Micromachined Integrated Optics for Free-Space Interconnections

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Abstract

A novel surface micro-machined *micro-optical bench* (MOB) has been demonstrated. Free-space micro-optics such as micro-Fresnel lenses, rotatable mirrors, beam-splitters and gratings are implemented on a single Si chip using IC-like microfabrication processes. Self-aligned hybrid integration with semiconductor lasers are also demonstrated for the first time. The MOB technology realizes a micro-optical system on a single Si chip and has significant impact on free-space integrated optics, optical switching, optical data storage, and optoelectronic packaging.

1 Introduction

Integrated optics has attracted intense attention since its proposal in 1969 [1]. It offers many advantages such as high functionality, reduced packaging cost of individual optoelectronic components, and improved performance by eliminating parasitic effects. To date, most of the research efforts in integrated optics emphasize on guided-wave approach [2,3]. On the other hand, free-space integrated optics offers many advantages over guided-wave approach such as high spatial bandwidth (diffraction limited), non-interfering optical routing, three-dimensional optical interconnection, and optical signal processing capability (e.g., Fourier optics). However, it is more difficult to integrate free-space optics on a single substrate since most monolithically fabricated free-space optical elements lie on the surface of the substrate.

Micromachining of silicon substrate has been applied to integrated optics and the realization of miniature optical bench since 1970's [4]. Recently, surface micro-machined hinges and spring-latches [5] have been employed to achieve monolithic fabrication of three-dimensional micro-optics [6,7]. This technology opens a new area for integrated optics in free-space. Using this new technique, three-dimensional micro-optical components can be fabricated integrally on a single Si chip. The Si substrate serves as a "*micro-optical bench* (MOB)" on which micro-lenses, mirrors, gratings and other optical components are pre-aligned in the mask layout stage using computer-aided design and then constructed by microfabrication. Additional fine adjustment can be achieved by the on-chip micro-actuators and micro-positioners such as rotational and translational stages. With hybrid integration of active optical devices, a complete optical system can be constructed on the MOB, as illustrated in Fig. 1.

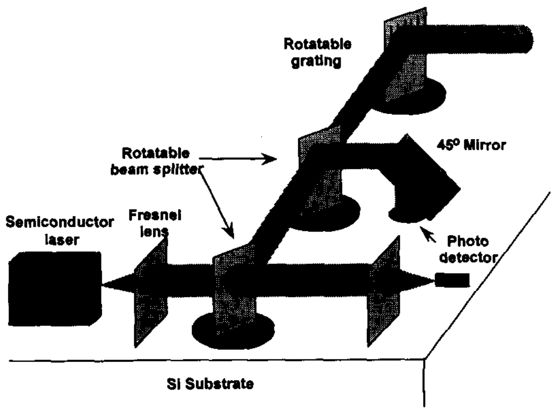

Fig. 1. The schematic diagram illustrating the micromachined free-space micro-optical system on a single Si chip.

A micro-Fresnel lens standing perpendicular to the substrate has been successfully fabricated [6]. The lens has a diameter of 650 μm and an optical axis of 1 mm above the Si substrate, with focal length equal to 1 mm. Excellent collimating ability for this lens has been achieved and will be shown in Sec. 3A. The fabrication process of MOB is compatible with the IC-process. The MOB offers a new approach for optoelectronic packaging, free-space optical interconnect, and single-chip micro-optical systems.

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2 Fabrication

The three-dimensional micro-optical system is constructed on a Si substrate by surface micromachining technique. The fabrication process integrating micro-optics with micro-hinges and spring-latches is described in the following (see Fig. 2): First, a 2-μm-thick phosphosilicate glass (PSG-1) is deposited on the silicon substrate as the sacrificial material. It is followed by the deposition of a 2-μm-thick polysilicon layer (poly-1) on which the micro-optics patterns such as Fresnel lenses, mirrors, beam splitters and gratings are defined by photolithography and dry etching. The hinge pins holding these three-dimensional structures are also defined on this layer. Following the deposition and patterning of poly-1, another layer of sacrificial material (PSG-2) of 0.5 μm thickness is deposited. 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. The poly-2 structures can also be contacted with poly-1 by etching contact holes through PSG-2 only, as required in the rotatable mirror and grating to be described later. The micro-optics plates are released from substrate by selectively removing the PSG material using hydrofluoric acid after fabrication. After the release etching, the poly-plates with micro-optics patterns are free to rotate around the hinge pins. 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 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. After the three-dimensional micro-optical element is assembled, a layer of gold is coated on the lifted poly surfaces. In binary-amplitude Fresnel zone plates or micro-mirrors, a thick layer of gold is needed to completely block the light passing through the dark zones or to make a perfectly reflecting mirror. On the other hand, thinner gold is desired for partially transmitting mirrors or beam splitters.

