Low-loss, thermally stable waveguide with 45° micromirrors fabricated by soft molding for fully embedded board-level optical interconnects

Li Wang, Xiaolong Wang, Jinho Choi, David Hass*, Jerry Magera*, and Ray T. Chen,

University of Texas at Austin

Sanmina-SCI*

ABSTRACT

A high performance polymer waveguide array with 45° micromirrors was fabricated by soft molding to achieve fully embedded board-level optoelectronic interconnects. One-step-transferring of a 3-D polymer structure is demonstrated. Low-loss and thermally stable UV curable polymers based on fluorinated acrylate are chosen as waveguide core and cladding materials. A 45° total interior reflection (TIR) micromirror was formed by two methods: blade cutting and mechanical polishing. And the surface roughnesses are further improved by using a focused ion beam (FIB) technique. The high-quality 45° micromirror was obtained to provide surface-normal light coupling between waveguide and the optoelectronic devices. The measured propagation loss of the multimode waveguide was 0.156dB/cm at 850nm wavelength. The excess loss of the mirror was less than 1.5dB.

Keywords: soft molding, micromirror, polymer waveguide, PDMS, optical interconnects, VCSEL, Photodetector, FIB

1 INTRODUCTION

The capability of high speed data transfer rate is pivotal in high performance computer systems. However, conventional electrical interconnections fail to meet with the increasing data rate requirements due to their built-in limitations. Optical interconnect has become the alternative to resolve these limitations. We proposed a fully embedded board level optical interconnect for high-performance computing systems. It not only provides process compatibility with a standard printed circuit board (PCB) production process, but also reduces the footprint of the PCB by fully embedding all optical components as one single optical-interconnect layer among other electrical interconnection layers [1] [2]. In our system, the optical layer includes a Vertical Cavity Surface Emitting Laser (VCSEL) array, a photodetector (PD) array, surface-normal waveguide couplers, and a polymeric channel waveguide functioning as the physical layer of optical interconnection. The driving electrical signals to modulate the VCSEL and the demodulated signals received at the photo-receiver flow through electrical vias connecting to the surface of the PC board (see Fig. 1). Within the optical-interconnect layer, the light from the VCSEL is coupled into the waveguide through a 45° micromirror coupler and then travels in the polymer waveguide to the destination, where it is coupled out by another a 45° micromirror coupler, and is detected by the photodetector. The light signal is then converted to an electrical signal and sent to the receiving IC. To implement a fully embedded optical-interconnect layer, two components are crucial: Low-loss, thermally stable and flexible optical waveguides and highly efficient 45° micromirror couplers to provide light coupling between the waveguide and the optoelectronic devices.

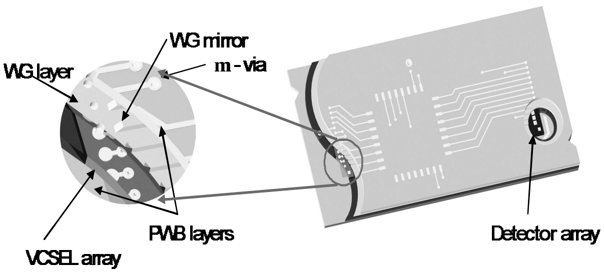

Fig. 1 Illustration of a fully embedded board level optical interconnect

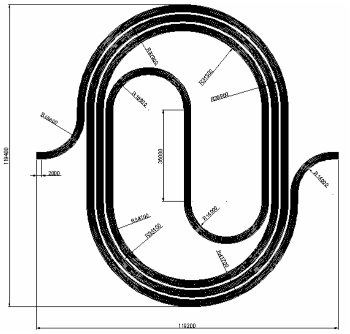

Fig. 2 The total length of 109 cm waveguide layout design

Photonics Packaging and Integration V, edited by Randy A. Heyler, Ray T. Chen,
Proceedings of SPIE Vol. 5731 (SPIE, Bellingham, WA, 2005)
0277-786X/05/$15 · doi: 10.1117/12.589519

In our waveguide design, multimode waveguide with a large core size (50µm×50µm) is utilized to relax alignment tolerances for the VCSEL and the PD array and a waveguide array contains 12 waveguide channels with 250µm separation between individual channels. For board-level interconnection, the interconnection distance can be easily in the range of tens of centimeters up to 1 meter. We designed a 109 cm long waveguide pattern shown in Fig.2.

