Optoelectronic Integration of Polymer Waveguide Array and Metal–Semiconductor–Metal Photodetector Through Micromirror Couplers

Yujie Liu, Lei Lin, Chulchae Choi, Bipin Bihari, and Ray T. Chen, *Senior Member, IEEE*

***Abstract*—We report the design and formation of a high-performance polymer waveguide array with 45° micromirror couplers for achieving fully embedded board-level optoelectronic interconnects. We have used Si CMOS process compatible polymer as the fabrication material, which is relatively easy to process and has low propagation loss at 850-nm wavelength. 45° total interior reflection (TIR) micromirror couplers fabricated within the channel waveguides provide surface-normal light coupling between the waveguide and the optoelectronic devices, thus forming a fully embedded three-dimensional optoelectronic interconnect. We have demonstrated a hybrid optoelectronic integrated system of GaAs MSM photodetector array and polymer channel waveguide array with 45° micromirror couplers, showing an aggregate 3-dB bandwidth of 32 GHz.**

***Index Terms*—45° micromirror coupler, optical interconnect, optoelectronics integration, polymer waveguide.**

IMPLEMENTATION of optoelectronic components in board-level interconnects is becoming necessary to keep up with rapidly growing bandwidth demands in data communications. Board-level optical interconnects are being vigorously investigated and are thought to be one of the most promising alternatives whenever conventional electrical interconnects fail to meet the requirements for bandwidth, packaging density, fanout, and power dissipation [1]–[4]. A fully embedded optoelectronic interconnection provides an opportunity to solve the bottleneck faced by conventional electrical interconnects at board level for high-performance computing systems. To realize a fully embedded structure, two components are crucial: an optical waveguide with low propagation loss, and a surface-normal optical coupler with high efficiency to provide light coupling between the waveguide and the optoelectronic devices. We have designed fully embedded optoelectronic interconnects and experimentally demonstrated the integration of channel waveguide array and metal–semiconductor–metal (MSM) photodetector array. We used Si CMOS process compatible polymer material to form the low-loss channel waveguide array, and fabricated 45° total interior reflection (TIR) micromirror couplers with a reactive ion etching (RIE) process to provide the surface normal light coupling. In this letter, the fabrication of waveguide array and micromirror couplers is described. The experimental results of the performance of the integrated system are also given.

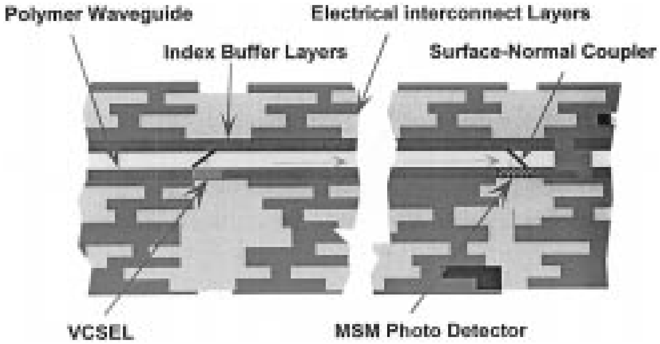

Fig. 1. Fully embedded electrical/optical interconnects on an MCM board.

In the multichip module (MCM) environment, where interconnect distances range from a few millimeters to tens of centimeters, optical interconnections offer significant advantages such as large bandwidth, low noise and low crosstalk, low power dissipation and large fanout capability [5]. Fig. 1 shows a schematic of fully embedded electrical/optical interconnects on an MCM board. In this scenario, one layer of optical interconnect is sandwiched between several electrical interconnect layers. Within the optical interconnect layer, light from the thin-film VCSEL is coupled into the waveguide through a surface-normal coupler and then travels in the polymer waveguide to the destination, where it is coupled out by another surface-normal coupler, and is detected by the MSM photodetector. The light signal is then converted to an electrical signal and sent to the receiving IC. The waveguide grating or waveguide mirror-based coupler can function as the surface normal coupler in this kind of integrated optoelectronic system. However, a grating-based approach requires precise control of grating parameters for efficient coupling and usually has low tolerance to wavelength variations [6]. Therefore, we employ a 45° TIR micromirror coupler because it is easy to fabricate, reproducible, relatively insensitive to wavelength variations, and can provide high coupling efficiency [7], [8].