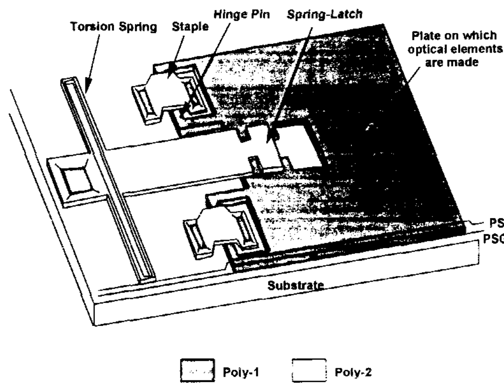


Fig. 2. The schematic structure of micromachined micro-optical element before assembly.

3 Results

A. Micro-Fresnel lenses

Figure 3 shows the SEM photograph of a three-dimensional micro-Fresnel lens after assemble. The diameter of this lens is 280 μm, with a designed optical axis of 254 μm for passive integration of an edge-emitting semiconductor laser, as will be shown in Sec. 3C. Because of the height of the lens plate, the angles between the lens plates and the substrate have some variations even though they are coarsely defined by the spring latches. Such variations are not tolerable in large optical systems. Therefore, a new set of "lens-mount" is designed to precisely define the angles of the three-dimensional micro-optical elements. The lens mount consists of two folded polysilicon plates which are fabricated integrally with the micro-lens. 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. It can be made as tall as the lens itself, therefore, the angle defined by the lens mount are much more precise. The lens mount also greatly improves the mechanical strength and stability of the micro-optical elements.

The optical performance of the three-dimensional micro-Fresnel lens has been tested by collimating a divergence beam emitted from a single mode fiber at $\lambda = 1.3$ μm. The divergence of the optical beam with and without the collimating lens is compared in Fig. 4. The intensity FWHM divergence angle is reduced from 5.0° to 0.33° by the lens. The collimated beam profile fits very well to the Gaussian shape (95% fit). Similar experiment has also been performed using a semiconductor edge-emitting laser with $\lambda = 1.3\ \mu m$ as the light source. The intensity FWHM far-field angles of the semiconductor laser are $18° \times 40°$. The collimated beam has an elliptical shape, as shown in Fig. 5, and the intensity FWHM measured at 5 cm behind the lens are $330\ \mu m \times 788\ \mu m$, which corresponds to divergence angles of $0.38° \times 0.9°$.

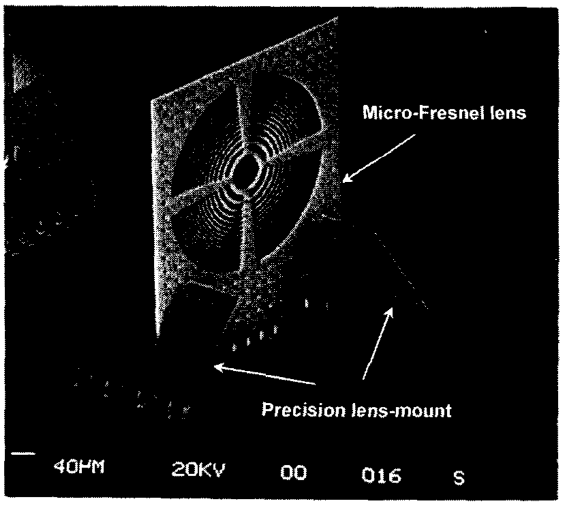


Fig. 3. SEM photograph of a micro-Fresnel lens with precision lens-mount.

