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Self-aligned hybrid integration of semiconductor lasers with micromachined micro-optics for optoelectronic packaging

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Novel self-aligned hybrid integration of semiconductor lasers with three-dimensional micro-optical components has been demonstrated. The self-alignment structures are fabricated integrally with other three-dimensional micro-optical elements such as micro-Fresnel lenses, mirrors, and gratings on a single Si chip by surface micromachining technology. The Si substrate serves as a free-space micro-optical bench for active and passive optoelectronic components. A divergent beam emitted from an edge-emitting semiconductor laser has been successfully collimated by the integrated micro-Fresnel lens. The integration scheme offers a new approach for optoelectronic packaging and a new technology platform for integrating complete free-space micro-optical system on a single chip. © *1995 American Institute of Physics.*

Integrated optics has been an active research area since its proposal in 1969[1] because it offers many advantages: higher functionality, reduced packaging of individual optoelectronic components, improved performance by eliminating parasitics, and more uniform control of the environment (temperature, etc.). To date, most of the research in integrated optics focuses on guided-wave approach. For example, photonic integrated circuits (PIC) integrate lasers, detectors, and modulators with passive guided-wave components.[2] On the other hand, free-space integrated optics offers advantages such as high spatial bandwidth (diffraction limited resolution), 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. Surface micromachining has been used to produce three-dimensional micro-optics.[3,4] Previously, we have proposed a micro-optical bench (MOB) fabricated by surface micromachining technology for optoelectronic packaging and free-space integrated optics.[5,6] On the micro-optical bench, three-dimensional micro-optical elements such as micro-lenses, mirrors and gratings are fabricated integrally on a silicon chip. The fabrication process is similar to that of integrated circuit (IC) processing. The micro-optic system can also be pre-aligned in the mask layout stage using computer-aided design. Additional fine adjustment can be achieved by on-chip micro-actuators and micro-positioners such as the rotational and translational stages.

To implement a complete micro-optical system on micro-optical bench, it is necessary to incorporate active optical devices. Passive alignment of active optical devices with micro-optics is desirable to minimize cost. Hybrid optical packaging on silicon which combines flip-chip mounting and silica waveguide has been proposed.[7] However, the waveguide interconnection is two-dimensional in nature and cannot be used for free-space integrated optics. In this letter, we demonstrate the first hybrid integration of semiconductor edge-emitting lasers with micro-optics using novel three-dimensional alignment structures. The optical performance of the edge-emitting laser/ micro-Fresnel lens module is reported. Other packaging issues such as heat sinking are also discussed.

The three-dimensional micro-optics and the self-alignment structures are fabricated integrally with micro-hinges and micro-spring latches[8] by surface micromachining process. The Si substrate serves as a micro-optical bench. The fabrication process is summarized in the following: First, a 2-μm thick of phosphosilicate glass (PSG) is deposited as the sacrificial material. It is followed by the deposition of a 2-μm-thick polysilicon layer on which the micro-optics patterns and the self-alignment structure are defined by photolithography and dry etching. The hinge-pins holding these three-dimensional structures are also defined on this layer. Then another layer of PSG material with a thickness of 0.5 μm is grown uniformly. Before the deposition of second polysilicon layer, contact holes are opened by dry etching through the PSG material to the silicon substrate. Finally the hinge-staples and spring-latches are defined on the second polysilicon layer and their bases are connected to the substrate via the contact holes. The micro-optics plates are released from substrate by selectively removing the PSG material using hydrofluoric acid after fabrication. The polysilicon plates with micro-optics patterns and self-alignment structures can then be rotated out of the substrate plane. The position of the rotated polysilicon plate is fixed by the spring latches which are pushed up by the plate itself.

