed by micro-spring latches [13]. The fabrication process is described in the following: First, a 2-μm-thick phosphosilicate glass (PSG-1) is deposited on the silicon substrate as the sacrificial layer. Then the first polysilicon layer (poly-1) of 2 μm thickness is grown on PSG-1. Various optical elements such as Fresnel lenses, mirrors, beam splitters, and gratings are made on the poly-1 layer using photolithography and dry etching. The hinge pins holding the optical elements are also defined on this layer. Following the deposition and patterning of poly-1, another layer of sacrificial material (PSG-2) of 0.5 mm thickness is deposited (Fig. 3-1). The supporting structures such as staples and spring latches are defined on the second polysilicon (poly-2) layer. The base of the staples and torsion springs are fixed on the Si substrate by opening contact holes through both PSG-2 and PSG-1 before the deposition of poly-2 layer (Fig. 3-2). The poly-2 structures can also be fixed on poly-1 by etching contact holes through PSG-2 only, as required in the rotatable mirror to be described later. The optical elements are released from substrate by selectively removing the PSG materials. After the release etching, the poly-plates with micro-optics patterns are free to rotate around the hinge pins (Fig. 3-3). When the plate is lifted up, the top portion of the spring latch slides into the slot on the plate, and snaps into the narrower part of the slot, thus preventing further motion of the plates. The torsion-spring

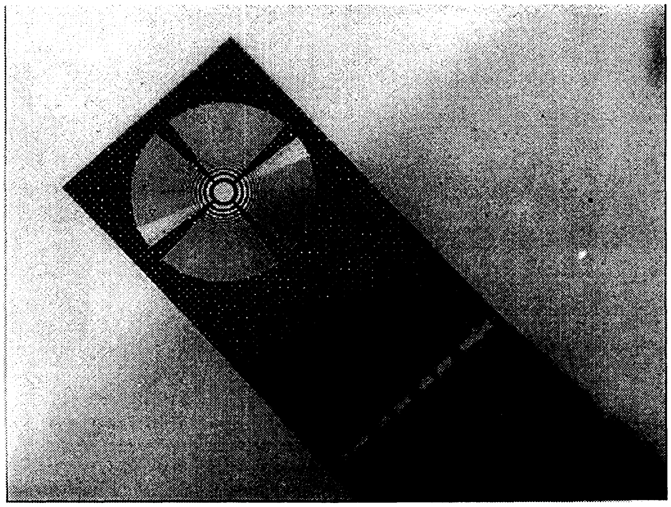


Figure 4. The photograph of the assembled vertical micro-Fresnel lens. The lens has a diameter of 650 μm, an optical axis of 1 mm above the Si surface and a focal length of 1 mm.

connecting the spring-latch to the substrate creates the spring force, which tends to force the spring-latch back to the substrate, therefore locks the plate in its place. The length of the spring latch defines the angle between the plate and the substrate, which is approximately 90°. After the three-dimensional micro-optics is assembled, a layer of gold is coated on the lifted poly surfaces (Fig. 3-4). In Fresnel zone plates or micro-mirrors, a thick layer of gold is coated to completely block the light passing through the dark zones or to make a perfectly reflecting mirror. On the other hand, thinner gold is used for partially transmitting mirrors or beam splitters.

3. MICRO-FRESNEL LENS

Figure 4 shows the photograph of the three-dimensional micro-Fresnel lens after assembly [14]. The shadow below the actual lens is the mirror image of the lens reflected from the Si substrate. The Fresnel zone pattern is defined on the first polysilicon layer by photolithography and dry etching. This lens has a diameter of 650 μm, an optical axis of 1 mm above the Si surface, and a primary focal length of 1 mm. The height of the lens plate is 1.4 mm. Because of the height of the lens plate, the angles between the lens plates and the substrate has some variations even though they are coarsely fixed by the spring latches. Such variations are not tolerable in large optical systems. We have designed a new "lens-mount" to precisely define the angles of the three-dimensional micro-optical elements. The lens-mount consists of two folded polysilicon plates similar to the lenses but the folding direction is orthogonal to that of the lens plate. The scanning electron micrograph (SEM) of an assembled micro-Fresnel lens with lens mount is shown in Fig. 5. The diameter of the this lens is 280 μm, and the optical axis is 254 μm above the silicon surface. The lens mount has a V-shaped opening at the top to guide the lens plate into a 2-μm-wide groove in the center. The latches of the lens mount are folded from two sides of the lens plate, and can be made as tall as the lens itself. Therefore, the angle defined by the lens mount are much more precise. Indeed, this has been observed experimentally. Under optical microscope, the mirror image of the lens reflected from the Si surface forms a straight extension of the lens itself. The lens mount also greatly improve the mechanical strength and stability of the micro-optical elements.