Various techniques are used to fabricate the polymer waveguides such as reactive ion etch (RIE) [3], photolithography [4], laser direct writing [5] and molding [6]. Soft molding (microtransfer molding) is chosen to fabricate the large-core-size waveguide because it is low cost, suitable for mass production and compatible with the PCB manufacturing process. In addition, soft molding is also suitable to replicate 3-D structure, which enables us to fabricate the waveguides and 45° micro mirrors in one single step.

For the integration of polymer waveguides into multi-layer PC boards to occur, the waveguide film has to withstand more than 1 hour exposure of 180ºC during the lamination[7]. For this reason, the ultraviolet-curable polymers based on perfluorinated acrylate (available by Zen Photonics) with low loss, low birefringence, and good environmental stability were chosen as waveguide core and cladding materials. The refractive index of the core WIR30-470 is 1.47 at 850nm and that of the cladding WIR30-450 is 1.45 at 850nm. The polymeric foil Topas (cyclo-olefin-copolymer) from Ticona was chosen as the mechanical support for optical layer. The Topas film is highly transparent, has a low loss at 850nm and has a high glass transition temperature (150°C). The flexible waveguide film provides transparent, lightweight substrate and it is easy to laminate on the PCB.

The 45° micromirror plays a critical role in optical interconnection applications. Although optical signals can be coupled from VCSELs to waveguides by titled grating couplers, 45° micro mirrors are still an attractive choice because of their high coupling efficiency and insensitivity to wavelength [8]. There are various techniques to fabricate 45° micromirror such as laser ablation, reactive ion etching (RIE), and machining. In this paper, we reported the 45° mirror was formed by two methods: blade cutting and mechanical polishing.

The blade cutting method is a simple fabricating technique. The roughness of 45° mirror surface is not always smooth because of the rough blade quality. To improve the roughness of 45° mirror surface, a focused ion beam (FIB) system was used to polish the mirror surface. FIB system uses a focused beam of Gallium (Ga) ions to scan on the surface of the sample. The ion beam interacts with the sample and results in ejection of secondary particles (neutral atoms, ions and electrons) from the surface. The ions and electrons are collected and generate an image of the surface. If the beam is rastered over one area for a long time, the material will be removed from that area. This is called milling process. Since the spot size is in the range from a few nanometers to 100nm or less, the precision modification can be made on the 45° micromirror surface. FIB is a powerful tool for imaging, modification, and analysis of nano-scale devices. No mask is required [9] [10]. For micro-size mirror, it is time-effective for us to combine the blade cutting with FIB polishing.

We also use the mechanical polishing method to polish the waveguide ends at a 45° tilt angle using a tripod polisher. A tripod polisher is often used to prepare high-precision micro-sized samples for TEM and SEM. Here we apply it to form the 45° tilt angle mirror and it is proved that the tripod polisher is a very effective tool to make high quality mirror surfaces.

The hybrid integration of optical layer with electrical layers is very challenging. At first, the alignment between optoelectronic devices and waveguides is critical for high coupling efficiency. Secondly it should be compatible with PCB technology and low cost. After we fabricated the waveguide film, the VCSEL and PD array were attached on the TOPAS film by UV curable adhesive and melt bonding. The optoelectronic devices integration was demonstrated.

2 FABRICATION OF WAVEGUIDES WITH 45° MICROMIRRORS

Soft molding technique uses elastomeric polydimethylsiloxane (PDMS) molding with patterned relief on the surface to form the patterns. The PDMS mold was prepared by casting prepolymers against masters, patterned by conventional lithographic techniques [11]. Our procedures for fabricating waveguides using soft molding consist of three steps as shown in Fig. 3: (1) Fabrication of the master with a 45° micromirror, (2) The Fabrication of the PDMS mold, and (3) Molding of the waveguide. We will explain each step in detail.

