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Short Note

Hybrid Integration of 1 × 12 Metal–Semiconductor–Metal Photodetector and Polyimide Waveguide Array

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We report here a demonstration of hybrid integration of a 1 × 12 metal–semiconductor–metal (MSM) photodetector array and polyimide channel waveguides via 45° total-internal-reflection (TIR) micro-couplers. The two-layer polyimide waveguide array was constructed using Ultradel 9120D for the core and Ultradel 9020 for the lower cladding layer. The coupling loss and propagation loss of the waveguide are 0.2 dB and 0.21 dB/cm, respectively. The cross talk of the adjacent channels is −32 dB. The MSM photodetector array was fabricated on a semi-insulated GaAs wafer. The photodetectors are integrated to operate in the conventional vertical illumination mode. We measured the external quantum-efficiency and 3 dB bandwidth of the integrated MSM photodetectors at 0.4 A/W and 2.648 GHz, respectively. The aggregate 3 dB bandwidth of the 12-channel integrated system is 32 GHz.

Key words: MSM photodetector, optical interconnect, polymer waveguide, integrated system, mirror coupler

The speed and complexity of integrated circuits have increased rapidly in recent years, and this trend continues. With the increase in the number of components per chip, chips per board, the clock speed, and the degree of integration, electrical interconnects which rely primarily on metallic (aluminum/copper) or poly-silicon lines are approaching fundamental limitations of speed, packaging density, fan-outs, and power dissipation.[1,2] The Semiconductor Industry Association (SIA) road map for CMOS technology predicts that by the year 2009 more than 5000 chip I/O's (pads) will be required and off chip (chip to board) clock rates will reach 2–3 GHz.[3] Conventional electrical interconnects are unable to offer this high-frequency and wide-band performance due to poor isolation at frequencies greater than a few giga-hertz. Furthermore, it is extremely difficult for multiprocessor computing systems involving a large number of fan-outs and long interconnection lengths (>15 cm) to obtain synchronous high-speed (>500 MHz) clock distribution using electrical interconnections.[4] Recently, there has been emphasis on the employment of optical technology for improving the connection of devices on a signal chip and between chips on a multi-chip-module.[5,6] Just as fiber optics offers advantages in long-haul communication systems, optical interconnection promises benefits for the future in computer system communication. Its potential advantages include large bandwidth, no capacitive loading, immunity from electromagnetic interference (EMI), and inherent parallelism. Thus it can facilitate communication within computers by means of its high speed, high capacity and high component-packaging density. In contrast to electrical interconnections, the optical interconnection transmits information at a higher data rate, consumes less power, and occupies less real estate on the board for circuits requiring complex interconnections. Because of the dominance of silicon CMOS technology, however, the system under investigation should have the potential of integrating with today's silicon technology.

In this paper, we present a new system architecture to fulfill such a scheme. Unlike the previous approaches,[7,8] a fully embedded board-level guided-wave optical interconnection is shown in Fig. 1. The three main parts of the system are the thin film MSM photodetector array, the thin film vertical cavity surface emitting laser (VCSEL) and the multi-mode polyimide waveguide array with 45° micro-couplers. The pulsed laser light from the VCSEL is normally coupled into the multi-mode waveguide through a 45° TIR micro-coupler. It propagates through the waveguide, then is reflected at the output interface of the waveguide by another 45° TIR micro-coupler, and finally is illuminated vertically on the active area of the photodetector. The driving circuit of the VCSEL and the amplifying circuit of the photodetector are located on the surface of the PC board. The two circuits connect the VCSEL and photodetector through electrical vias. In this way, all the opto-electronic parts are buried under layers of PC board. These buried parts improve the performance without occupying the PC-board surface or interfering with the function of the electrical parts.

To test the feasibility of the new architecture, we demonstrate a preliminary integration of multi-channel optical interconnect between a GaAs-based MSM photodetector array and multi-mode waveguides with TIR micro-couplers. Fig. 2 illustrates the schematic of this integration. The two main parts of the integration are the 1 × 12 MSM photodetector array and the multi-mode polyimide waveguide array with 45° micro-couplers. The center-to-center distances between detectors in the 1 × 12 MSM photodetector array and channel spacing in the waveguide array are all 250 μm. Each detector in the array has an active area of 50 × 50 μm. The waveguide array channels are 50 μm wide and 13 μm deep. Having coupled into one end of the waveguide, the pulse laser light propagates through the waveguide, reflects at the 45° TIR micro-coupler and illuminates the surface normally on the active area of the photodetector.