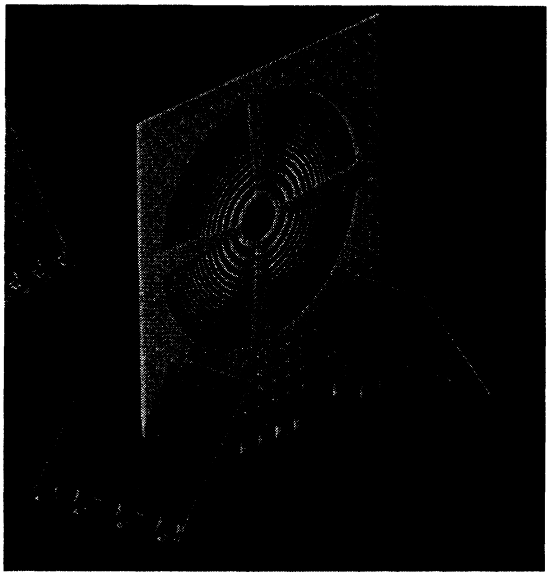


Figure 5. The schematic diagram and the SEM micrograph of a micro-Fresnel lens with precision lens mount.

The optical performance of the three-dimensional micro-Fresnel lens has been tested by collimating a divergent beam emitted from a single mode fiber at $\lambda = 1.3$ μm. The experimental setup is shown in Fig. 6. The micro-Fresnel lens was originally designed for semiconductor lasers with numerical apertures (NA) of approximately 0.2 to 0.4 and, therefore, does not match the NA of the optical fiber used in the measurement. The measurement was done using optical fiber as emitting source because of the accessibility of the micro-lens. Please note that the lens is located in the center of a 1 cm × 1 cm Si chip, on which many other micro-optical components are fabricated at the same time. It is accessible by single mode optical fibers, which typically have NA of around 0.1. Multimode fibers with higher NA does not give satisfactory results due to multiple spatial modes. The measurement only meant to demonstrate the function of the micro-Fresnel lens and does not mean to limit optical sources to fibers. Figure 7 compares the divergence of the optical beams with and without the collimating lens. The intensity FWHM divergence angle is reduce from 5.0° to 0.33° (the corresponding 1/e angles of Gaussian beams are 8.3° and 0.56°). The collimated beam profile fits very well to the Gaussian shape (95% fit), as shown in Fig. 8. A measurement has also been made with a higher NA source. A semiconductor laser with FWHM far-field angles of 18° × 40° is mounted in front of the micro-lens on the same Si chip. The collimated beam has an elliptical shape, and the intensity FWHM measured at 5 cm behind the lens are 330 mm and 788 mm, respectively. The diffraction efficiency of the micro-Fresnel lens was measured to be 8.6 % using the method described by Rastani et al. [21]. This is in agreement with theoretical value for binary-amplitude Fresnel zone plates. Higher theoretical diffraction efficiency of 41% can be achieved by binary-phase Fresnel lens, which can be realized by an additional dry etching step.

4. ROTATIONAL STAGES

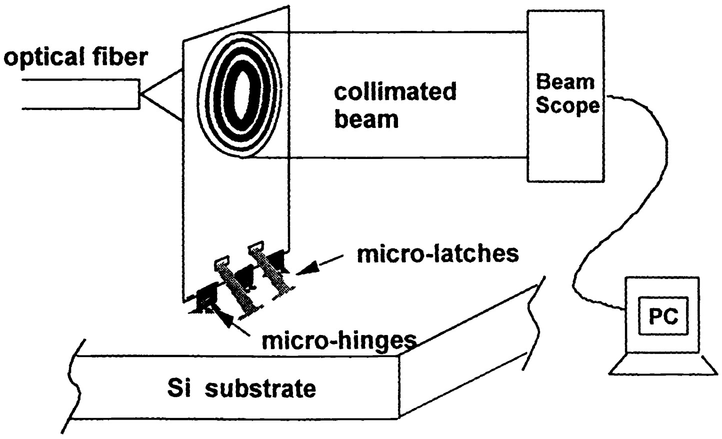


Figure 6. Schematic diagram of the experimental setup for characterizing the micro-Fresnel lens.