Figure 1(a) shows the schematic diagram of the self-aligned hybrid integration of an edge-emitting laser with a micro-Fresnel lens. The Fresnel lens is held by two precision mounting plates fabricated by the same processes to precisely fix its angle and position. The structure of the lens mount has been reported in detail in Ref. 6. The edge-emitting laser is mounted on its side for accurate position of the active emitting spot. By precise scribing, the optical axis is placed at 254 μm above the Si substrate. The emitting

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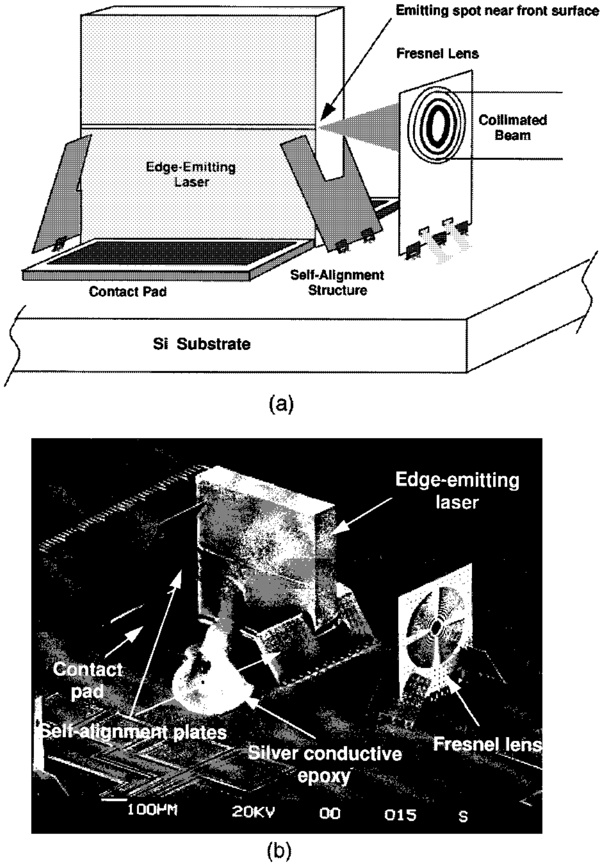

FIG. 1. (a) Schematic diagram and (b) SEM photograph of the self-aligned hybrid integration of an edge-emitting semiconductor laser and a micro-Fresnel lens.

spot of the edge-emitting laser is aligned to the center of the Fresnel lens by the self-alignment structures. Conductive silver epoxy is applied between the laser and the contact pads for 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. Figure 1(b) shows the scanning electron micrograph (SEM) of the laser and the micro-Fresnel lens.

Figure 2 is a top view photograph of the self-alignment structure before it is assembled. The edge-emitting laser is slid into the slot between two electric contact pads until the

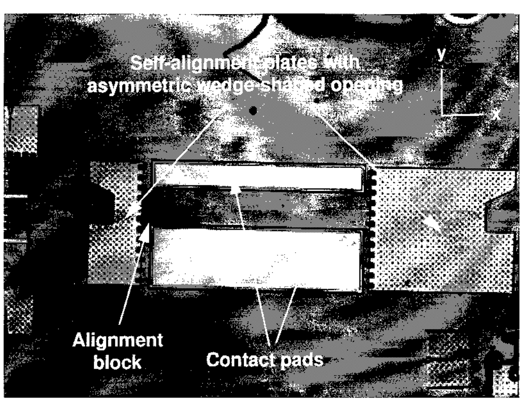

FIG. 2. Photograph of the self-alignment structures before they are released and assembled (top view).

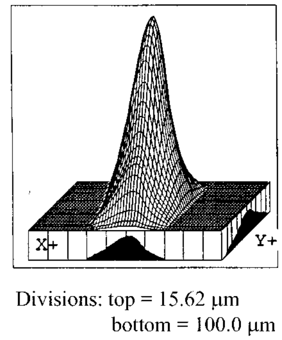

FIG. 3. Beam profile of the semiconductor laser ($\lambda = 1.3\ \mu$m) after collimated by the micro-Fresnel lens. The profile fits very well with the Gaussian shape.

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 are then rotated up and the asymmetric wedge-shaped opening on the top gradually guides the active side (waveguide side) of the laser toward 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 thick). The height of the self-alignment structure (400 μm tall for the self-alignment plate on the back facet of the laser) permits more precise alignment.

There are other possible schemes for mounting semiconductor lasers: Flip-chip mounting and upright (junction side up) mounting. Flip-chip mounting using solder bumps can achieve an alignment accuracy of around 1 μm, however, the emitting spot is too close to the Si substrate and is much lower than the optical axis of the free-space optical system. The heat conduction for this mounting scheme might not be sufficient for high power dissipation due to small contact areas. Heat sinking can be improved by increasing the contact area at the expense of alignment accuracy. The upright mounting has good heat conduction because of the large contact area between the semiconductor laser and the Si substrate. However, the height of the optical axis is now 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. Therefore, the side mounting scheme was chosen for the hybrid integration of semiconductor lasers on MOB. The height of the emitting spot is precisely defined by scribing. In our current design, it is placed at 254 μm above the Si substrate, which is suitable for the optical axis of MOB.