The good coupling efficiency of the 45° TIR micro-

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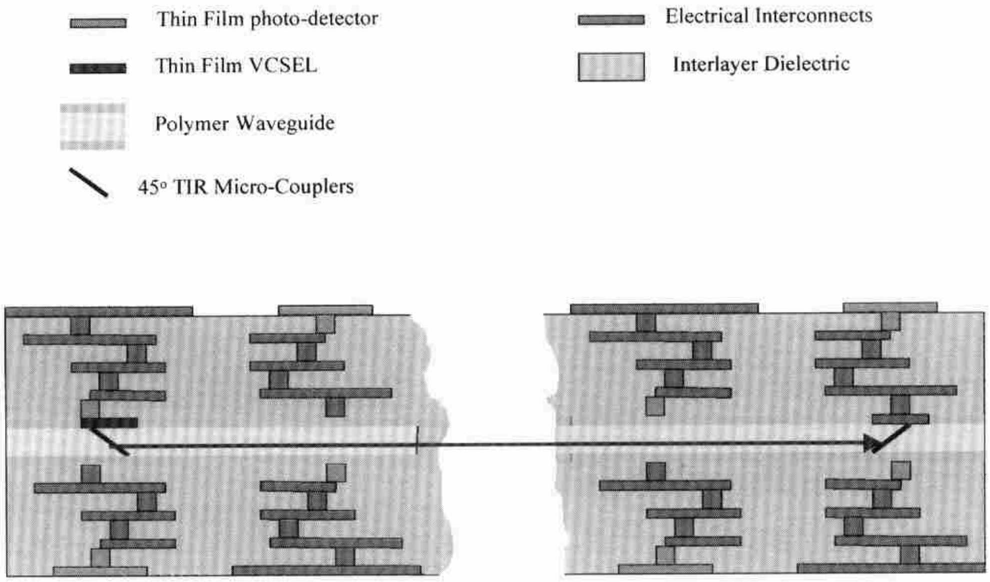

Fig. 1. System architecture of fully embedded optical interconnect.

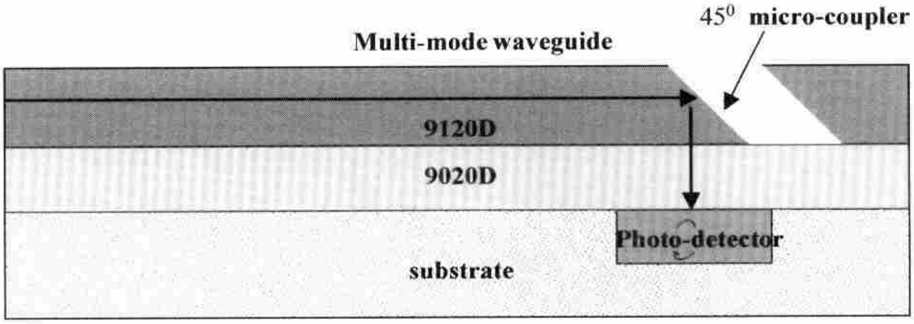

Fig. 2. Schematic of system integration.

coupler makes this three-dimensional optical interconnect possible. When a laser pulse illuminates the active area of the photodetector, electron-hole pairs are generated inside GaAs. By providing the proper biasing voltage, the electron-hole pairs are collected by the inter-digitated electrodes. The high-frequency electrical signals resulting from this process are sent out to the external IC circuit. The integrated array of MSM photodetector and polyimide channel waveguides with micro-couplers are critical components for implementing very dense guided-wave optical interconnects. Compared to free space optical interconnects, guided wave optical interconnects achieve higher package density, have an easier fabrication process and offer more relief for alignment of different components than free-space optical interconnects.[9,10] thereafter, we describe the fabrication procedures and the experimental characteristics of the integrated system.

