3-D Integration of MQW Modulators Over Active Submicron CMOS Circuits: 375 Mb/s Transimpedance Receiver–Transmitter Circuit

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Abstract— We accomplish the integration of GaAs–AlGaAs multiple quantum well modulators directly on top of active silicon CMOS circuits. This enables optoelectronic VLSI circuits to be achieved and also allows the design and optimization of the CMOS circuits to proceed independently of the placement and the bonding of surface-normal optical modulators to the circuit. Using this technique, we demonstrate operation of a 0.8 micron CMOS transimpedance receiver-transmitter circuit at 375 Mb/s.

THE EFFICACY of many system designs based on free-space optical interconnects depends on the availability of a flexible, high-density, silicon-compatible, optoelectronic technology platform. To this end, we demonstrate the hybrid three-dimensional (3-D) integration of reflection-mode, surface-normal GaAs–AlGaAs 850 nm multiple-quantum-well (MQW) absorption modulators directly over active 0.8 μm silicon CMOS circuits. Fig. 1 shows the structure of the resulting device. To test this technique, an MQW modulator used as an input light detector was flip-chip bonded [1] on top of a transimpedance receiver circuit, whose output was fed to a simple transmitter circuit and then to another SEED device that served as an output-light modulator. Fig. 2 shows a microphotograph of the fabricated circuit. The MQW diode was bonded directly over the circuit. The bonding pad on the silicon circuit was designed in the third-level metal; an opening in the uppermost passivation layer allowed for deposition of the Ti–Ni–Au wetting metal alloys and solder. After the alignment and bonding of the silicon and GaAs chips was completed, epoxy was flowed in-between the chips to act as an etch-protectant, and the substrate was removed to expose the reflection-mode quantum-well modulators as detailed in [1]. Several chips with modulators bonded directly over various logic circuits were implemented. These included flip-flops, ring-oscillators, and a 2 Kb first-in, first-out buffer with 64 optical input/outputs [2]. The MQW
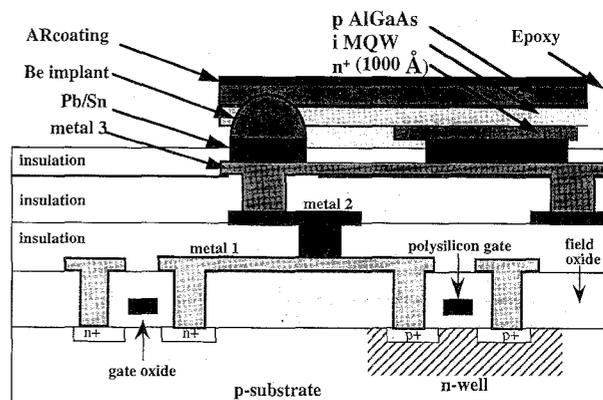
Fig. 1. Structure of the hybrid GaAs MQW/silicon CMOS circuit. Modulators may be bonded directly over active gates.
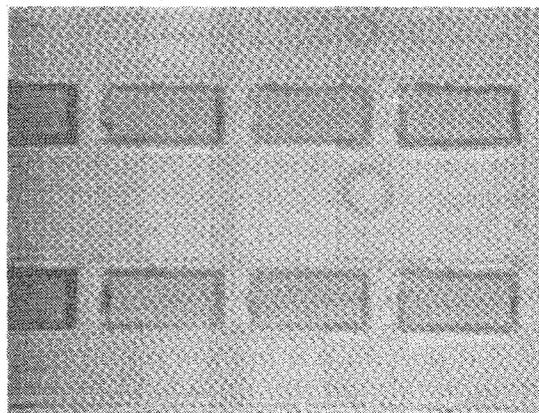

Fig. 2. Microphotograph of fabricated circuit showing MQW modulators bonded directly over active CMOS circuits. Receiver-transmitter circuits are on the right and VLSI logic circuits are on the left.

modulators were approximately 20 μm $\times$ 45 μm, and had a dark current of approximately 10 nA (with 10 V reverse bias) and a responsivity of approximately 0.45–0.5 A/W when used as detectors. In each case, the circuit's operation and performance was unaffected by the bonding and substrate removal operations. Here, we report on a simple optical receiver-transmitter circuit.