The collimating performance of the binary amplitude micro-Fresnel lens has been demonstrated successfully using a divergent beam emitted from a single mode fiber as light source.[6,9] A similar experiment has also been conducted using the integrated edge-emitting laser as the light source. Figure 3 shows the Gaussian beam profile of the collimated beam. The profile is measured at 5 cm after the lens. The laser has a wavelength of 1.3 μm and divergence angles of 18°×40°. After collimation by the micro-Fresnel lens, the

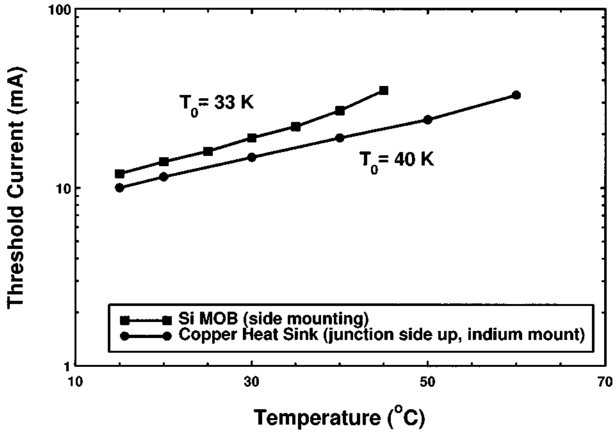

FIG. 4. Temperature dependence of the threshold currents for the semiconductor lasers with side mounting and upright mounting.

Gaussian beam widths become 330 μm$\times$788 μm, which corresponds to divergence angles of 0.38°$\times$0.9°.

To investigate the heat sinking capability of the side mounting scheme, we compared the temperature dependence of the threshold current I_{th} for semiconductor lasers with side mounting on MOB and with upright mounting on copper heat sink. The experimental results are shown in Fig. 4. The laser used in this experiment is an edge-emitting laser with wavelength of λ=1.3 μm. In the upright mounting scheme (—●— in the figure), the laser is mounted directly on a copper heat sink using indium solder. The characteristic temperature of T_0=40 K is typical of long wavelength lasers. For side mounting in the hybrid integration (—■— in the figure), the laser is first mounted on the MOB and the MOB is fixed on a copper heat sink using a thermal joint compound (whose thermal conductivity is much lower than the indium solder). The threshold currents increase slightly and T_0 becomes 33 K. The threshold current increase at I_{th}=12 mA is equivalent to a 7 °C rise in the junction temperature. To gain more insight into the thermal conduction of this packaging scheme, we compare the thermal resistivity of these two mounting schemes using the effective thermal resistivity model developed by Joyce and Dixon.[10] From the simulation, it is found that the dominant thermal resistance of the side mounting scheme comes from the thermal joint compound (thermal conductivity=0.43 Btu•Ft/Hr•Ft^2•°F) between the MOB and the copper heat sink. This thermal joint compound is not used in the upright-mounted laser which is directly soldered to the copper heat sink by indium. Therefore, heat conduction for the hybrid integration can be improved by choosing better thermally conducting material for the mounting of the Si MOB on the copper heat sink.

In summary, we have demonstrated the first self-aligned hybrid integration of semiconductor edge-emitting lasers and three-dimensional micro-optics. Novel self-alignment structures and micro-optics are fabricated integrally on a Si chip using surface micromachining techniques. The divergent beam from the semiconductor laser is successfully collimated by the micro-Fresnel lens. The hybrid integration of semiconductor lasers and three-dimensional micro-optics such as micro-lenses, mirrors and gratings enables micro-optical systems to be built on a single Si substrate. The proposed scheme is also applicable to other optoelectronic devices, for example, the integration of vertical cavity surface-emitting laser array and micro-Fresnel lens array has been demonstrated.[11] The MOB offers a new approach for opto-electronic packaging, free-space optical interconnect, and single-chip micro-optical systems.

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