A Single-Fiber Bidirectional Optical Link Using Colocated Emitters and Detectors

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Abstract—**This letter reports the bonding of a small, thin-film GaAs-based emitter onto a larger silicon detector to realize spatial colocation of the emitter and detector. These colocated devices enable single fiber bidirectional communication between the two analog/digital silicon circuits that contain the emitter/detector pairs. Bidirectional communication between two of these circuits is demonstrated with a single plastic optical fiber.**

I. Introduction

OPTICAL signals have traditionally traveled in only one direction through optical fiber. Bidirectional transmission requires an emitter and detector at each end of the fiber. An emitter and detector can be the same device, by switching between forward and reverse bias. However, the speed and device optimization limitations of this approach make it impractical. Alternatively, waveguide splitters can be used to separate the emitter and detector [1]–[4]. In this letter, a single fiber bidirectional link for an automotive optical interconnect is reported that uses the colocation of an emitter and detector at each end of the fiber, thus eliminating the need for splitters at both ends.

The bidirectional optical link reported herein includes a thin-film emitter integrated onto a silicon detector, analog optoelectronic transceiver interfaces, and digital signal processing circuitry. To colocate the optoelectronic devices, a thin-film GaAs-based light emitting diode was bonded into the center of a silicon CMOS bipolar junction detector, as shown in the photograph in Fig. 1. In this demonstration, a large core plastic optical fiber with a diameter similar to the detector size was used. To realize a fully functional communication link, CMOS analog optoelectronic receiver and transmitter circuits which had digital input/output were fabricated adjacent to the silicon detector. Digital circuitry for multiplexing, data sampling and encoding, and microprocessor interfacing were also included in this silicon integrated circuit.

II. Fabrication

For this system an $Al_{0.3}Ga_{0.7}As$–GaAs double heterostructure light emitting diode (LED) was designed and grown for integration with the silicon circuit. The device structure was composed of a 100 Å highly doped p-type GaAs contact layer, a 2.24-μm p-type $Al_{0.3}Ga_{0.7}As$ buffer layer, a 5000-Å intrinsic GaAs active layer, a 2.24-μm n-type $Al_{0.3}Ga_{0.7}As$ injection layer, and a 100 Å highly doped n-type GaAs contact layer. This structure was grown on top of a 2000-Å AlAs sacrificial etch layer on a GaAs substrate. The AlAs layer was the etch stop layer or sacrificial layer which enabled the separation of the epitaxial device layers from the growth substrate. To create the thin-film devices, the LED structure was mesa etched to define the devices, coated with a handling layer to protect the devices, and the AlAs was laterally etched to separate the thin-film devices from the growth substrate [5]. The devices were then bonded to a transfer diaphragm for subsequent bonding to the silicon circuit [6].

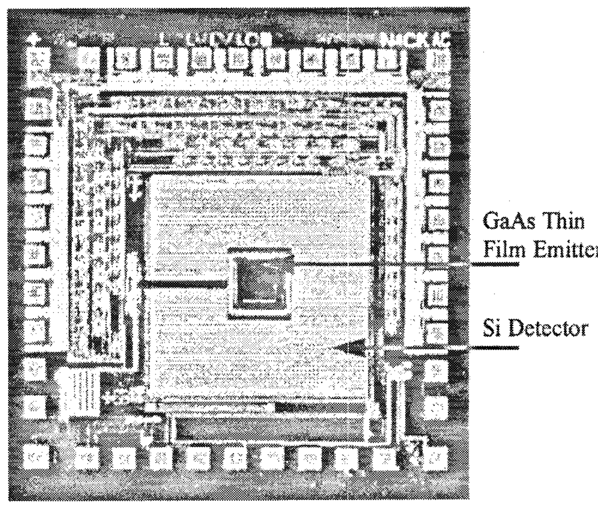

Fig. 1. Photograph of the hybrid integrated CMOS circuit where the LED is in the center of the phototransistor detector array.