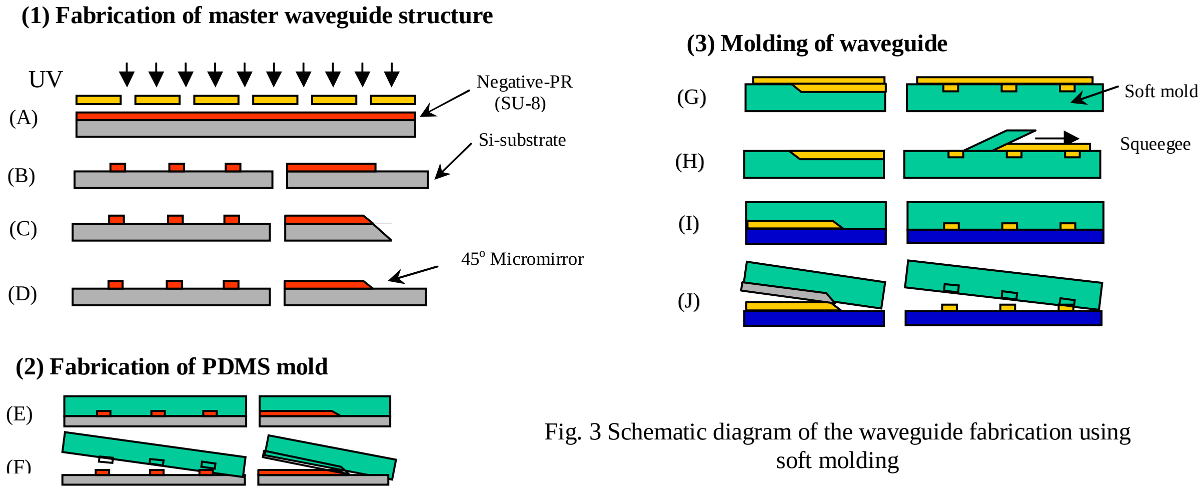

Fig. 3 Schematic diagram of the waveguide fabrication using soft molding

2.1 Fabrication of the master with a 45° micromirror

The master waveguide structure is made using a pattern SU-8 photoresist (MicroChem Corp.) on the silicon wafer using conventional photolithography. The procedure mainly consists of six sub-steps:

(1) Substrate Cleaning. To improve the adhesion of SU-8 film on the substrate, the silicon wafer was first cleaned by a piranha solution (H_2SO_4: H_2O_2=2:1) and then dehydrated on a hot plate at 200° C for 5min.

(2) Coating and Pre-baking. A 50-µm-thick SU-8 (MicroChem Corp.) film was spin coated on the six-inch silicon wafer and pre-baked at 65°C for 30min followed by 90°C for 30min on the hot plate with 30°C/h ramping rate. After the bake, we cooled down SU-8 film slowly at room temperature.

(3) Exposure. The SU-8 film was then exposed using a Karl Suss mask aligner with the exposure dose of 220mJ/cm2. T-toping phenomena were success fully corrected by filtering out ultraviolet radiation below 350nm. A straight and smooth sidewall profile (See Fig. 4) was formed allowing for easy removal of the PDMS mold from the waveguide structure.

(4) Post exposure bake. The film was post exposure baked on the hot plate at 65° C for 1min and 90° C for 2min.

(5) Develop. The wafer with SU-8 film was placed into the SU-8 developer (PGMEA) for 3min to remove the unexposed resist.

(6) To get 45° micro-mirror couplers, the master waveguide structure is put on a 45° tilted stage and cut both end by the commercial blade. Then the FIB instrument (Model Strata DB-235 System, FEI Company) was employed to polishing the mirror surface. The FIB machine is integrated with a scanning electron microscope (SEM) and uses a focused Ga^+ ion beam of 30keV energy with beam current of 1pA – 20nA. The samples are mounted on a motorized five-axis stage in the chamber, which can be rotated to 360°, and tilted to the angle of 0-52°.

Firstly the master waveguide structure was tilted 7° to ensure the ion beam will incident on the surface of the waveguide structure with 45° direction (see figure 5), whereas the E-beam is tilted 7° with respect to the surface of the sample which allows you to view the cross section directly during the milling process. Secondly the suitable ion beam current is selected to get the smooth mirror surface. Since our pattern is in the range of micron size, the beam current was set to 5nA in the experiment to smooth the mirror surface and keep reasonable milling time. At last the milling area is chosen and the milling process began to finely polishing the mirror surface. The Fig. 6 shows the 45° micromirror was obtained by FIB polishing.