Polyimides are the materials of choice for the waveguide fabrication in the optical interconnects layer due to their high optical transparency, high thermal stability, and ease of fabrication. Specifically, Ultradel 9120D and 9020D (Amoco Chemicals) show promising features for optical component fabrication [9]. These polyimides are negatively photosensitive; therefore, they can be patterned by conventional photolithography

Manuscript received August 3, 2000. This work was sponsored by the Defense Advanced Research Projects Agency (DARPA), Texas-ATP, BMDO, the Office of National Research (ONR), and RRI.

The authors are with the Microelectronics Research Center, The University of Texas at Austin, Austin, TX 78758 USA (e-mail: raychen@uts.cc.utexas.edu).

Publisher Item Identifier S 1041-1135(01)03105-6.

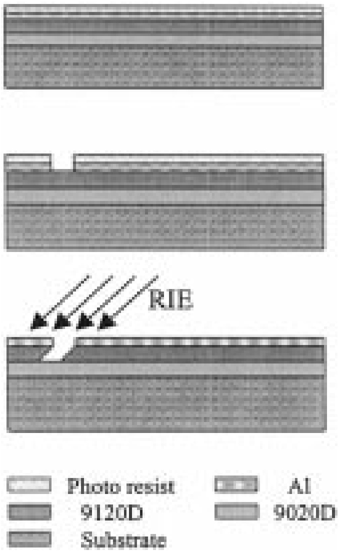

Fig. 2. Procedures to fabricate polymer channel waveguide with fully embedded 45° TIR micromirror coupler.

processes. The polyimides 9120D and 9020D having refractive index at the wavelength of 850 nm of approximately 1.56 and 1.54, respectively, (which can be tailored slightly by controlling the processing conditions) form waveguides with excellent propagation properties and light confinement. The propagation loss of the TE_0 mode in such polymer channel waveguide was measured to be 0.21 dB/cm at 850 nm and 0.58 dB/cm at 632.8 nm.

Fig. 2 shows the main processing steps for fabricating the polymer channel waveguide array and the 45° TIR micromirror couplers. To form the two-layer structured channel waveguides, we first spin-coat the substrate with a 6–7-μm-thick layer of 9020D, and perform a short soft-bake to remove the residual solvents. This layer acts as the buffer layer or bottom cladding. A similar process is carried out to forms a core layer of 6–7-μm-thick 9120D on the bottom cladding. Both layers are patterned through photolithography forming an array of channel waveguides with 50 μm width and 12–13 μm height. The length of the waveguide can be varied to satisfy the requirements of specific applications. The formed waveguide array has 250 μm center-to-center separation between adjacent channels. 45° TIR micromirror couplers are formed within the channel waveguide by reactive ion etching (RIE) technique. A layer of 0.3-μm-thick aluminum deposited on the surface serves as the protective mask in the RIE process. Using photolithography and wet etching, a $50\ \mu\mathrm{m} \times 50\ \mu\mathrm{m}$ square window is opened in the aluminum layer at the end of each channel, where the micromirror is to be etched. During the RIE process, the sample is placed at a 45° angle with respect to the electrode in the chamber. A Faraday cage [10], [11] covers the sample so that the directional high-speed ions attack the polymer at a 45° angle with respect to the substrate through the square openings. This process results in a 45° slanted etched surface formed on each channel waveguide, which can provide input or output surface-normal coupling of light into or out of a channel waveguide.