The receiver-transmitter circuit [Fig. 3(a)] was 17 μm $\times$ 18 μm. A transimpedance configuration was used because it
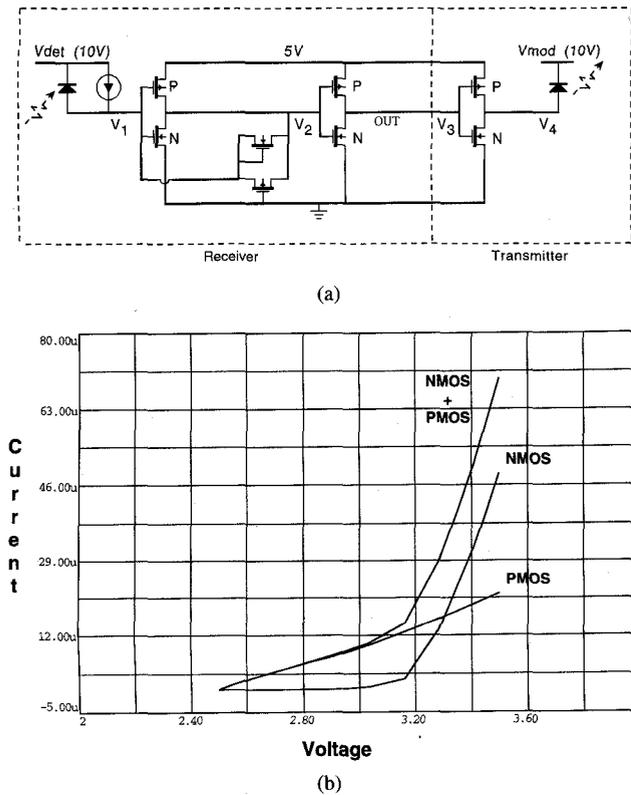
(a)

Voltage

(b)

Fig. 3. (a) Transimpedance receiver circuit diagram. V_{det} and V_{mod} are, respectively, the detector and modulator bias voltages (b) dc characteristics of the feedback element used in the transimpedance receiver. The feedback element is a parallel combination of pmos and nmos devices.

provided good sensitivity and dynamic range, and because it allowed the receiver's bandwidth to be increased, compared to an equivalent high-impedance (integrating) configuration, by the open-loop gain of the circuit. The input stage of the receiver consisted of the reverse-biased MQW diode connected to an inverter. A single amplification stage was used to limit dc power consumption to approximately 3.5 mW (0.7 mA static current). The transimpedance feedback to this stage was accomplished using a parallel combination of a diode-connected nmos device (gate attached to drain) with a pmos device. Fig. 3(b) shows a dc SPICE simulation of the feedback element used in the transimpedance receiver. For high optical power (input current) levels, the nmos device extends the usable dynamic range by lowering the effective resistance, with minimal bandwidth or sensitivity penalty at lower optical power levels due to the added capacitance of the device. Note that this receiver was single-ended, but can be modified to permit differential operation with an additional diode at the input. Fig. 4 shows the simulated transient characteristics of the transimpedance receiver/transmitter at 375 Mb/s when the transmitter output was loaded with a total modulator capacitance (including pads and bump) estimated at 70 fF from ring-oscillator data [3]. Input voltages of approximately 100 mV were amplified to about 0.9 V in the first stage. At the output of the receiver, logic levels (5 V) were obtained. An additional inverter stage constituted the transmitter (modulator driver) circuit. DC simulations verified that the gain of the input stage was 9 and the overall gain of the circuit was ap-
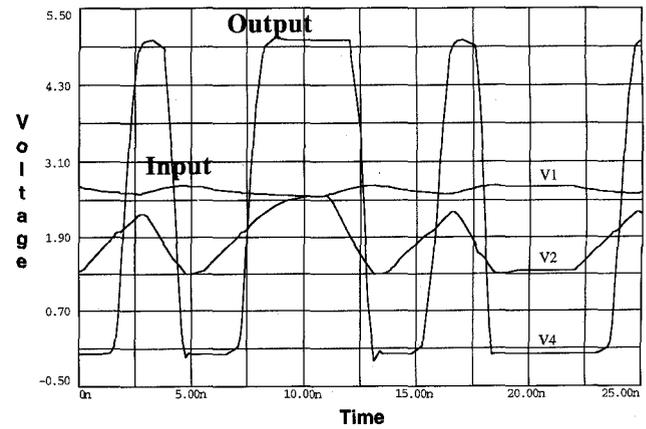

Fig. 4. Simulation of the transimpedance receiver/transmitter circuit at 375 Mb/s with peak input current of 11 μA. Output is loaded with modulator capacitance ($\approx$70 fF).

