APPLIED PHYSICS LETTERS **87**, 141110 (2005)

45° polymer-based total internal reflection coupling mirrors for fully embedded intraboard guided wave optical interconnects

Li Wang, Xiaolong Wang, Wei Jiang, Jinho Choi, Hai Bi, and Ray Chen
Microelectronics Research Center, Department of Electrical and Computer Engineering, The University of Texas at Austin, Austin, Texas 78758

(Received 30 June 2005; accepted 18 August 2005; published online 30 September 2005)

An array of 50 μm × 50 μm polymer waveguides with 45° total internal reflection (TIR) wideband coupling mirrors were fabricated by soft molding to achieve fully embedded boardlevel optoelectronic interconnects. The 45° TIR coupling mirrors were formed at the ends of the waveguides to provide surface normal light coupling between waveguides and optoelectronic devices. Three-dimensional optoelectronic interconnects were replicated in one-step transfer by the soft molding technique. The measured propagation loss of the multimode waveguide was 0.16 dB/cm at 850 nm wavelength. The coupling efficiency of the silver-coated 45° micromirrors buried under the top cladding was 92% with low polarization sensitivity. *© 2005 American Institute of Physics*. [DOI: 10.1063/1.2084331]

As the clock rate of microprocessors and the integration density of complementary metal oxide semiconductor (CMOS) circuitry continue to increase, electrical interconnects are facing their fundamental bottlenecks, such as speed, packaging, fanout, and power dissipation. Optical interconnection technique offers a promising solution to overcome these inherit limitations.[1,2] A fully embedded board level optical interconnect system is schematically shown in Fig. 1. It not only provides process compatibility with a standard printed circuit board (PCB) production process, but also reduces the footprint of a PCB by fully embedding all optical components as one single optical-interconnect layer among other electrical interconnection layers. Within the optical-interconnect layer, light from a Vertical Cavity Surface Emitting Laser (VCSEL) is coupled into a waveguide through a waveguide coupler, and then travels horizontally in the polymer waveguide to the destination, where it is vertically coupled out by another a waveguide coupler to reach a photodetector.

Waveguide couplers play a key role for the realization of three-dimensional fully embedded board-level optical interconnection owing to their surface-normal coupling of optical signals into and out of in-plane waveguides. A waveguide grating[1] or a waveguide mirror based coupler can serve as a surface normal coupler. However, the grating based approach requires precise control of grating parameters for efficient coupling and usually has low tolerance to wavelength variations. Therefore, we employ 45° total internal reflection (TIR) coupling mirrors at both ends of waveguides because they are easy to fabricate, reproducible, and relatively insensitive to wavelength variations, and can provide high coupling efficiency.

There are various techniques to fabricate 45° micromirrors, such as oblique reactive ion etching (RIE),[1] laser ablation,[3] machining[4] and hard molding.[5] In this Letter, we report one-step replication of waveguides with 50 μm × 50 μm cross section and 45° micromirrors by soft molding (microtransfer molding). Soft molding has been recently developed as a convenient, effective and low cost fabrication technique for micro- and nanostructures.[6] It is not only compatible with PCB manufacturing technology but also suitable to replicate three-dimensional structures, which enables us to fabricate the waveguides and 45° micromirrors in one single step. Such a reduction of processing steps constitutes a significant advantage over photolithography.

Soft molding utilizes properly shaped flexible molds—often made of elastomeric polydimethylsiloxane (PDMS) for pattern transfer.[7] A PDMS mold is generally prepared by casting prepolymers against a master patterned by conventional lithographic techniques. In addition to the waveguide structures, the master used herein contains the 45° mirror structures formed by mechanically polishing the ends of waveguide structures at a 45° tilt angle using a tripod polisher. A tripod polisher is often used to prepare high precision microsized samples for Transmission Electron Microscopy (TEM) and Scanning Electron Microscopy (SEM). In this work, we applied this tool to obtaining the 45° micromirror structures, and it was proven to be a very effective tool to produce high quality mirror surfaces.