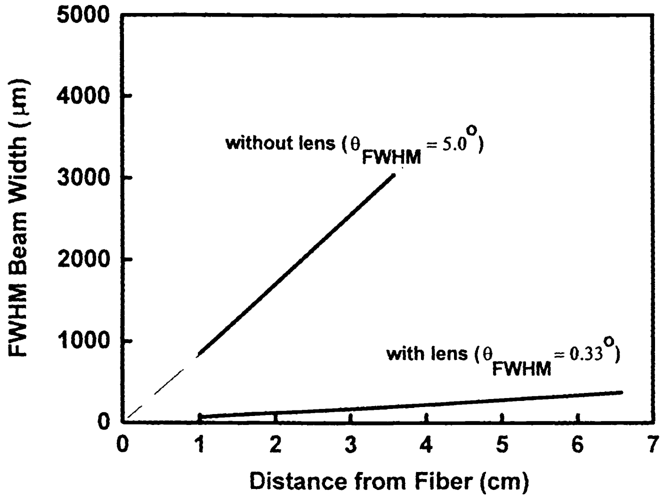
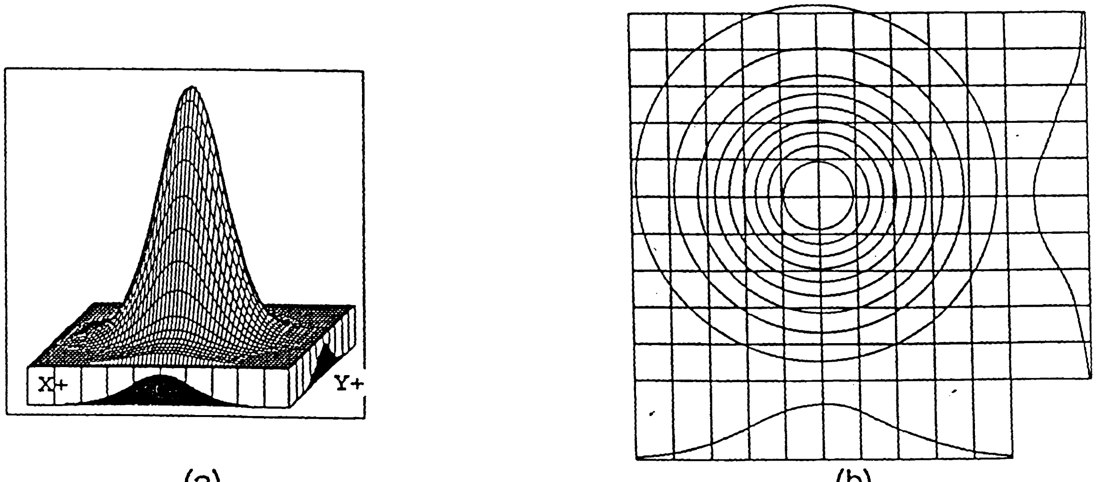


Figure 7. The optical beam divergence of the light emitted from a single mode fiber with and without passing the micro-Fresnel lens.



(a) (b)

Figure 8. The measured beam profile of the collimated light.

