Reconfigurable Optical Switches with Monolithic Electrical-to-Optical Interfaces

Julian Cheng, Ping Zhou

University of New Mexico, Center for High Technology Materials, Albuquerque, NM 87131

J. C. Zolper, K. L. Lear, G. A. Vawter

Sandia National Laboratory, Albuquerque, NM 87185

R. E. Leibenguth, A.C. Adams

AT&T Bell Laboratories, Breinigsville, PA 18031

ABSTRACT

Vertical-cavity surface-emitting lasers (VCSELs) can be integrated with heterojunction phototransistors (HPTs) and heterojunction bipolar transistors (HBTs) on the same wafer to form high speed optical and optoelectronic switches, respectively, that can be optically or electrically addressed. This permits the direct communication and transmission of data between distributed electronic processors through an optical switching network. The experimental demonstration of an integrated optoelectronic HBT/VCSEL switch combining a GaAs/AlGaAs heterojunction bipolar transistor (HBT) with a VCSEL is described below, using the same epilayer structure upon which binary HPT/VCSEL optical switches are also built. The monolithic HBT/VCSEL switch has high current gain, low power dissipation, and a high optical to electrical conversion efficiency. Its modulation response has been measured and modeled.

1. INTRODUCTION

Dynamically reconfigurable optical interconnection networks¹ are useful for a variety of applications involving the handling of parallel channels of optical data. For example, they provide a flexible switching network for routing high speed data between spatially-multiplexed optical channels that interconnect a large number of distributed electronic processors (Figure 1), some of which may be separated by significant distances. Data is transmitted through an interactive optical network whose interconnections are programmed by a host computer. To facilitate the communication between processors through the optical network, each node must not only provide an optical-to-optical (O-O) data link to other nodes, but also an electrical-to-optical (O-E and E/O) interface to the corresponding VLSI electronic processor to which it is electrically connected. While all the transceiver and switching functions may be individually implemented using electronic and optoelectronic integrated circuits, it is desirable to consolidate some of these disparate functional entities into a single monolithic technology. In particular, the optical switch itself should provide for an easily integrable electronic interface. In the following, we will describe the integration of vertical-cavity surface-emitting laser (VCSEL)-based optoelectronic switches with heterojunction bipolar transistor (HBT) technology. Using a single epilayer design, we demonstrate both optical and electrical switching using integrated HPT/VCSEL and HBT/VCSEL switches, respectively.

2. THE OPTICAL SWITCHING TECHNOLOGY

The optical switching technology is based on the integration of GaAs VCSELs and heterojunction phototransistors (HPTs),² which are also readily integrated with HBTs³ using the same epitaxial structure to form a high speed E/O interface. Individual HPT/VCSEL optical switches have achieved high optical gain (10-20) and contrast (30 dB), and can perform digital logic as well as amplification and memory functions.⁴ The HPTs and VCSELs can also be combined into more complex binary switch nodes that can spatially reconfigure and thus re-route the optical signal paths using bypass-exchange operations,⁵ which form the basis for a multi-stage optical switching network.^{1,2}

The device design and epilayer structure of a binary HPT/VCSEL optical switch⁵ are shown in Figures 2(a) and 2(b). The 2x2 switch contains 2 HPT input ports and two VCSEL output ports. Each input port contains a segmented HPT, each half of which is controlled by a separate bias voltage (V_1 or V_2) and each is serially connected to a different VCSEL output port. The input optical data impinges upon both HPT segments, and depending on the state (V_1, V_2) of the control voltages, the photoinduced and amplified current is routed alternatively to VCSEL #1 (1,0), VCSEL #2 (0,1), or to both

MASTER

REPRODUCTION OF THIS DOCUMENT IS UNLIMITED

Figure 1. Simplified schematic lay-out of a two-stage optical interconnection network in which each stage contains a 2x2 binary optical switch each of whose nodes contains an interface (input/output) to an electronic processor. Each processor sends electrical data to a transmitting node, which converts it into optical data and spatially routes it through the network by means of the binary optical switches (with fiber links). At the destination node, the optical signal is converted back into electrical data, which is sent to the receiving processor.

VCSELs (1,1), where it is regenerated as optical output data. Thus alternate routing as well as an optical fan-out of 2 can be achieved. For a 2x2 switch (Fig. 2b), routing of the two input data channels is controlled by the voltages (V_1 , V_2) and (V_2' , V_1'), which provide the bypass (1,0)(0,1) and exchange (0,1)(1,0) routing operations.