For the integration of polymer waveguides into a multilayer PCB to occur, the waveguides have to withstand temperatures as high as 180 °C for more than 1 h during the lamination process.[8] For this reason, the ultraviolet-curable polymers based on perfluorinated acrylate (available from ChemOptics) with low loss, low birefringence, and good environmental stability were chosen as the waveguide core and cladding materials. The refractive index of the core material WIR30-470 is 1.47 at 850 nm and that of the cladding material WIR30-450 is 1.45 at 850 nm.

There are three steps in the molding procedure: (1) master fabrication, (2) PDMS mold formation, and (3) pattern

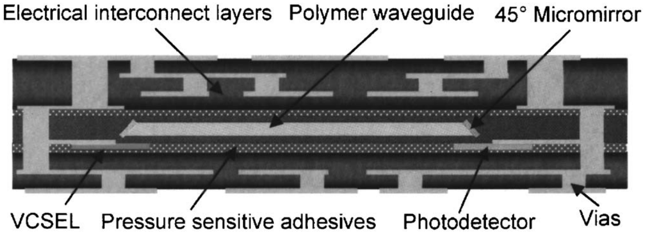

FIG. 1. (Color online) Schematic of fully embedded electrical/optical interconnects on a PCB.

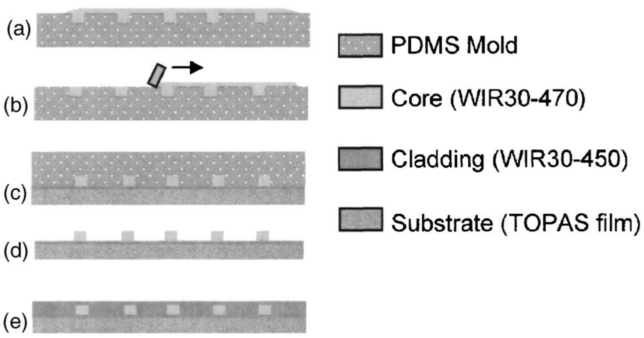

FIG. 2. (Color online) Schematic diagram of the waveguide fabrication using soft molding. (a) Core material was applied. (b) Excess material was removed. (c) The filled PDMS was placed on the substrate and core material was cured. (d) PDMS mold was released.

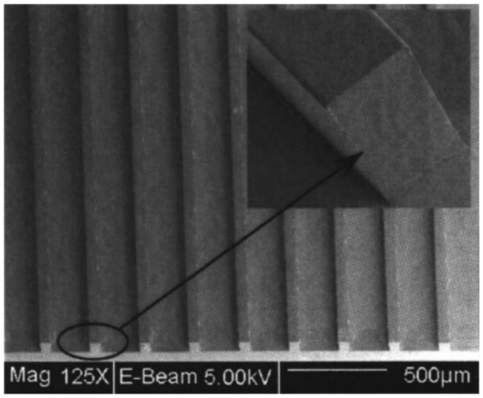

FIG. 3. (Color online) SEM image of the waveguides with 45° silver coating micromirrors.

transfer. A master was made by patterning SU-8 on a silicon wafer with conventional lithographic techniques.[9] The waveguide ends of the master were further polished to 45° with a sequence of diamond lapping film from 30 μm grits to 0.1 μm grits. By casting prepolymers against the master, a PDMS mold was obtained after low-temperature curing for 6 h.

The procedures of the soft molding are illustrated in Fig. 2. For the waveguide formation, a 20 μm layer of WIR30-450 was spincoated on a substrate as the bottom cladding layer. Then a drop of WIR30-470 is applied on the patterned structure of the PDMS stamp and excess WIR30-470 is scraped off. The filled PDMS mold is then placed in contact with the bottom cladding, followed by UV irradiation through the transparent PDMS. After curing the waveguide cores, the PDMS mold is peeled off, leaving the waveguide array with 45° micromirrors. By using the above procedures, the *one-step* transfer of waveguides and 45° micromirrors are realized. The samples are subsequently postbaked.

If we directly coat the top cladding, the efficiency of 45° TIR mirrors will be almost zero because of the small refractive index difference ($\Delta n = 0.02$) between the core and cladding. In this work, a layer of metal was deposited on the 45° mirror surfaces prior to coating top cladding.