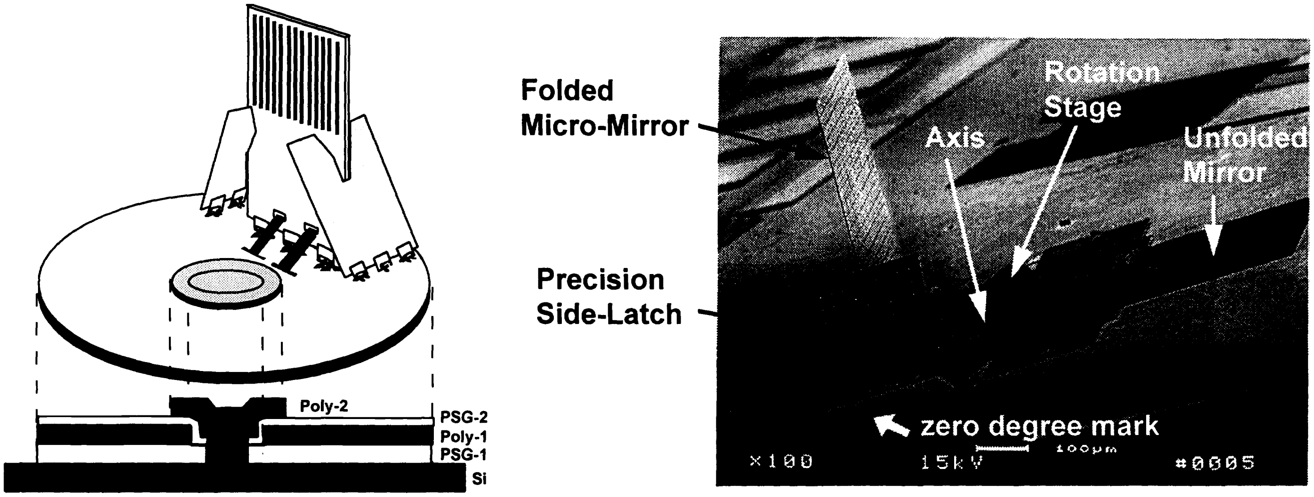


Figure 9. The vertical micro-mirror integrated with a rotational stage. The rotational stage has been rotated by 20°.

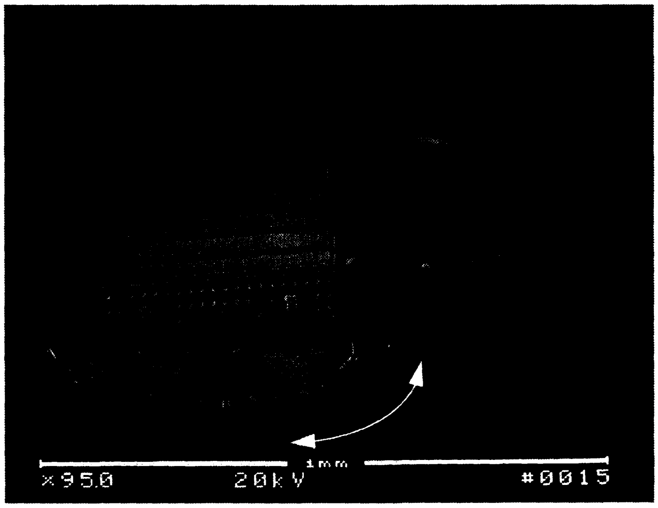


Figure 10. The diffraction grating integrated with a rotational stage.

One unique advantage of using surface micro-machining to implement micro-optical bench is that micro-positioners and micro-actuators can be monolithically integrated using the same fabrication processes. This allow the alignment of the optical systems be fine adjusted, in addition to the coarse alignment done at the design stage using CAD layout tools. Using similar structures as the micromotors [22], rotational stages and linear micro-positioners can be realized. We have successfully integrated the flipped-up micro-mirrors with a rotational stage using this process [15]. Figure 9 (a) shows the schematic diagram of the rotatable mirror. The rotatable plate is fabricated on the first polysilicon layer, and the axis and hub is defined on the second polysilicon layer. The optical elements defined on the second polysilicon layer can be placed on the rotatable plate. The fabrication process is similar to that in Figure 2, except the poly-2 the spring-latches and staples are now connected to poly-1 (the rotatable plate). After the PSG materials are selectively removed, and the poly-1 plate is free to rotate on the substrate plane. The micro-hinges are defined on the rotating poly-1 plate. The bottom of the poly-2 optics plate