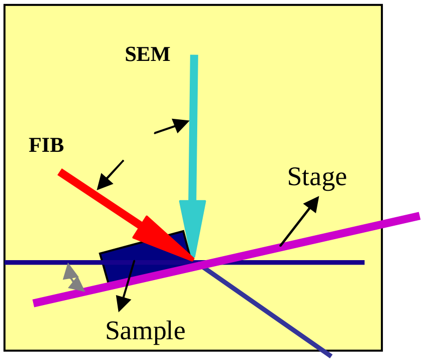

Fig. 5 The schematic figure of sample mounted in the FIB/SEM chamber

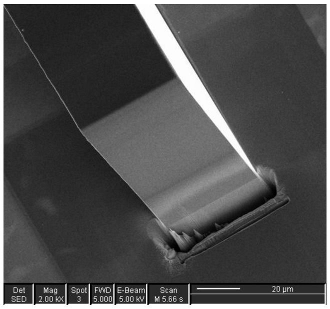

Fig. 6 SEM picture of 45° micromirror was obtained by FIB polishing

The second method is mechanical polishing. The master waveguides are cleaved and mounted onto a tripod polisher. We then place the tripod polisher on a flat surface and adjust its two rear micrometers to ensure that the waveguide is perpendicular to the flat surface from the front view of the tripod polisher and the polishing plane is at a 45° tilt angle with the flat surface from the side view of the tripod polisher. We polished the ends of waveguides to be 45° with a sequence of diamond lapping film from 30 µm grits to 0.1 µm grits. Fig. 7 shows the 45° micromirror obtained by our mechanical polishing.

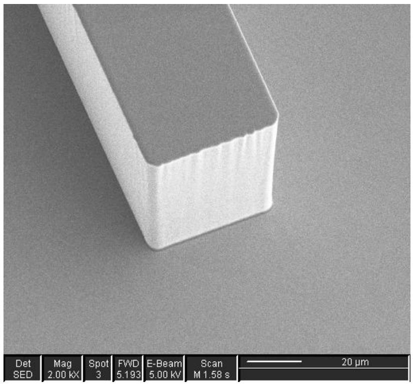

Fig. 4 SEM image of SU-8 pattern on Si wafer

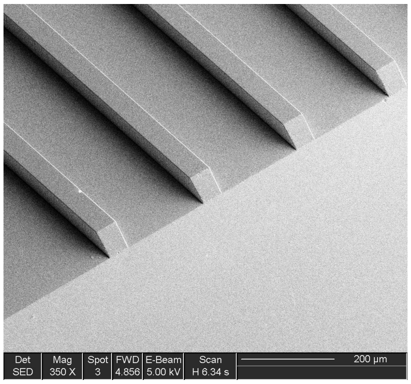

Fig. 7 SEM image of 45 micromirror obtained by mechanical polishing

2.2 Fabrication of PDMS mold

We mixed the base and the curing agents of PDMS with a ratio of 10:1 and degassed them at (30inHg) vacuum to remove air bubbles in the mixture. We then pour the un-polymerized PDMS onto the master, cure it on a hot plate at 40°C for 12 hours, and peel the PDMS mold off of the silicon wafer. In this way, the waveguide's patterns with 45° micromirrors were transferred from the master waveguide structure on to the PDMS stamp.

To obtain a complete pattern, before we pour the un-polymerized PDMS onto the master, we extend the substrate by bonding another piece of substrate with -45° tilt angle.

2.3 Molding of waveguide

(a) A drop of UV curable resin WIR30-470 is applied on the patterned structure of the PDMS stamp and excess resin is scraped off. (b) The filled PDMS mold is placed in contact with the substrate and slight pressure is applied. The applied pressure should be less than 1N/mm^2 otherwise the PDMS will be collapse and the waveguide will be deformed. (c)The pre-polymer WIR30-470 is cured by UV irradiating. Then the PDMS mold is peeled off, leaving the waveguide array. The waveguides were post-baked at 160° C for 30min in a nitrogen atmosphere.