The layout of the monolithic 2x2 binary HPT/VCSEL switch is shown in Fig. 2(a). The VCSEL and HPT epilayers are vertically stacked together and are electrically isolated by a thick, low-doped GaAs layer. The VCSEL structure is grown by molecular beam epitaxy (MBE) on an n-GaAs substrate. It contains a lower and an upper distributed Bragg reflector (DBR) mirror containing 34.5 pairs of n-doped ($3 \times 10^{18}/\text{cm}^3$) AlAs and $\text{Al}_{0.15}\text{Ga}_{0.85}\text{As}$ quarterwave layers, and 21 pairs of p-doped ($5 \times 10^{18}/\text{cm}^3$) AlAs and $\text{Al}_{0.15}\text{Ga}_{0.85}\text{As}$ quarterwave layers, respectively. Each AlAs/AlGaAs heterointerface of the DBR mirror is compositionally graded by a thin, intermediate $\text{Al}_{0.58}\text{Ga}_{0.42}\text{As}$ layer to improve carrier transport, and the top-most period of the DBR mirror is p-doped to $1 \times 10^{19}/\text{cm}^3$ for ohmic contact. An active layer consisting of four 100 Å thick GaAs quantum wells separated by 70 Å wide $\text{Al}_{0.30}\text{Ga}_{0.70}\text{As}$ barriers is sandwiched between the DBR mirrors, with $\text{Al}_{0.30}\text{Ga}_{0.70}\text{As}$ cladding layers providing a total cavity length of one optical wavelength. A 1000 Å undoped AlAs layer is grown above the VCSEL as an etch-stop layer, followed by a 1.3 μm thick undoped GaAs isolation layer and the HBT epilayers. The HBT structure, which is epitaxially regrown on the underlying VCSEL and isolation layers by MBE, contains a 5000 Å n⁺-GaAs collector contact layer (doped $4 \times 10^{18}/\text{cm}^3$), a 3000 Å n-GaAs subcollector layer (doped $1 \times 10^{18}/\text{cm}^3$), a 3000 Å n-GaAs collector layer (doped $2 \times 10^{16}/\text{cm}^3$), a 2500 Å p-GaAs base layer (doped $1 \times 10^{18}/\text{cm}^3$), a 3000 Å n- $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ emitter layer (doped $2 \times 10^{17}/\text{cm}^3$), and a 200 Å n⁺-GaAs emitter contact layer (doped $5 \times 10^{18}/\text{cm}^3$). The heterojunction interface is graded, and a thicker and lower doped base layer was chosen to relax the processing tolerances.

Figure 2. (a) Epitaxial structure and device design, and (b) circuit layout and operating principle of a monolithic binary HPT/VCSEL optical switch, while (c) and (d) are the corresponding figures for a monolithic HBT/VCSEL optoelectronic switch, shown together to show that they can be integrated using the same epitaxial structure.

Each GaAs/AlGaAs VCSEL is current-confined by means of proton-implantation, which delineates an active area diameter of 20 μm . Each HPT input port contains two nearly contiguous but electrically-isolated 40 μm by 80 μm segments. All the VCSELs and HPTs are also isolated laterally by a multiple-energy, multiple-dose proton-implant. The threshold of the VCSEL is 6 mA, and the differential current gain β of the HPT typically ranges from 100 to 200. VCSELs with InGaAs quantum wells can be used for through-substrate optical emission, however this would be unsuitable for applications requiring optically cascaded stages.

The operation of monolithic arrays of 2x2 switches in the bypass (1,0,0,1) and exchange (0,1,1,0) modes have been experimentally demonstrated, as shown in Fig. 3. Electrical routing within each stage is limited to very short distances within a compact array of switch nodes. Here the inputs A and B are two optical pulse trains with different modulation frequencies and amplitudes, which are incident upon the segmented HPT #1 and HPT#2, respectively. As the control voltages ($\approx 6.5\text{V}$) toggle between the (1,0,0,1) and the (0,1,1,0) states, the output traces (Fig. 3a) show that the optically regenerated data pulses of A emerge alternately from the output ports (VCSELs) 1 and 2, respectively; while the regenerated data pulses of B emerge alternately from the output ports 2 and 1, respectively. The former represents the bypass (straight-through) operation, and the latter the exchange (crossover) operation. Figure 3b shows that by setting (V_1, V_2) equal to (1,0) and (0,1), the pulses of A are regenerated at the output port (VCSEL) 1 and 2, respectively, which demonstrates the routing or deflection of a single optical channel.