To fabricate the 1 × 12 MSM photodetector array, the 100 nm thick SiO_2 was first deposited on the surface of a semi-insulating LEC-grown GaAs (100) wafer by plasma-enhanced chemical vapor deposition (PECVD). The inter-digitated electrode pattern was formed by the conventional photolithography technique and then the finger part of SiO_2 was etched away using 1 : 6 oxide etchant. The inter-digitated gold electrodes were formed by depositing 100 nm gold directly on the surface of the GaAs wafer using electron beam evaporation; these form the Schottky contacts between GaAs and gold. The inter-digitated contacting fingers have the same 2 μm width and spacing, resulting in a relative photosensitive area of 50%. Fig. 3 is a SEM photograph of the active area of a single MSM photodetector. Finally, 100 nm of gold was deposited and then lift-off to form a contacting pad for probing the devices. After fabricating the photodetector, the channel waveguide array of polyimide was built on top of the MSM photodetector array, as shown in Fig. 4. The VLSI-compatible fabrication process was used to construct the multi-mode channel waveguides with 45° TIR micro-mirrors. The two-layer polyimide waveguides consist of 6–7 μm thick Ultradel 9020D as a buffer layer and the same thickness 9120D layer as a core layer. The 45° micro-couplers were formed by reactive ion etching (RIE). The coupling efficiency of the 45° micro-coupler was experimentally estimated to be nearly 100%.[11] The polyimide waveguide array was aligned with the MSM photodetector array by the conventional microelectronic process. We measured the propagation loss of the TE_0 mode of polyimide waveguide array as 0.21 dB/cm at 850 nm. The

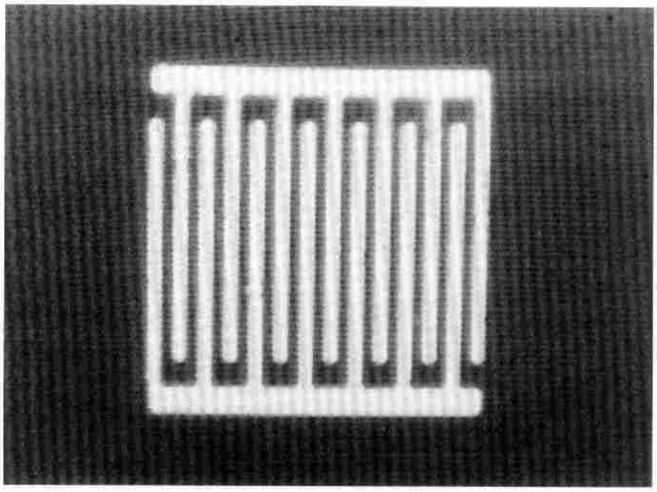

Fig. 3. SEM photograph of the MSM photodetector with 2 µm figure width and spacing.

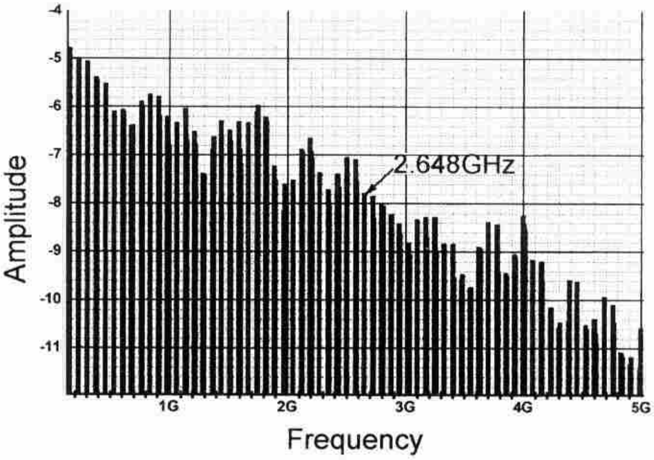

Fig. 5. The frequency response of integrated MSM photodetector and polyimide waveguide with 45° TIR mirror. The 3 dB bandwidth is 2.648 GHz.

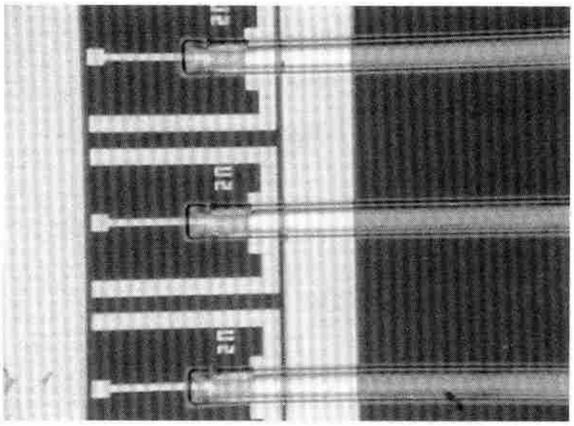

Fig. 4. MSM photodetector array integrated with polyimide channel waveguides with 45° micro-coupler.

coupling loss and crosstalk were measured to be 0.2 dB and −32 dB respectively. Details of the fabrication process and the analysis of polyimide waveguide array with 45° micro-couplers are reported elsewhere.[12]