It is necessary for the substrate to have a cladding layer with a lower refractive index than the core materials. Here a 20 µm layer of WIR30-450 was spin-coated on the substrate and cured with 365nm wavelength UV light in a nitrogen atmosphere for 10min and followed 30min post-bake at 160°C under N_2.

3 EXPERIMENTAL RESULTS

We fabricated the channel waveguides with 50µm × 50µm cross-sections by soft molding, in which smooth 45° micromirror surface and waveguide sidewalls were obtained (see Fig. 8(a) and Fig. 8(b)). In soft molding approach, there often exists a residual layer between the mold and the substrate. When the thickness of the residual layer is larger than 0.8 micrometer, the light will be guided into the residual layer, and this will result in the waveguide loss and crosstalk. In our system, we reduced the amount of pre-polymer applied on the PDMS mold and are able to control the thickness of the residual film to be less than 0.8µm. Optical loss was measured by the cut-back method. The 850nm VCSEL light was butt-coupled to the waveguide by using a 50/125µm graded index (GI) multimode fiber and the output light was then butt-coupled to photo detector by using a 62.5/125µm graded index (GI) multimode fiber. The measured propagation loss was 0.156dB/cm at 850nm wavelength as shown in Fig. 9. The optical loss is low enough to use in the board-level interconnects whose distance is less than one meter and proved our design for low- low-loss waveguide is feasible.

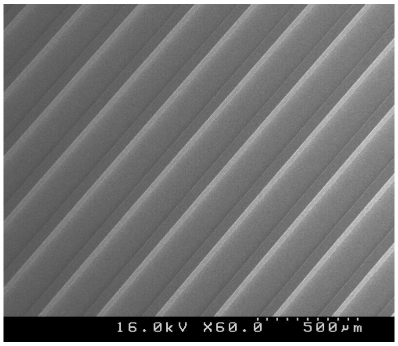

Fig. 8(a) SEM image of channel waveguides obtained by soft molding

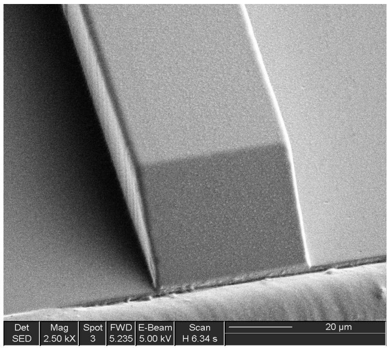

Fig. 8(b) SEM image of waveguide with 45° micromirror obtained by soft molding

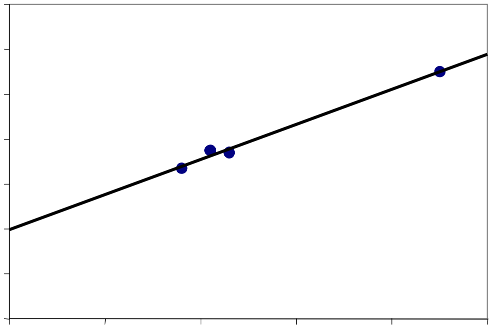

Fig. 9 The insertion losses as a function of waveguide length

The excess loss caused by 45° micromirror was measured by comparing the insertion losses of two waveguide arrays of the same length with mirrors and without mirrors. A multimode waveguide was butt-coupled to an 850nm VCSEL light by a 50/125µm graded index (GI) multimode fiber and the output light was collected by photodetector with large-area aperture (5mm × 5mm). We measured the insertion losses of individual waveguides in the waveguide arrays as shown in Fig. 10. Based on our measurements, we calculated the average mirror loss was less than 1.52dB. This proves our 45° micromirror coupler is very efficient. Currently, our TIR mirror is formed by large refractive index difference between core material and air. In the future, we plan to coat one layer of high reflectivity metal on the mirror surface before coating the top cladding to increase the coupling efficiency.