Figure 3. Experimental demonstration of (a) the routing of two optical input channels via the bypass and exchange operations, and (b) the routing of a single optical input channel, using the monolithic binary optical switch structure depicted in Figures 2a and 2b.

3. THE OPTICAL-TO-ELECTRONIC SWITCHING INTERFACE

In addition to providing optical-to-optical (O-to-O) switches to spatially route high speed data between parallel optical channels, each VCSEL or HPT/VCSEL switch can also be integrated with heterojunction bipolar transistors (HBTs) to form a high speed optical-to-electronic (O-to-E and E-to-O) interface to the electronic processor (Fig. 1). These interfaces perform many of the control and routing functions in the electronic domain, while the high speed data is routed optically through the switching fabric.² Because of the structural similarity between the HPTs and HBTs, the integration of VCSELs with HBTs provides simple E-to-O and O-to-E interfaces between the HPT/VCSEL optical switch and its electronic control functions, thus combining the ability of optics to transmit a large amount of data over large distances at high speed with the functional versatility of electronics. We describe below the monolithic integration of an HBT with a VCSEL, demonstrating the achievement of very high gain and efficient electrical-to-optical signal conversion.

The VCSEL has previously been integrated monolithically with a field-effect transistor (FET).⁶ Integrating a VCSEL with an HBT combines the advantages of the HBT technology (small area, high current gain and high speed) with those of the VCSEL (compactness, high speed, high efficiency, and low threshold). The higher current handling capability of the HBT per unit area (10^4 A/cm^2) provides a better match in device size with the VCSEL, whose threshold current density J_{th} is around 1 kA/cm^2 . The greater processing tolerance of the HBT also provides better performance uniformity, which is crucial for large scale integration.

The monolithic HBT/VCSEL switch, shown in Figures 2c and 2d, uses the same epilayer design as the HPT/VCSEL optical switch described above (Figures 2a and 2b). The area of the HBT ranges from $10 \mu\text{m} \times 10 \mu\text{m}$ to $100 \mu\text{m} \times 100 \mu\text{m}$, while the proton-implant-isolated VCSEL has a $20 \mu\text{m}$ active area diameter. A cross sectional view of the switch depicting its epilayer structure and the process design is shown schematically in Fig. 2c. The VCSEL and HBT epilayers are vertically stacked together and are isolated by a thick, low-doped GaAs layer. The corresponding devices are horizontally integrated and are electrically isolated by a multi-step proton implant. The HBT and VCSEL are interconnected in a simple emitter-follower configuration, with electrical contacts made to the base and collector contacts.

To demonstrate the dc operation of the HBT/VCSEL switch, a bias voltage V_c is applied to the collector contact with the substrate at ground, and a base current I_b is applied to the base contact to modulate the HBT. Figure 4a shows the collector current I_c of a switch with a $50\mu\text{m} \times 50\mu\text{m}$ emitter area as a function of V_c and I_b , while Fig. 4b shows the VCSEL output power P_{out} as a function of V_c and I_b . The switch exhibits sharp turn-on characteristics, with a 1.8V off-set which is mostly attributed to the turn-on of the VCSEL. The current gain $\beta = (\partial I_c / \partial I_b)$ of the HBT is shown as a function of the collector current in Fig. 4c, which shows that it increases with I_c and saturates at a maximum value of about 250 at a current density of about 240 A/cm^2 . The VCSEL turns on at a threshold current $I_c = 4.7 \text{ mA}$ (point A) and outputs more than 1.0 mW dc at $I_c = 11 \text{ mA}$ (point C), with a slope efficiency of about 18%. Fig. 4d summarizes the data of Figs. 4a and 4b by plotting the output power P_{out} and its derivative, the differential electrical-to-optical power conversion efficiency ($G = \partial P_{\text{out}} / \partial I_b$, in mW/mA), as a function of I_b . The P_{out} vs I_b plot shows that the VCSEL is switched on at $I_b = 24 \mu\text{A}$, as a result of the high current gain of the HBT ($\beta > 200$). An output power of 1.25 mW is obtained with a base current of $50 \mu\text{A}$. This is shown more explicitly by the differential power conversion efficiency G , which shows a high electrical-to-optical gain of more than 60 mW/mA . The power dissipation of the switch at $P_{\text{out}} = 1.1 \text{ mW}$ ($V_c = 4.0 \text{ V}$, $I_c = 10.6 \text{ mA}$) is 42.4 mW dc, and at threshold it is 18.6 mW dc ($V_c = 4 \text{ V}$, $I_c = 4.6 \text{ mA}$).