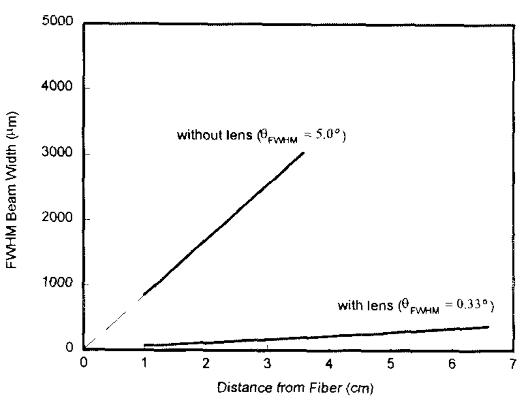
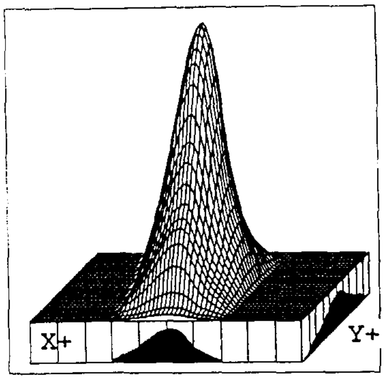


Fig. 4. Collimating performance of the three-dimensional micro-Fresnel lens.



Divisions: top = 15.62 uM
bottom = 100.0 uM

Fig. 5. Beam profile of the semiconductor laser ($\lambda = 1.3\ \mu m$) after collimated by the micro-Fresnel lens.

B. Rotational stages

One unique feature of implementing micro-optical bench using surface micromachining is that micro-positioners and micro-actuators can be monolithically integrated in the same fabrication processes. This allows the alignment of the optical systems to be fine adjusted, in addition to the coarse alignment done at the design stage using CAD layout tools. Using similar structures as the micromotors [8], rotational stages and linear micro-positioners can be realized. We have successfully integrated the three-dimensional micro-optical elements with rotational stages using this process. Figure 6 shows the SEM photograph of a rotatable mirror. The rotatable plate is fabricated on the first polysilicon layer, and the axis and hub are defined on the second polysilicon layer. The fabrication process is similar to that described in Sec. 2, except that the optical elements are patterned on the second polysilicon layer so that the patterning of the rotatable plate won't be affected, and the bases of the poly-2 spring-latched and staples are now connected to poly-1 rotatable plate. The micro-hinges are defined on the rotating poly-1 plate. The bottom of the poly-2 plate on which optical patterns are defined is connected to the micro-hinges by poly1-poly2 via holes. After the PSG material is selectively removed, the poly-1 plate is free to rotate on the substrate plane. Thirty-six ticks are made on the substrate to indicate the rotation angle of the plate, as shown in Fig. 6 (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, 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. 7.

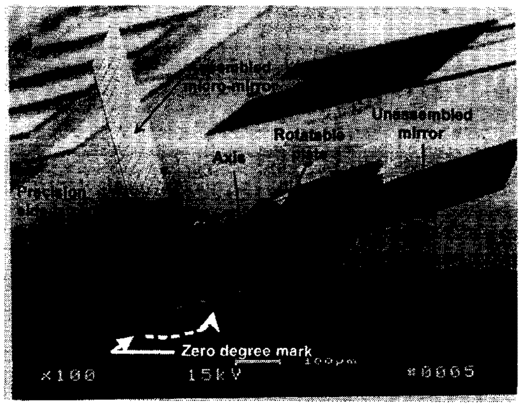


Fig. 6. A rotatable micro-mirror. The rotation stage has been rotated by 20°.