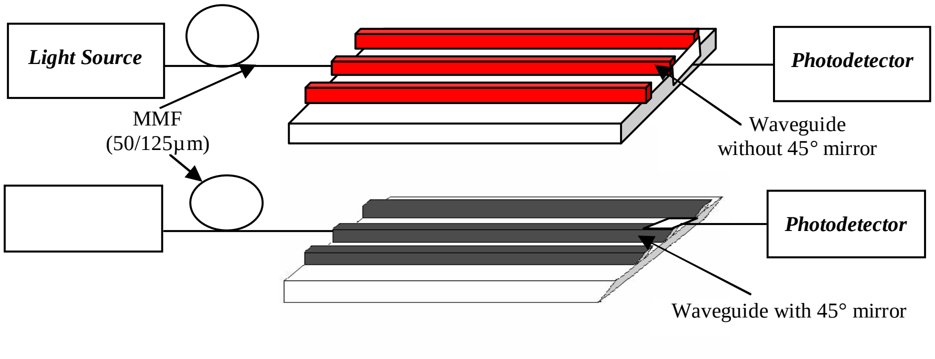

Fig. 10 Insertion Loss Measurement Scheme for 45° micromirror

4 DEVICE INTEGRATION ON FLEXIBLE WAVEGUIDE FILM

The flexible waveguide film will be inserted between electrical circuit layers and laminated with them on the PC board. The driving electrical signals are through micro vias connecting to the surface of the PC board. Fig. 11 illustrates device integration process.

(1) Laminate one mil thick copper foil on the top of the flexible waveguide film. The micro vias can not be electroplated without copper foil lamination since the aspect ratio of the thickness of additional electrical layers and the diameter of device pad is large than 100. The aspect ratio of vias is reduced by introducing the copper foil just above the waveguide layer; hence, we can electroplate micro via. Furthermore, the patterns on the copper foils can be bigger. This means that larger registration error can be allowed during laminating process with electrical layers.

(2) This copper foil is patterned to form the top electrical pads for VCSEL and photo-detector.

(3) Micro vias are drilled by UV-Nd: YAG laser.

(4) Optoelectronics device bonding on the flexible film. There are two ways to bond the VCSEL array and PIN photodiode array: UV curable adhesive and melt bonding.

The melt bonding means the devices is heated to the glass transition temperature of the TOPAS film to bond the device on to the film.

The UV curable adhesive bonding was performed on our lab. The integration was performed on Karl-Suss mask aligner. The flexible waveguide film was first bonded on a piece of clear glass wafer. The VCSEL array and PIN photodiode array were placed on the sample holder. Very small amount of UV curable adhesive (Norland Optical Adhesive 61) was applied on the top of the VCSEL array and PIN photodiode array. After the apertures of VCSEL array was aligned with micro-mirror couplers of waveguide, UV curable adhesive was cured by UV exposure. Then the VCSEL array was attached on the TOPAS film. Same aligning procedure was performed on the PIN photodiode array. Fig. 12 shows the integrated VCSEL and PIN photodiode array on a flexible waveguide film.

(5) Electroplating. The flexible waveguide film was submerged in the copper electroplating solution to plate the side walls of the micro vias and device pads. Now the optical interconnection layer is ready to be laminated with the electrical layers on the PC board.