Figure 4. (a) The collector current I_c , and (b) the output optical power P_{out} of a monolithic HPT/VCSEL switch as a function of the collector bias voltage V_c and the base modulation current I_b . The corresponding points A (threshold), B, and C are shown on both plots. (c) The output optical power P_{out} and the differential electrical-to-optical power conversion efficiency G (in W/A) as a function of the base modulation current I_b . (d) The current gain of the HBT as a function of collector current.

4. MODULATION RESPONSE OF HBT/VCSEL SWITCH

In order to evaluate the modulation speed of the HBT/VCSEL switch, the small signal modulation characteristics of a monolithic HBT/VCSEL switch has been measured, although its design parameters have not been optimized for high-speed operation. In particular, the large area of the HBT ($50 \mu\text{m} \times 50 \mu\text{m}$) gives rise to an excessively large effective capacitance. In the experiment, a small amplitude RF modulation voltage is combined with a dc bias voltage, and the sum is applied to the base of a switch in the emitter-follower configuration, with a collector bias of $V_C = 7.5\text{V}$. The dc component of the base voltage biases the VCSEL at an operating level above threshold. The output power of the VCSEL is measured by a high-speed Si p-i-n photodetector using a high-speed sampling scope. The normalized optical modulation response ($dP_{\text{out}}(\nu)/dI_b(\nu)$), shown in Fig.5(a) as a function of the modulation frequency ν , shows a 3 dB modulation bandwidth of 100 MHz. This is not limited by the VCSEL's (multi-GHz) modulation bandwidth, but by the large capacitance of the HBT.

Figure 5. (a) Measurement and modeling of the normalized small-signal electro-optical modulation response G of a monolithic HBT/VCSEL switch as a function of the modulation frequency. (b) The small-signal equivalent circuit of the HBT-VCSEL switch for modeling its modulation response.

This modulation response has been modeled using the small-signal equivalent circuit model shown in Fig. 5(b). The VCSEL is modeled as a capacitance C_L in parallel with a shunt resistance R_L and a series resistance r_L . The HBT contains a base-collector junction and a base-emitter junction, plus the resistances r_e , r_b , and r_c at the emitter, base, and collector, respectively. The forward-biased base-emitter junction contains the diffusion capacitance C_{de} and the junction capacitance C_{je} in parallel with the emitter resistance $R_e = kT/eI_e$, while the reverse-biased base-collector junction contains the junction capacitance C_{jc} in parallel with a current source $\alpha I_e'$, where $\alpha = \beta/(\beta+1)$ and I_e' is the emitter current. The optoelectronic gain G of this switch, defined as the ratio of the light output (mW) to the base current (mA), is given by $G(\omega) = (\eta hc/\lambda e)\beta/(1+i\omega\tau)$, where η is the slope efficiency of the VCSEL, λ is the lasing frequency, c is the speed of light, $\omega = 2\pi\nu$ is the angular modulation frequency. The time constant τ of the switch is given approximately by:

$$\tau \approx (1+\beta)R_e[C_{de}+C_{je}+C_{jc}(1+g_m(r_e+R_L+r_c))] + C_LR_L,$$

where $g_m = 1/R_e$. Using $C_{jc} = 0.35$ pF, $C_{je} = 5.9$ pF, $C_{de} = 2.46$ pF, $R_e = 3.5$ Ω , $r_L + R_L \approx 280$ Ω , $\beta = 20$, and $r_e = r_b = r_c = 0$, we obtain $\tau = 2.65$ ns, giving a 3 dB bandwidth of 104 MHz. This model gives a good fit to the experimental data, as shown in Fig. 5(a).