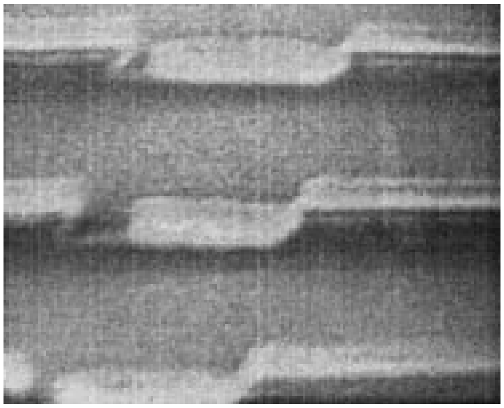

Fig. 3. SEM microphotograph of polymer channel waveguide array with fully embedded 45° TIR micromirror coupler.

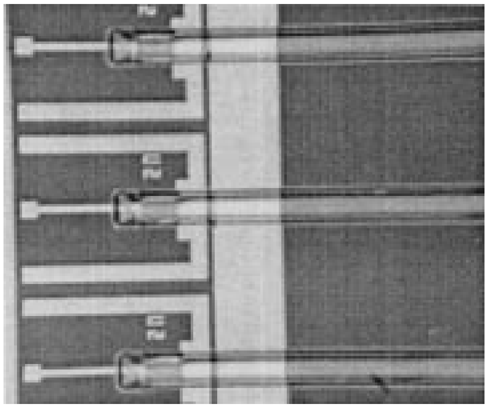

Fig. 4. Polymer channel waveguide array aligned with MSM photodetector array.

The RF power, gas flow rate, and chamber pressure in RIE determine the etching rate and quality of the mirror surface. Low pressure in the RIE chamber is critical to obtaining a high-quality mirror surface. At low gas pressure, the reactive ions have a longer free path, and, therefore, better anisotropic etching is achieved. In our process, the pressure maintained in the chamber during etching was 10 mtorr, the RF power 150 W, and the oxygen flow rate (the etchant gas) 20 sccm. After RIE process, the aluminum mask was removed through wet etching. Fig. 3 shows an SEM photograph of a portion of the device made by this technique. The etched mirrors are approximately 7 μm deep.

For demonstrating an optoelectronic interconnection employing this structure, we integrated the polyimide channel waveguide array with a 1×12 GaAs MSM photodetector array through 45° TIR micromirror couplers. We first fabricated on the GaAs substrate the high-speed MSM photodetector array. Each photodetector has an active area of $50\mu\mathrm{m} \times 50\mu\mathrm{m}$. The details of the MSM photodetector array fabrication have been reported separately [12]. The polymer channel waveguide array was fabricated on the substrate containing photodetector array such that the active area of detectors overlap with waveguide output couplers. A photograph of a portion of the integrated system is shown in Fig. 4. 45° TIR micromirror couplers were formed on each channel at the position directly above the active

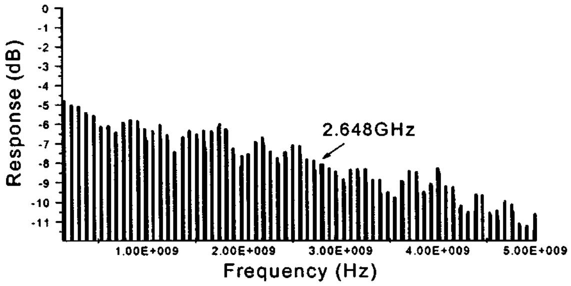

Fig. 5. Frequency response of the optoelectronic integrated system.

area of the photodetector. Such an integration facilitates precise alignment of the light coupler with the receiver, avoiding difficult optical alignment and packaging processes.

To characterize this integrated system, we polished the input ends of the channel waveguides and used a single mode fiber to butt-couple the light into the waveguide. When the light propagating in the channel waveguide arrives at the 45° TIR micromirror couplers, it is reflected to the MSM photodetector beneath the coupler. The photocurrent was monitored by an Ampere meter, and the signal received by the photodetector was analyzed by a spectrum analyzer. Fig. 5 shows the frequency response of this integrated optoelectronic system, from which we obtained the 3 dB bandwidth of the integrated system as 2.648 GHz. The demonstrated waveguide array with microcouplers provides an efficient interconnects among the optoelectronic devices, without severely degrading their performance, and a feasible method to build high-speed optoelectronic integrated systems.