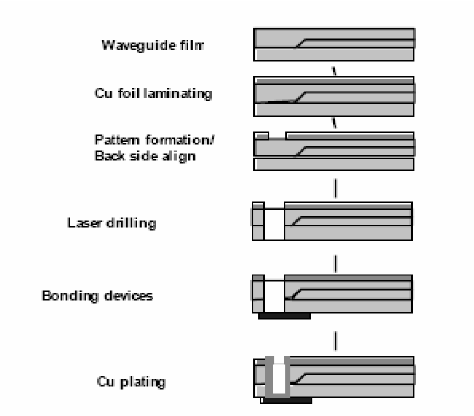

Fig.11 Device integration process flow chart

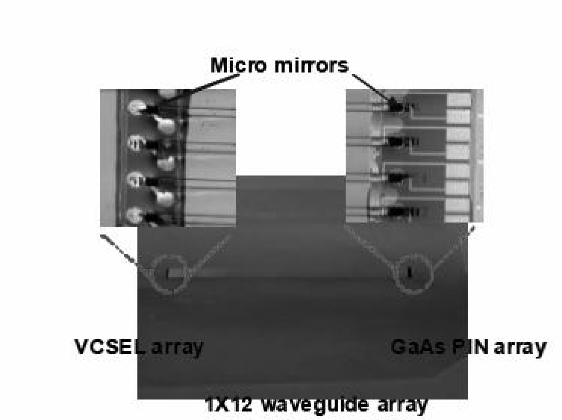

Fig.12 Integrated VCSEL and detector arrays on a waveguide film

5 CONCLUSION

We used soft molding to fabricate the polymer waveguide array with 45° micromirrors. The measured propagation loss of the multimode waveguide was 0.156dB/cm at 850nm wavelength. For the master fabrication, 45° micromirror was formed by blade cutting or mechanical polishing the waveguide's ends to provide surface-normal light coupling between waveguide and the optoelectronic devices. The excess loss of the mirror fabricated by soft molding was measured to be less than 1.52dB. The low-loss and thermal stable waveguide with high quality 45° micromirror enables to realize high-speed fully-embedded board level optical interconnects. We demonstrated an optical waveguide film with integrated optoelectronic devices (VCSEL and PIN photodiode arrays) for fully embedded board level optical interconnects.

References

[1] Ray T. Chen, Lei Lin, Chulchae Choi, Yujie Liu, B. Bihari, L. Wu, R. Wickman, B. Picor, M. K. Hibbs-Brenner, J. Bristow, and Y.S. Liu, “Fully embedded Board-Level Guided-Wave Optoelectronic Interconnects,” Proc. of the IEEE, 88(6), (2000).

[2] E. M. Mohammed, T. P. Thomas, D. Liu, H. Braunisch, S. Towle, B. C. Barnett, I. A. Young and G. Vandentop, “Optical I/O Technology for Digital VLSI”, Proceedings of SPIE, Vol. #5358, January 2004

[3] R. Yoshimura, M. Hikita, S. Tomaru, and S. Imamura, “Low-loss Polymeric Optical Waveguides with 45° mirrors”, Jpn. J. Appl. Phys., Vol. 37, pp. 3657-3661, 1998

[4] A. Borreman, S. Musa, A.A.M. Kok, M. B. J. Diemeer and A. Driessen, “Fabrication of Polymeric Multimode Waveguides and Devices in SU-8 Photoresist Using Selective Polymerization” Proceedings Symposium IEEE/LEOS Benelux Chapter, 2002, Amsterdam

[5] L.Eldada and L. W. Shacklette, “Advances in Polymer Integrated Optics”, IEEE J. select. Topics Quantum Electron, Vol. 6, pp54-68, 2000

[6] Xiao-Mei Zhao, S.P. Smith, S.J. Waldman, G.M. Whitesides, M. Prentiss, “Demonstration Of Waveguide Couplers Fabricated Using Microtransfer Molding”, Appl. Phys. Lett., Vol. 71, 1017-1019 (1997).

[7] Schroder, H., Bauer, J., Ebling, F., Scheel, W., “Polymer optical interconnects for PCB”, Polymers and Adhesives in Microelectronics and Photonics, 2001. First International IEEE Conference on, 21-24 Oct. 2001 Pages: 337 – 343.

[8] Chulchae Choi, Lei Lin, Yujie Liu, Jinho Choi, Li Wang, David Haas, Jerry Magera, Ray T. Chen, “Flexible Optical Waveguide Film Fabrications and Optoelectronic Devices Integration for Fully Embedded Board-Level Optical Interconnects”, Journal of Lightwave Technology, Volume 22, Issue 9 (2004).

[9] Steve Reyntjens, Robert Puers, “A review of focused ion beam applications in microsystem technology”, J. Micromech. Microeng. 11 (2001) 287-300.

[10]Yongqi Fu, Ngoi KokAnn Bryan, “Semiconductor microlenses fabricated by one-step focused ion beam direct wirting”, IEEE transactions on semiconductor manufacturing, Vol. 15, No.2, May 2002.

[11]Y. Xia and G. M. Whitesides, “Soft lithography,” Annu. Rev. Mater. Sci. 28, 153-184 (1998).