proximately 30. The fabricated receiver required a peak input power of approximately 14 μW to switch. Transient operation of the light receiver-transmitter circuit was confirmed at 375 Mb/s, at 11.3 μW average power, with a calculated switching energy of 60 fJ. At this bit rate, the feedback resistance (R) was calculated to be approximately 85 KΩ according to (1), where I_d is the photodetector current and A is the open-loop gain of the amplifier:

$$V_2 = -A \cdot V_1$$

with

$$\frac{V_2 - V_1}{I_d} = R. \tag{1}$$

The resulting bandwidth of the transimpedance receiver is:

$$BW = \frac{A+1}{2\pi RC_T}$$

with

$$C_T = C_I + (A+1)C_P, \tag{2}$$

where C_I is the input capacitance of the open-loop circuit, and C_P is the parasitic capacitance of the feedback-loop elements [4].

Sensitivity, bandwidth, and dynamic range data were acquired for the optical receiver-transmitter circuit. Fig. 5 shows the observed 375 Mb/s NRZ bit-pattern when the receiver was operating with an average input light intensity of 11.5 μW corresponding to approximately 61 fJ optical energy. The operating contrast ratio of the transmitter was 2 : 1 and the power dissipation of the transmitter circuit (at 37.5 Mb/s) was about 2 mW. The measured minimum average optical powers, determined from eye-pattern observations, at 155, 250, and 331 Mb/s, were approximately 9, 10, and 11 μW, respectively. This corresponds to switching energies of 116 fJ, 80 J, and 66 fJ, respectively. The dynamic range (defined as the ratio between the overload and sensitivity powers) at these frequencies were over 16, 13, and 6 dB, respectively. The minimum energy required to operate this single-ended receiver (with a fixed transimpedance feedback element) drops with frequency due
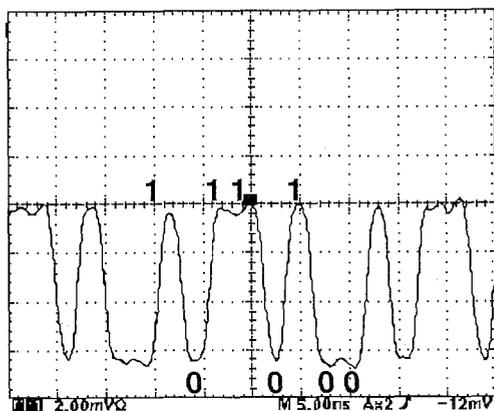
Fig. 5.   Experimental NRZ data at 375 Mb/s. Contrast ratio is 2 : 1.
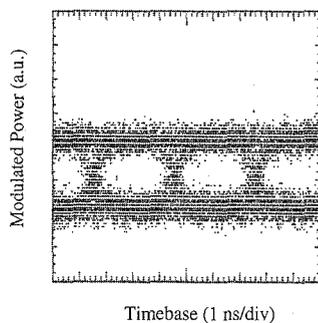

Timebase (1 ns/div)

Fig. 6.   Eye pattern of the receiver/transmitter circuit operating at 331 Mb/s with a switching energy of 66 fJ.

to the fact that the receiver is normally biased well below the switching threshold, and a minimum holding current is required to keep the receiver above its tripping point for the duration of the bit period. Fig. 6 shows the eye pattern of receiver/transmitter circuit operating at 331 Mb/s with a switching energy of 66 fJ. For this measurement, a pseudo-random bit-stream (2^{23} 1 bits) was applied to the circuit and a persistence of 10s was used to collect the eye pattern.

In summary, we have demonstrated that reflection-mode MQW absorption modulators and detectors can be flip-chip bonded directly over active silicon CMOS circuits. This will permit high-density siliconVLSI circuits to be integrated with optical inputs and outputs. In addition, the design and optimization of the CMOS circuits can proceed independently of the placement and the bonding of surface-normal optical modulators to the circuit. The layout of the silicon circuit does not have to be constrained to avoid the regular opto-electronic device array, allowing state-of-the-art silicon design tools to be used. We have demonstrated a transimpedance receiver-transmitter circuit operating at 375 Mb/s, limited by the receiver, based on this principle. The receiver design incorporates 60 fJ sensitivity and over 16 dB dynamic range (depending on the bit-rate) in a compact and relatively low power circuit. Further increases in sensitivity and bit-rate will be possible through improvements in circuit design and smaller silicon feature sizes. We anticipate that such hybrid optoelectronic circuits will permit aggregate I/O bandwidths in excess of 1 Tb/s from a single silicon chip.

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