The large effective capacitance $C_{eff} \approx C_{je} + C_{dc} + C_{jc}(1 + g_m R_L)$ of the HBT (≈ 11.5 pF) limits the response time of the integrated HBT/VCSEL switch, which can be significantly reduced by reducing the area of the HBT. This has been demonstrated with a hybrid HBT/VCSEL switch (Figure 6), which contains an HBT with a small $3\mu\text{m} \times 5\mu\text{m}$ junction area and $\beta=50$, and a VCSEL similar to that used above. The response of the packaged switch to a 1 Gb/s, 0.8V amplitude pseudorandom pulse modulation voltage applied to the base of the HBT (which modulates the VCSEL between 0 and 1 mW) is shown in Fig. 6. The 150ps width of the VCSEL output pulse shows that high speed modulation at a 1 Gb/s rate is possible with a better optimized HBT/VCSEL switch.

Figure 6. (b) Optical response of a hybrid HBT/VCSEL switch to (a), the large-amplitude voltage modulation at a data rate of 1 Gb/s, which is applied to the base of the HBT. (c) shows its response to pseudo-random pulse modulation in the Return-to-Zero (RZ) format.

5. CONCLUSIONS

In conclusion, we have shown that an optically addressed binary HPT/VCSEL switch and an electrically addressed HBT/VCSEL switch can both be integrated on the same epitaxial structure. High performance optical and electrical switching have been achieved. The spatial routing of optical signals using monolithic HPT/VCSEL optical switchies has been demonstrated. For the HBT/VCSEL switch, high current gain (250), low switching current (24 μA at threshold), and a high electrical-to-optical power conversion efficiency (60 mW/mA) have been achieved, with an output power of $>1\text{mW}$. Experimental measurements using unoptimized monolithic switches have demonstrated a small-signal modulation bandwidth of 100 MHz, while better optimized hybrid switches can achieve a large signal electrical modulation bandwidth of ≈ 1 GB/s.

6. ACKNOWLEDGMENTS

The research at UNM is supported by Rome Labs (Griffiss AFB), AFOSR (Bolling AFB), and ARPA. The work performed at Sandia was supported by DOE Contract No. DE-AC04-94AL85000.

7. REFERENCES

- [1] J. Cheng, P. Zhou, "Optoelectronic Technology for a Reconfigurable Optical Interconnection Architecture", SPIE Vol.1850, Laser Diode Technology and Applications V, pp. 93-99, 1993.
- [2] J. Cheng, P. Zhou, S. Z. Sun, and D. R. Myers, "Surface-emitting Laser-based Smart Pixels for Two-dimensional Optical Logic and Reconfigurable Optical Interconnections", IEEE J. of Quantum Electronics, Special Issue on Smart Pixels, JQE-29, pp. 741-756, 1993.
- [3] P. Zhou, J. Cheng, J. C. Zolper, K. L. Lear, S. A. Chalmers, G.A.Vawter, R.E. Leibenguth, and A.C. Adams, "Monolithic Optoelectronic Switch Based on the Integration of a GaAs/AlGaAs Heterojunction Bipolar Transistor and a GaAs Vertical-Cavity Surface-Emitting Laser", IEEE Photonics Technology Letters, Vol. 5, No. 9, pp. 1035-1038, Sept., 1993.
- [4] J. Cheng, P. Zhou, "Integrable Surface-emitting Laser-Based Optical Switches and Logic Gates for Parallel Digital Optical Computing", Applied Optics, Special Issue on Optical Computing, Vol. 31, pp.5592-5603, Oct. 1992.
- [5] Bo Lu, Ping Zhou, Y.C.Lu, J. Cheng, R.E. Leibenguth, A. C. Adams, J. L. Zilko, J. C. Zolper, K. L. Lear, S.A. Chalmers, G. A. Vawter, "Reconfigurable Binary Optical Routing Switches with Fan-out Based on the Integration of GaAs/AlGaAs Surface-Emitting Lasers and Heterojunction Phototransistors", IEEE Photonics Technology Letters, Vol. 6, No. 2, February 1994.
- [6] Y. J. Yang, T. G. Dziura, T. Bardin, S. C. Wang, R. Fernandez, and A. Liao, "Monolithic integration of a vertical cavity surface emitting laser and a metal semiconductor field transistor," Appl. Phys. Lett., 62, 600-602(1993).

DATE

FILMED

4/18/94

END