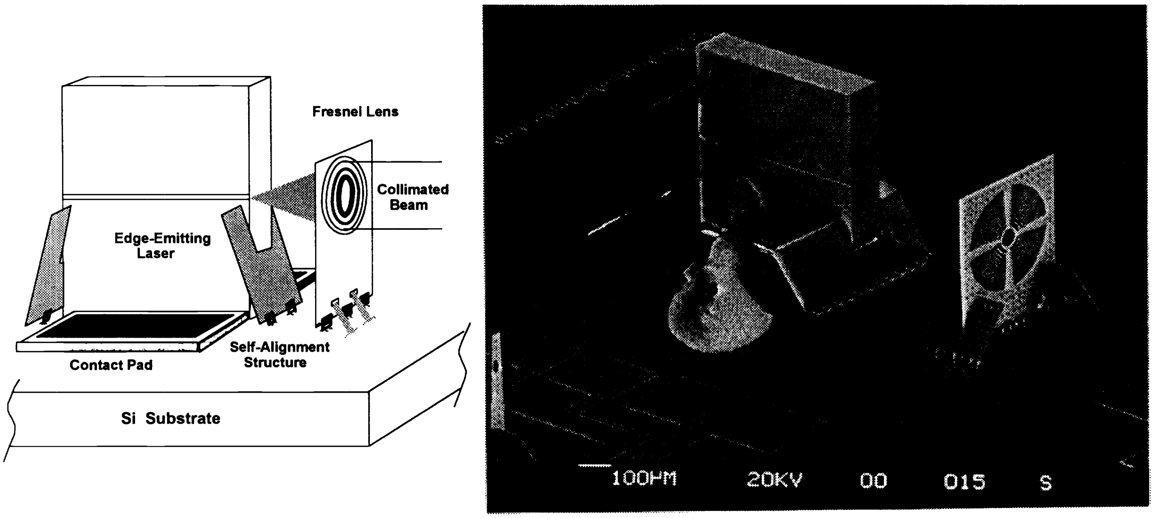


Figure 11. The schematic and the SEM micrograph of the self-aligned hybrid integration of an edge-emitting laser with a micro-Fresnel lens.

is connected to the micro-hinges on poly-1. Figure 9 (b) shows the SEM photograph of a three-dimensional micro-mirror fabricated integrally on a rotational stage. The dimension of the mirror is 400 × 480 μm^2. Thirty-six ticks are made on the substrate to indicate the rotation angle of the plate (due to the contrast of the photograph, only part of the ticks are shown). The angle between adjacent ticks is 10°. The indicator on the lower part of the picture, originally pointing at the 0° tick (indicated by the white arrow), has been rotated counter-clockwise by 20° after the mirror is assembled, as shown on the picture. A diffraction grating integrated with the rotational stage is also successfully demonstrated using the same technology, as shown in Fig. 10.

5. SELF-ALIGNED HYBRID INTEGRATION WITH ACTIVE OPTICAL DEVICES

Free-space micro-optical bench (MOB) enables a large optical system to be monolithically integrated on a small Si chip. Active optical components (semiconductor lasers, light-emitting diodes (LED) and photodetectors) are needed in most optical systems. It is therefore desirable to integrate these active devices on MOB. Hybrid integration is necessary for active devices that cannot be made by Si micromachining (e.g., lasers). Unlike the conventional silicon optical bench technology where waveguides are used to connect various optical devices [23], the MOB integrated active devices with vertical, three-dimensional micro-optical elements in free-space. Stationary and movable micro-optical components are fabricated on Si substrate using micro-machining technique. In this section, we describe a novel, three-dimensional self-alignment structure (400-µm-tall) for integrating active optical components such as semiconductor lasers or isolators on MOB.

In order to integrate the MOB with active optical devices such as semiconductor lasers, we have designed a set of novel self-alignment structures using the same two-layer polysilicon technology. Figure 11 (a) shows the schematic diagram of the self-aligned hybrid integration of an edge-emitting semiconductor laser with a micro-Fresnel lens [18]. The edge-emitting laser is mounted on its side for accurate positioning of the active emitting spot. There are other possible schemes for mounting semiconductor lasers: upright mounting and flip-chip mounting. Since the thickness of the lapped laser substrate usually has a tolerance of 5 µm, upright mounting is not suitable for MOB without employing additional adjustable optics. Flip-chip mounting has alignment an accuracy of around 1 µm, however, the emitting spot is very close to the Si surface and is much lower than the optical axis of the free-space optical system. Since the laser chip size can be precisely defined by scribing, side mounting can place the emitting spot accurately on the optical axis (in current design, it is placed at 254 µm