The DC *I–V* characteristics of the MSM photodetector was measured to obtain the dark current before it was integrated with the polyimide waveguide array. The dark current was measured by a semiconductor parameter analyzer. The device exhibited a dark current of 4.6 pA under 5 V biasing voltage. The frequency dependence of the photo-response of the MSM photodetector and polyimide waveguide was measured by using a spectra-analyzer operating over a frequency range from 9 k to 26 GHz. The light source for frequency response measurement was a Ti:sapphire mode-locked laser operating at 800 nm with a pulse width of about 150 fs and a repetition rate of 76 MHz. We used an optical attenuator to attenuate the laser power from its original 200 mW to 10 mW before it was coupled into the waveguide array. An ampere-meter was serially connected between the contact-probe and biasing DC power supply. Validation of the coupling laser light into the channel waveguide array and vertical illumination on the active area of the MSM photodetector was demonstrated by measuring the photo-current of the photodetector, usually around 10–20 µA. A 40 GHz ground-signal-ground (GSG) microwave probe was used for the device contact. The biasing voltage was provided by DC power supply through a 100 k–18 GHz biasing tee. The pulsed laser light was butt-coupled into the input end of the waveguide array through a bare, cleaved-end, single-mode fiber. At the output end the guided light was reflected from the 45° micro-coupler onto the active area of the photodetector. The optical input pulses and the complete measurement system were calibrated using a 30 GHz bandwidth photodetector module. The 3 dB bandwidth of a single MSM detector was 2.648 GHz, as shown in Fig. 5. The aggregated bandwidth of the 1 × 12 photodetector array is 32 GHz. The 3 dB bandwidth of the photodetector had been measured before it was integrated with the waveguide array and micro-coupler, and was found to be 3.0 GHz at 5 V biasing-voltage. The small reduction in the bandwidth of the detector after the integration process may be due to a slight change in the Schottky barrier at the interface between gold and GaAs while the polyimide waveguide array and photodetector array were cured at 200°C for 30 min.

In summary, we have demonstrated the fabrication of a MSM photodetector array integrated with polyimide channel waveguides and 45° micro-couplers. To the best of our knowledge, this is the first demonstration of such integration. The Si-CMOS compatible process was used in fabricating the photodetector array, polyimide channel waveguides and 45° micro-couplers. Pulsed laser light at 800 nm was efficiently coupled into the active area of the photodetector through a 45° micro-coupler. The array MSM photodetector exhibited a low 4.6 pA dark current. A single MSM photodetector exhibited a 3 dB bandwidth of 2.648 GHz, resulting in a total aggregated bandwidth of 32 GHz for a 12-channel integrated system. The three dimensional architecture of this optical interconnect system is advantageous for intra-chip, inter-chip, and inter-board interconnects.

References

1) M. Ishikawa and N. McArdle: IEEE J. Quantum Electron. **5** (1999) 250.
2) C. Lund: Proc. 4th Int Conf Massively Parallel Processing Using Optical Interconnections, 1997, p. 156.
3) Semiconductor Industry Association: The National Technology Roadmap for Semiconductors, 1997.
4) R. T. Chen and L. Wu: Proc. 4th Int. Conf. Massively Parallel Processing Using Optical Interconnections, 1997, p. 10.
5) T. Maj, A. G. Kirk and D. V. Plant: Appl. Opt. **39** (2000) 683.
6) S. Matsuo and T. Nakahara: IEEE Photon. Technol. Lett. **7** (1995) 1165.
7) Y.-S. Liu, B. Robertson, G. C. Boisset, M. H. Ayliffe, R. Iyer and D. V. Plant: Appl. Opt. **37** (1998) 2895.
8) M. H. Ayliffe, D. Kabal, F. Lacroix, E. Bernier, P. Khurana, A. G. Kirk, F. A. P. Tooley and D. V. Plant: J. Opt. A **1** (1999) 267.
9) O. Sjolund, D. A. Louderback, E. R. Hegblom, J. Ko and L. A. Coldren: IEEE J. Quantum Electron. **35** (1999) 1015.
10) D. A. Louderback, O. Sjolund, E. R. Hegblom, S. Nakagawa, J. Ko and L. A. Coldren: IEEE J. Quantum Electron. **5** (1999) 157.
11) J. Gan, L. Wu, H. Luan, B. Bihari and R. T. Chen: IEEE Photon. Technol. Lett. **11** (1999) 1452.
12) Y. Liu: Proc. SPIE **3950** (2000) 210.