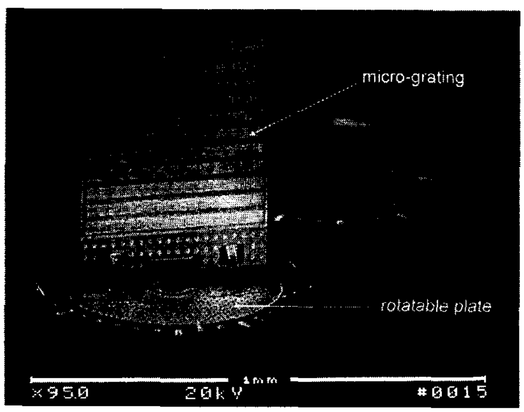
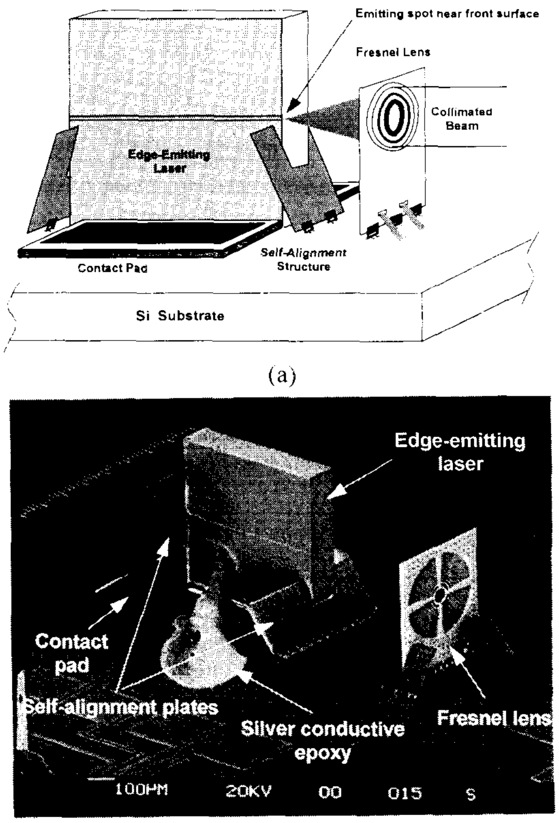


Fig. 7. The diffraction grating integrated with a rotational stage.

C. Self-aligned hybrid integration with semiconductor Lasers

To implement a complete micro-optical system on the MOB, it is necessary to incorporate active optical devices such as semiconductor lasers, light emitting diodes (LED) and photodetectors. Hybrid integration is necessary for active devices that cannot be made by Si micromachining (e.g., semiconductor lasers). Hybrid optical packaging on silicon which combines flip-chip mounting and silica waveguide interconnection has been proposed [9]. However, most of the optoelectronic packaging methods confine the optical components on the surface of the substrate, which is two-dimensional in nature and cannot be used for free-space integrated optics. The approach of MOB enables the hybrid integration of active optical devices with three-dimensional micro-optical elements in free-space. Stationary and movable micro-optical components are fabricated on Si substrate using surface micromachining technique. In this section, a novel, three-dimensional self-alignment structure fabricated integrally with the other micro-optics for the hybrid integration of active optical components will be described.

In order to integrate the MOB with active optical devices such as semiconductor lasers, we have designed a set of self-alignment structures using the same two-layer polysilicon surface micromachining technology as described in Sec. 2. Figure 8(a) shows the schematic diagram of the self-aligned hybrid integration of an edge-emitting semiconductor laser with a micro-Fresnel lens. The edge-emitting laser is mounted on its side for accurate positioning of the active emitting spot. There are also other possible schemes for mounting semiconductor lasers: Flip-chip mounting and upright (junction side up) mounting. Flip-chip mounting using indium solder balls can achieve an alignment accuracy of around 1 μm, however, the emitting spot is very close to the Si substrate and is much lower than the optical axis of the free-space optical system. The height of the optical axis in upright mounting scheme is defined by the laser substrate thickness, which usually has a tolerance of more than 5 μm and is not suitable for MOB without employing additional adjustable optics. Since the laser chip size can be precisely defined by scribing, side mounting can place the emitting spot accurately on the optical axis. In our current design, it is placed at 254 μm above the Si substrate, which is suitable for the optical axis of MOB.



(a)

(b)

Fig. 8. (a)Schematic diagram and (b) SEM photograph of the self-aligned hybrid integration of an edge-emitting laser with a micro-Fresnel lens.

Figure 8(b) shows the SEM photograph of the hybrid integration of the semiconductor laser with a micro-Fresnel lens. The emitting spot of the edge-emitting laser is aligned to the center of the Fresnel lens by the self-alignment structures. Figure 9 is the top view photograph of the self-alignment structure before it is assembled. The edge-emitting laser is slided into the slot between two electric contact pads until the front facet hits the alignment block built on the MOB, which defines the longitudinal (x-direction, as shown on the picture) position of the emitting spot. The self-alignment plates can then be rotated up and the asymmetric wedge-shaped opening on the top gradually guides the active side (waveguide side) of the laser towards the flat edge of the wedges, which defines the transverse (y-direction) position of the emitting spot. This unique design allows us to accommodate lasers with a large variation of substrate thickness (from 100 μm to 140 μm). After the alignment, conductive silver epoxy is applied between the laser and the contact pads for the electrical contact. Permanent fixing of the semiconductor laser is achieved by curing the silver epoxy. Potentially, the epoxy can be replaced by other three-dimensional micromechanic structures.