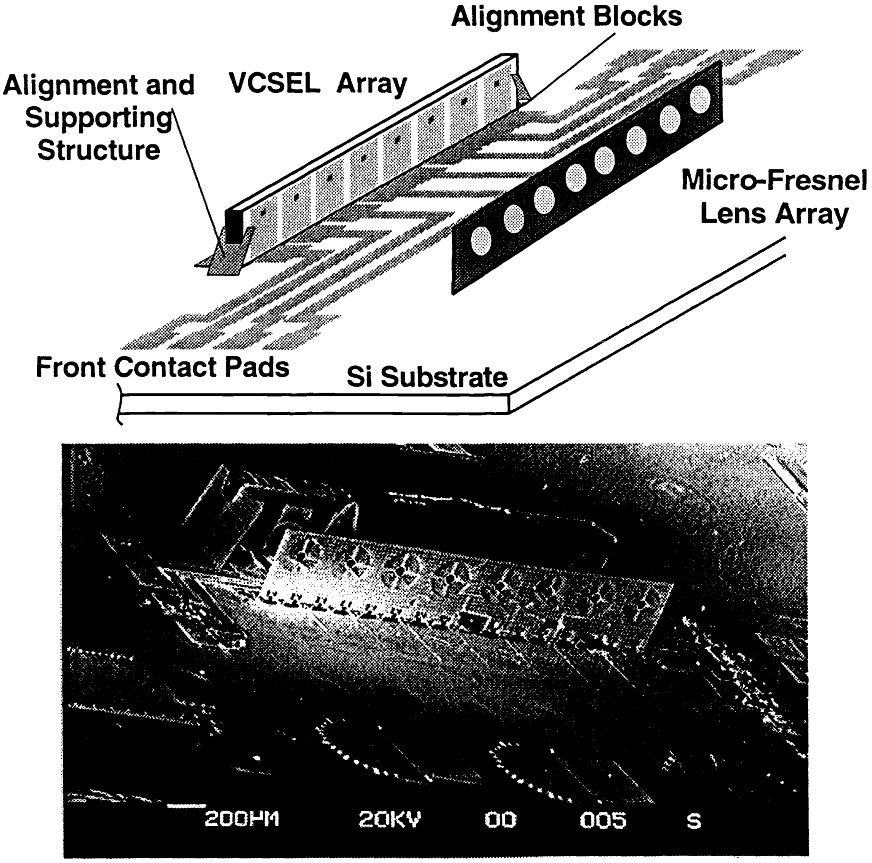


Figure 12. The schematic diagram and the SEM micrograph of the self-aligned hybrid integration of the 8×1 vertical cavity surface-emitting laser array and the 8×1 array of micro-Fresnel lens.

above the Si substrate). There are two alignment plates at the front and the back sides of the laser, respectively. These alignment plates are fabricated at the same time as the micro-lenses. The asymmetric wedge-shaped opening on the self-alignment plates gradually guides the active side (junction side) of the laser towards the flat edge of the wedges. This unique design allows us to accommodate lasers with large variation in thickness (from 100 µm to 140 µm thick). The height of the self-alignment structure permits more precise alignment. After assembly, the laser is electrically contacted by silver epoxy. It is conceivable that the electrical contact be made with indium mount or another flipped-up plate covered with indium. Figure 11 (b) is the SEM micrograph of a laser diode integrated with a micro-Fresnel lens.

For optical interconnect and many other applications, vertical cavity surface-emitting lasers (VCSEL) are desired for their unique characteristics: low threshold current, circular far-field pattern, narrow beam divergence and two-dimensional arrays. The VCSEL is also particular suitable for integrating with the micro-lens using *passive alignment* because it has small numerical aperture and, therefore, higher misalignment tolerance. In addition, two dimensional arrays can be formed in both VCSELs and micromachined lenses. Therefore, the combination of vertical three-dimensional micro-Fresnel lens arrays with passively aligned VCSEL arrays are ideal for free-space optical interconnect and laser array packaging. A self-aligned mounting scheme is developed for integrating VCSELs with the MOB [17]. We have demonstrated for the first time the integration of 8 × 1 arrays of VCSELs and micro-Fresnel lenses using passively alignment.