Due to its high reflectivity (bulk reflectivity ~97% @850 nm for normal incidence in air) and good adhesion on the polymer WIR30-470, silver was chosen as the material for mirror metallization. Two layers of photoresist AZ4620 (available from Hoechst Celanese Corp.) are spincoated at low speed to completely cover the waveguide cores. A regular photolithography step opened up the window for *e*-beam deposition of a 150 nm silver layer on the micromirror surface, followed by a lift-off process. A thick top cladding was coated to cover the waveguides cores and the silver-coated micromirrors.

Figure 3 shows an array of polymer waveguides with a 45° micromirrors fabricated by soft molding. The measured crosstalk between waveguides separated by 250 μm was less than −30 dB. In the soft molding approach, there often exists a residual layer[10,11] between the mold and the substrate. When the thickness of the residual layer is less than 0.8 μm in our waveguide design, there is no transverse-electric polarized light at 850 nm wavelength to be guided in the residual layer. Otherwise, the residual layer will result in waveguide loss and crosstalk. By reducing the amount of prepolymer applied on the PDMS mold, we were able to control the thickness of the residual film to be less than 0.8 μm, as seen in the near field image of the fabricated waveguide at 850 nm wavelength (shown in the inset of Fig. 4). The propagation loss of waveguides with crosssection 50 μm $\times$ 50 μm was measured by the cutback method. The 850 nm VCSEL light was coupled into the waveguides by using a 50/125 μm graded index (GI) multimode fiber and the output light was then coupled into a photodetector by using a 62.5/125 μm graded index (GI) multimode fiber. The measured propagation loss was 0.16 dB/cm at 850 nm as shown in Fig. 4.

The coupling efficiency of the mirror is of critical importance for the fully embedded optical interconnect systems.[1] The coupling efficiency of silver coated mirrors was measured by comparing the insertion losses of two waveguide arrays of the same length with and without TIR mirrors, respectively. The 850 nm VCSEL light was surface-normal coupled into the waveguide through a 45° micromirror. The diameter of the input beam is 9 μm and its numerical aperture is about 0.06. And the output light was then coupled into a photodetector through a 62.5/125 μm graded index (GI) multimode fiber. We measured the insertion losses of individual waveguides in the waveguide arrays. The measured insertion losses of the waveguides with 45° mirrors were 1.12 dB on average, whereas the insertion losses of the waveguides without 45° mirrors were 0.76 dB on average. The coupling loss for the silver-coated 45° micromirror was 0.36 dB, corresponding to a coupling efficiency of 92%; whereas the theoretical value is about 96% based on the tabulated refractive indices and extinction coefficients.[12] We also conducted experiments for Aluminum-coated micromir-

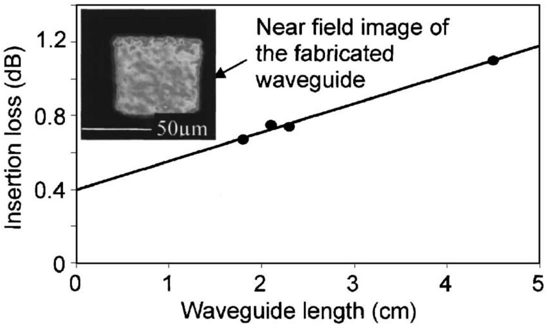

FIG. 4. (Color online) The insertion losses as a function of waveguide length.

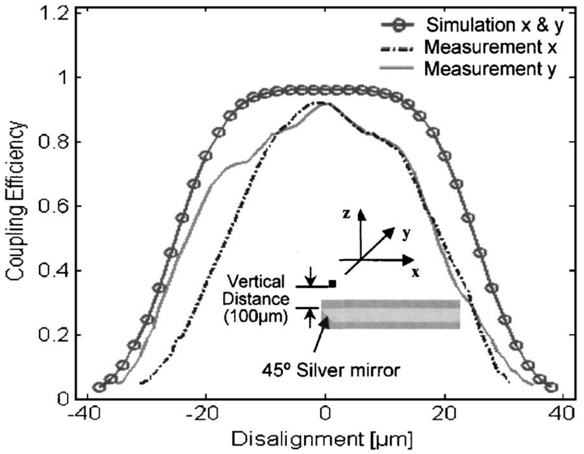

FIG. 5. (Color online) Optical misalignment of light source to waveguide by 45° silver coating micromirror at 100 μm vertical distance.

rors as well; the measured coupling efficiency was around 82%. The coupling efficiencies were almost same when the distance between the light source and mirror surface was less than 100 μm.