The silicon detector was a 1 mm × 1 mm array of phototransistors with the base current controlled by the input optical signal. The lateral bipolar phototransistor [7] is illustrated in Fig. 2. This photodetector was sufficient for absorbing wavelengths approximately less than 1 μm, but due to the CMOS circuit process, only small junction depths were available, which limited the absorption length. In addition, the absorption coefficient for silicon is low compared to GaAs, and as a result, the responsivity of Si detectors are often small. Thus, the use of a bipolar junction transistor with the photocurrent injected into the base produced a gain in the photodetector that compensated for the low responsivity. As

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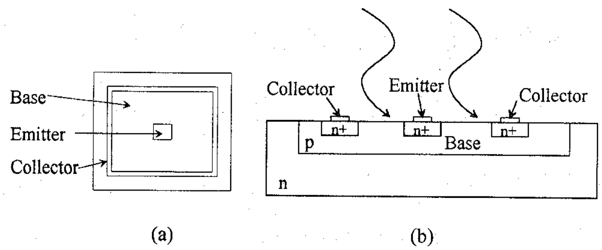

Fig. 2. Silicon CMOS bipolar junction phototransistor: (a) Top view and (b) cross-sectional view.

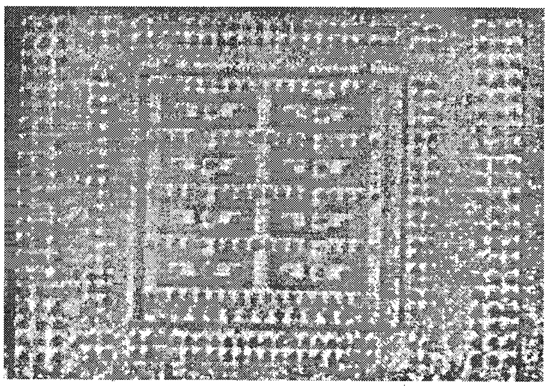

Fig. 3. Photograph of 2 × 4 array of phototransistors in Si CMOS.

shown in Fig. 2, the silicon photodetector was composed of a small n-type central emitter diffusion, a large area p-type base diffusion, and a ring electrode n-type collector. Fig. 3 is a photograph of a 2 × 4 array of these detectors fabricated in 2-μm silicon CMOS.

The thin-film GaAs-based LED was bonded directly into the center of the silicon detector array. The silicon circuit was fabricated in 1.2-μm CMOS by the MOSIS foundry. The 1 mm × 1 mm silicon detector array contained a 300 μm× 300 μm hole in the center to accommodate the emitter. A metal pad in the central detector hole served as the bottom contact for the LED, and a bar electrode for the top LED contact was located at one edge on the outer perimeter of the detector. Overglass cuts to these two contact pads were included in the circuit design. The bottom LED contact on the silicon circuit was metallized with Ti–Au (500/1500 Å), and the thin-film LED was aligned and bonded to this pad. Polyimide was used to electrically isolate the top and bottom contacts, and windows in this polyimide for the top contact were subsequently opened using reactive ion etching [8]. The AuGe–Ag–Au (800/800/1800 Å) top contact was then deposited onto the LED/circuit, completing a contact between the bar pad on the circuit and the top of the LED, as shown in Fig. 1.

The interface chip was fabricated using MOSIS 1.2 μm Si CMOS technology, and incorporates both digital and analog circuitry. The analog components included the detector amplifier, the emitter driver, and the analog-to-digital converter. The detector is followed by a large gain amplifier that, using an off-chip bias current, provides a binary signal corresponding to the incident light from the fiber. The maximum operating frequency of the system is 50 kHz and is slew rate limited by the large gain, low bandwidth amplifier. To drive the transmitter, inputs composed of on-chip digital and off-chip analog signals were used. The off-chip analog signal was converted to a digital signal for optical transmission using an analog-to-digital converter that utilized single-slope integration. To tune the transmitter and receiver circuits, the emitter driver and detector amplifier contained analog bias signals.

The digital circuitry was responsible for sampling, assembling, and encoding the serial data stream. The input control signals to be optically transmitted were multiplexed and encoded into a single serial data stream using a return-to-zero (RZ) protocol. The frequency of this data stream was 6.4 kHz. The digital circuitry accepted a variety of inputs, including the on-chip signals from the analog circuitry (7 low-speed and 1 high-speed timer). All of the control signals required for sampling the external inputs and creating the data stream were generated from a 13-b counter. The serial data stream was packaged into frames, each with four 8-b partitions. The A/D converter was under the control of the digital circuitry, and used two data partitions, one for the input signal and one for the reference signal. With this scheme, higher precision can be achieved in the analog to digital conversion. External circuitry included a crystal oscillator and an HC11 microcontroller at one end of the link for decoding the received protocol. All of the circuits operated at 5 V.