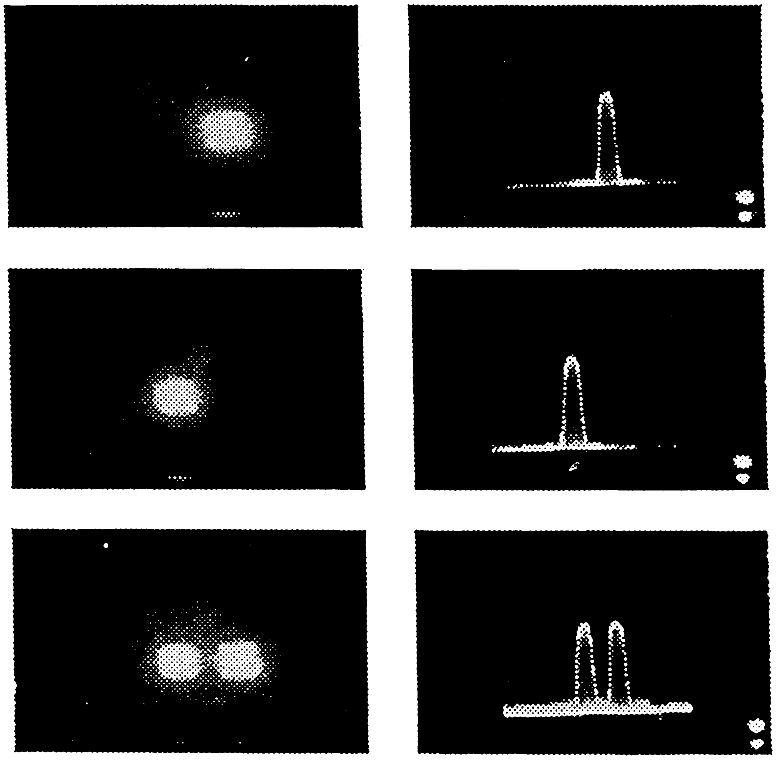


Figure 13. The CCD images of the ON-OFF characteristics of two individual VCSEL elements of the array in Fig. 12.

The schematic diagram of the hybrid integration and SEM picture of a vertical three-dimensional micro-Fresnel lens array and a VCSEL array are shown in Fig. 12 (a) and (b), respectively [17]. The VCSELs consist of AlGaAs/GaAs $\lambda/4$ DBR mirror pairs and InGaAs quantum wells active layer, designed for 0.98 μm wavelength. The dimensions of the VCSEL array are 2 mm wide, 350 μm high and 125 μm thick. The optical axis is designed to match that of the lens array, and the spacing between individual VCSEL is 250 μm. During the fabrication of lens arrays, the electric contacts and alignment mounting blocks for the VCSEL array are monolithically defined on the Si substrate. Therefore, by proper design of the VCSEL dimensions, VCSEL can be mounted precisely in the designed position. The two alignment plates push the VCSEL array forward so that the front surface of the VCSEL array is aligned with focal plane of the lens array. Individual switching of the VCSELs has also been demonstrated [19], as shown in Fig. 13.

6.CONCLUSION

In summary, a new surface-micromachined micro-optical bench (MOB) for free-space integrated optics is proposed and successfully demonstrated. Various three-dimensional (out-of-plane) optical elements and micro-positioners have been fabricated: micro-Fresnel lenses with various sizes and focal lengths, micro-mirrors, diffraction gratings, beam splitters, lens mounts, linear and rotational stages. Integration of optical elements and micro-positioners (e.g., gratings on a rotational stage) has also been demonstrated. Self-aligned hybrid integration of active optical devices with MOB is realized using a novel three-dimensional alignment plate. This new approach can drastically reduce the size, weight and cost of most optical systems, and have immediate applications in free-space optical interconnects, optical switches, optical storage systems, and optoelectronic packaging.

7. ACKNOWLEDGMENT

The authors wish to thank Professor K. S. J. Pister for valuable discussions. This research is supported in part by the David and Lucile Packard Foundation Fellowship for MCW, and ARPA through NCIPT.