We conducted the experiments and simulations based on ray tracing to determine the optical misalignment tolerance in the x-axis (along the axis of the waveguide) and y-axis directions (perpendicular to the x-axis on the horizontal plane) of the waveguides. The measured data were obtained by light beam scanning over the 45° mirrors along both the x-axis and y-axis directions using a six-axis Newport Autoaligner at about 100 μm vertical distance between the light source and mirror surface. Figure 5 shows the reasonable agreement between the measured data and the simulation data with 850 nm wavelength from a VCSEL.

The polarization dependence loss (PDL) of the waveguides with 45° silver-coated micromirrors was found below 0.1 dB in all tested samples. For the silver coated micromirrors, the theoretical PDL values are between 0.11 dB and 0.15 dB for incident angles between 41.5° and 48.5°. Yet the mode mixing in multimode waveguides tends to wipe out the small polarization dependence originating from the micromirrors.

In summary, we report the employment of the soft molding to fabricate multimode polymer waveguide arrays with 45° micromirrors through one-step transfer. The measured propagation loss of the multimode waveguide was 0.16 dB/cm at 850 nm wavelength. The coupling efficiency of the 45° silver-coated micromirrors was measured to be 92%. The low-loss and thermally stable molded waveguides with high quality 45° micromirrors offer a low-cost solution to high-speed fully embedded boardlevel optical interconnects.

This work is supported in part by DARPA, Texas ATP program and AFRL. The authors acknowledge the generous support from the State of Texas and Sematech through the AMRC program. The fabrication and characterization facilities at UT MRC are supported by NSF through the NNIN program. We thank CNM, Welch Foundation and SPRING for partial support of the device characterization.

[1] R. T. Chen, L. Lin, C. Choi, Y. Liu, B. Bihari, L. Wu, S. Tang, R. Wickman, B. Picor, M. K. Hibbs-Brenner, J. Bristow, and Y. S. Liu, Proc. IEEE **88**, 780 (2000).
[2] E. M. Mohammed, T. P. Thomas, D. Liu, H. Braunisch, S. Towle, B. C. Barnett, I. A. Young, and G. Vandentop, Proc. SPIE **5358**, 60 (2004).
[3] G. V. Steenberge, P. Geerinck, S. V. Put, J. V. Koetsem, H. Ottevaere, D. Morlion, and P. V. Daele, J. Lightwave Technol. **22**, 2083 (2004).
[4] R. Yoshimura, M. Hikita, S. Tomaru, and S. Imamura, Jpn. J. Appl. Phys., Part 1 **37**, 3657 (1998).
[5] S. Lehniacher and A. Neyer, IEE Electronic Letters **36**, 1052 (2000).
[6] Y. Xia and G. M. Whitesides, Annu. Rev. Mater. Sci. **28**, 153 (1998).
[7] X. Zhao, S. P. Smith, S. J. Waldman, G. M. Whitesides, and M. Prentiss, Appl. Phys. Lett. **71**, 1017 (1997).
[8] H. Schroder, J. Bauer, F. Ebling, W. Scheel, First International IEEE Conference on Polymers and Adhesives in Microelectronics and Photonics, 337 (2001).
[9] C. Choi, L. Lin, Y. Liu, J. Choi, L. Wang, D. Haas, J. Magera, and R. T. Chen, J. Lightwave Technol. **22**, 2168 (2004).
[10] Y. S. Kim, J. Park, and H. H. Lee, Appl. Phys. Lett. **81**, 1011 (2002).
[11] W. Kim, J. Lee, S. Shin, B. Bea, and Y. Kim, IEEE Photonics Technol. Lett. **16**, 1888 (2004).
[12] D. R. Lide, *Handbook of Chemistry and Physics*, 85th ed. (CRC, Cleveland, 2004).