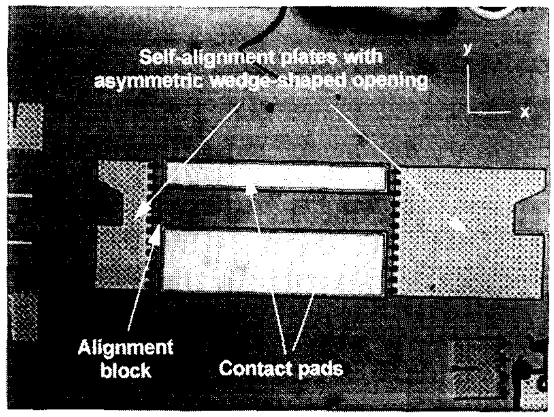
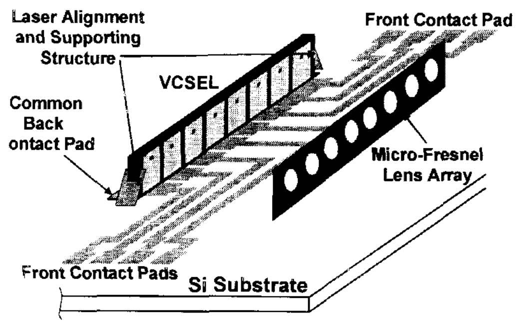


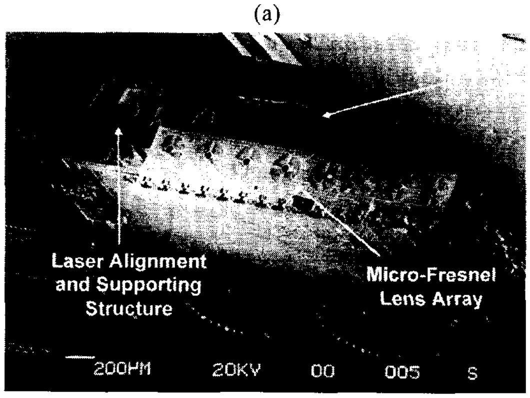
Fig. 9. Top view photograph of the self-alignment structure before they are assembled.

Vertical cavity surface-emitting lasers (VCSEL) possess unique characteristics for optical interconnect and many other applications: 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 of its small numerical aperture and, therefore, higher misalignment tolerance. In addition, two dimensional arrays of both VCSELs and micromachined lens can be easily fabricated. 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.

We have demonstrated for the first time the hybrid integration of 8 × 1 arrays of VCSELs and micro-Fresnel lens using passively self-aligned mounting scheme. The schematic diagram of the hybrid integration and SEM picture of a micro-Fresnel lens array and a VCSEL array are shown in Fig. 10(a) and (b), respectively. The VCSELs consist of AlGaAs/GaAs λ/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 have asymmetric wedge-shaped opening similar to that in Fig. 9, which can push the VCSEL array forward so that the front surface of the VCSEL array is aligned with focal plane of the lens array.



(a)



(b)

Fig. 10. (a) Schematic diagram and (b) SEM photograph of the self-sligned hybrid integration of the 8 × 1 VCSEL array and the 8 × 1 array of micro-Fresnel lens.

4 Conclusion

In summary, a new surface-micromachined micro-optical bench (MOB) for free-space integrated optics is proposed and successfully demonstrated. Various three-dimensional optical elements and micro-positioners have been fabricated: micro-Fresnel lenses with various size and focal lengths, rotatable micro-mirrors and diffraction gratings, beam splitters, lens mount. Self-aligned hybrid integration of active optical devices with MOB is also realized using novel three-dimensional alignment structure. This new approach can drastically reduce the size, weight and cost of most optical systems, and have applications in free-space optical interconnection, optical switches, optical storage systems, and optoelectronic packaging.

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