8. REFERENCE

1. S. E. Miller, "Integrated Optics: An Introduction," Bell Syst. Tech. J., Vol. 48, No. 7, pp. 2059-2068, 1969.
2. See for example, H. Nishihara, M. Haruna, and T. Suhara, *Optical Integrated Circuits*, McGraw-Hill, 1985.
3. See for example, T. Tamir, *Guided-wave Optoelectronics*, Springer-Verlag, 1990.
4. J. W. Goodman, F. J. Leonberger, S.-C. Kung, and R. A. Athale, "Optical interconnection of VLSI systems," Proc. of IEEE, , Vol. 72, No. 7, pp. 850-866, 1984.
5. J. W. Goodman, *Introduction to Fourier Optics*, McGraw-Hill, 1968.
6. F. B. McCormick and M. E. Prise, "Optical Circuitry for free-space interconnections," Applied Optics, Vol. 29, No. 14, pp. 2013-2018, 1990.
7. S. Kawai, "Free-space multistage optical interconnection networks using micro lens arrays," J. of Lightwave Tech., Vol. 9, No. 12, pp. 1774-1779, 1991.
8. For a review, see K. E. Petersen, "Silicon as a Mechanical Material," Proc. IEEE, Vol. 70, No. 5, pp. 420-457, 1982.
9. K. E. Petersen, "Silicon torsional scanning mirror," IBM J. Res. Develop., Vol. 24, p. 631, 1980.
10. L. J. Hornbeck, "Deformable-mirror spatial light modulators," Proc. SPIE, Vol. 1150, pp. 86-102, 1990.
11. M. T. Ching, R. A. Brennen, and R. M. White, "Microfabricated Optical Chopper," Proc. SPIE, Vol. 1992, pp. 40-46, 1993.
12. W. Ehrfeld, F. Gotz, D. Munchmeyer, W. Schelb, D. Schmidt, "LIGA process: Sensor construction techniques via X-ray lighography," Rec. of the IEEE Solid-State Sensor and Actuator Workshop, pp. 1-4, 1988.
13. K. S. J. Pister, M. W. Judy, S. R. Burgett, and R. S. Fearing, "Microfabricated hinges," Sensors and Actuators A, Vol. 33, pp. 249-256, 1992.
14. L. Y. Lin, S. S. Lee, K. S. J. Pister, and M. C. Wu, "Three-dimensional micro-Fresnel optical elements fabricated by micromachining technique," Electronics Letters, Vol. 30, No. 5, pp. 448-449, 1994.
15. L. Y. Lin, S. S. Lee, K. S. J. Pister, and M. C. Wu, "Micro-machined three-dimensional micro-optics for integrated free-space optical system," to be published.
16. O. Solgaard, M. Daneman, N. C. Tien, A. Friedberger, R. S. Muller, and K. Y. Lau, "Micromachined alignment mirrors for active opto-electronic packaging," *Conference on Lasers and Electro-Optics*, Postdeadline paper CPD6, Anaheim, CA, May 8 ~ 13, 1994.
17. S. S. Lee, L. Y. Lin, K. S. J. Pister, M. C. Wu, H. C. Lee, and P. Grodzinski, "An 8 × 1 Micromachined Micro-Fresnel Lens Array For Free-Space Optical Interconnect," *IEEE LEOS'94 Annual Meeting*, Paper OS4.3, Boston, MA, October 31 ~ November 3, 1994.

18. L. Y. Lin, S. S. Lee, K. S. J. Pister, M. C. Wu, H. C. Lee, and P. Grodzinski, "Micro-machined micro-optical bench for optoelectronic packaging," *IEEE LEOS'94 Annual Meeting*, Boston, MA, October 31 ~ November 3, 1994.
19. S. S. Lee, L. Y. Lin, K. S. J. Pister, M. C. Wu, H. C. Lee, and P. Grodzinski, "An 8 × 1 Micromachined Micro-Fresnel Lens Array For Free-Space Optical Interconnect," *International Electron Devcie Meeting (IEDM)*, San Francisco, CA, December, 1994.
20. D. S. Gunawan, K. S. J. Pister, and L. Y. Lin, "Micromachined coner cube reflectors as a communication link," submitted for publication.
21. K. Rastani, A. Marrakchi, S. F. Habiby, W. M. Hubbard, H. Gilchrist, and R. E. Nahory, "Binary phase Fresnel lenses for generation of two-dimensional beam arrays," Applied Optics, Vol. 30, No. 11, pp. 1347-1354, 1991.
22. L. S. Fan, Y. C. Tai, and R. S. Muller, "IC-processed electrostatic micromotors," Sensors and Actuators, Vol. 20, pp. 41-47, 1989.
23. C. H. Henry, G. E. Blonder, and R. F. Kazarinov, "Glass waveguide on silicon for hybrid optical packaging," J. Lightwave Tech., Vol. 7, No. 10, pp. 1530-1539, 1989.