III. Results

After the circuits were integrated, each circuit was initially tested before packaging to verify the function of the integrated emitter, and were then subsequently packaged and tested as a link. The emitter was initially tested by probing one external and one internal pad to measure an I–V characteristic and to visibly observe emission with an infrared camera. The integrated optoelectronic circuits (OEIC's) were then wire bonded into 40-pin dual inline pin (DIP) packages, and were inserted into a test fixture. The inputs for the experimental setup were a crystal oscillator, an 8-b DIP switch and two variable resistors. These provided the signals that the integrated OEIC's multiplexed for serial transmission. Using two XYZ stages, a 0.98-mm core plastic optical fiber (POF) was positioned above the LED and the detector, roughly centered on the emitter/detector pair. As the serial data stream was transmitted from one chip (Chip A in Fig. 4), the received signal from the detector on the other chip (Chip B in Fig. 4) was decoded using a HC11 microprocessor. Fig. 4(a) shows the received signal, the input signal and the reference trigger for this experiment. The same procedure was used to test transmission from Chip B to Chip A, as shown in Fig. 4(b). The top oscilloscope trace (received signal) in Fig. 4(b) was inverted.

IV. Conclusion

A single-fiber bidirectional link which uses the colocation of an emitter and detector at each end of the fiber is reported in this letter. To colocate the optoelectronic devices, a small thin-film GaAs-based light emitting diode was bonded into the center of a larger silicon bipolar junction detector. To

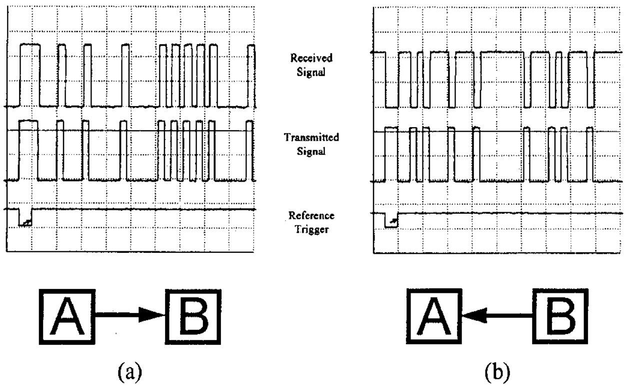

Fig. 4. Oscilloscope traces showing the received signal, the transmitted signal, and the reference trigger for transmission from one chip to another.

realize a fully functional communications link, CMOS analog optoelectronic receiver and transmitter circuits which had digital input/output were fabricated adjacent to the silicon detector. Digital circuitry for multiplexing, data sampling and encoding, and microprocessor interfacing were also included in this silicon integrated circuit.

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REFERENCES

[1] G. M. Foster, J. R. Rawsthorne, J. P. Hall, M. Q. Kearley, and P. J. Williams, "OEIC WDM transceiver modules for local access networks," *Electron. Lett.*, vol. 31, pp. 132–133, 1995.

[2] N. J. Frigo, P. P. Iannone, P. D. Magill, T. E. Darcie, M. M. Downs, B. N. Desai, U. Koren, T. L. Koch, C. Dragone, H. M. Presby, and G. E. Bodeep, "A wavelength-division multiplexed passive optical network with cost-shared components," *IEEE Photon. Technol. Lett.*, vol. 6, pp. 1365–1367, 1994.

[3] N. A. Rabou, H. Ikeda, and H. Yoshida, "Optical fiber two-way fm video signal transmission for video conferencing applications," *IEEE Trans. Consumer Electron.*, vol. 40, pp. 492–496, 1994.

[4] J.-P. Goedgebuer, A. Hamel, and H. Porte, "Full bidirectional fiber transmission using coherence-modulated lightwaves," *IEEE J. Quantum Electron.*, vol. 28, pp. 2685–2691, 1992.

[5] E. Yablonovitch, T. Gmitter, J. P. Harbison, and R. Bhat, "Extreme selectivity in the lift-off of epitaxial GaAs films," *Appl. Phys. Lett.*, vol. 51, pp. 2222–2224, 1987.

[6] C. Camperi-Ginestet, M. Hargis, N. M. Jokerst, and M. Allen, "Alignable epitaxial liftoff of GaAs materials with selective deposition using polyimide diaphragms," *IEEE Photon. Technol. Lett.*, vol. 3, pp. 1123–1126, 1991.

[7] C. Mead, *Analog VLSI and Neural Systems*. Reading, MA: Addison-Wesley, 1989.

[8] S. M. Fike, B. Buchanan, N. M. Jokerst, M A. Brooke, T. G. Morris, and S. DeWeerth, "8 $*$ 8 array of thin-film photodetectors vertically electrically interconnected to silicon circuitry," *IEEE Photon. Technol. Lett.*, vol. 7, pp. 1168–1170, 1995.