In summary, we developed a technology to form polymer channel waveguide array with 45° TIR micromirror couplers, a component which has promise to realize efficient board-level optoelectronic interconnects. We also demonstrated experimentally an integrated optoelectronic system to transmit optical signals through channel waveguides to the MSM photodetector array. The system shows high-speed performance and the 3-dB bandwidth of 2.648 GHz per channel. The aggregate 3-dB bandwidth of the 1×12 array is 32 GHz.

ACKNOWLEDGMENT

The authors thank B. Cavanagh for her helpful suggestions for the manuscript.

REFERENCES

[1] L. A. Hornak, S. K. Tewksbury, T. W. Weidman, and E. W. Kwock, "Advanced interconnection technologies and system-level communications functions," in *IEEE VMIC Conf.*, June 12–13, 1989, pp. 211–225.

[2] J. W. Goodman, F. J. Leonberger, S. Y. Kung, and R. A. Athale, "Optical interconnections for VLSI systems," *Proc. IEEE*, vol. 72, pp. 850–866, July 1984.

[3] M. R. Feldman, S. C. Esener, C. C. Guest, and S. H. Lee, "Comparison between optical and electrical interconnects based on power and speed considerations," *Appl. Opt.*, vol. 27, no. 9, pp. 1742–1751, 1988.

[4] R. T. Chen, "Polymer-based photonic integrated circuits," *Opt. Laser Technol.*, vol. 25, no. 6, pp. 347–365, 1993.

[5] P. Cinato and K. C. Young, Jr., "Optical interconnections within multichip modules," *Opt. Eng.*, vol. 32, no. 4, pp. 852–860, 1993.

[6] R. Waldhäusl, B. Schnabel, P. Dannberg, E. B. Kley, A. Bräuer, and W. Karthe, "Efficient coupling into polymer waveguides by gratings," *Appl. Opt.*, vol. 36, no. 36, pp. 9383–9390, 1997.

[7] J. Miller, N. de Beaucoudrey, P. Chavel, J. Turunen, and E. Cambril, "Design and fabrication of binary slanted surface-relief gratings for a planer optical interconnection," *Appl. Opt.*, vol. 36, no. 23, pp. 5717–5727, 1997.

[8] J. Gan, L. Wu, H. Luan, B. Bihari, and R. T. Chen, "Two-dimensional 45° surface-normal microcoupler array for guided-wave optical clock distribution," *IEEE Photon. Technol. Lett.*, vol. 11, pp. 1452–1454, Nov. 1999.

[9] Y. S. Liu, W. B. Hennessy, R. J. Wojnarowski, J. P. Bristow, Y. Liu, J. R. Rowlette, J. D. Stack, J. T. Yardley, L. A. Eldada, R. M. Osgood, R. Scarmozzino, S. H. Lee, and S. K. Patra, "Optoelectronic backplane interconnect technology development," in *Proc. SPIE, Optoelectronic Interconnects and Packaging IV*, vol. 3005, 1997, pp. 2–10.

[10] G. D. Boyd, L. A. Coldren, and F. G. Storz, "Directional reactive ion etching at oblique angles," *Appl. Phys. Lett.*, vol. 36, no. 7, pp. 583–585, 1980.

[11] B. O. Cho, S. W. Hwang, J. H. Ryu, I. W. Kim, and S. H. Moon, "Fabrication method for surface gratings using a Faraday cage in a conventional plasma etching apparatus," *Electrochem. Solid-State Lett.*, vol. 2, no. 3, pp. 129–130, 1999.

[12] L. Lin, C. C. Choi, Y. Liu, and R. T. Chen, "High-speed Si MSM photodetector and VCSEL for optoelectronic interconnects," *Proc. SPIE*, vol. 3952, pp. 312–317, Apr. 2000.