Low-Power Phototransceiver Arrays With Vertically Integrated Resonant-Cavity LEDs and Heterostructure Phototransistors

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***Abstract*—Low-power phototransceivers and phototransceiver arrays, with vertically integrated high-gain heterojunction phototransistors (HPTs) and resonant-cavity light-emitting diodes (RCLEDs), are demonstrated. A tunnel junction was used as a low resistance interconnect between the two devices. The input and output wavelengths are 0.63–0.85 and 0.98 μm, respectively. The phototransceiver exhibits an optical gain of 13 dB and power dissipation of 400 μW for an input power of 5 μW. The phototransceiver arrays demonstrate good uniformity, low optical crosstalk, and imaging capabilities.**

***Index Terms*—Arrays, monolithic integration, phototransceiver.**

I. Introduction

A DENSELY packed two-dimensional array of phototransceivers, which can detect, process, and transmit information with high sensitivity and efficiency, low-power dissipation, and compact size, would be an attractive component in imaging sensing and information transfer applications. Different integration schemes with integration of photodiodes and light sources have been studied [1]–[5]. We have reported the successful integration of a high gain heterojunction phototransistor (HPT) [6] and high efficiency resonant cavity light-emitting diode (RCLED) [7], [8] or vertical-cavity surface-emitting laser (VCSEL) [9] resulting in a phototransceiver with high gain, high sensitivity, low-power dissipation, and compact size [10]. More recently, we have also reported a phototransceiver in which a modulated barrier photodiode was monolithically integrated with a quantum-dot RCLED [11]. There remains, however, a need to reduce the size of the circuit to increase the array density.

In this letter, we describe the design, fabrication, and characteristics of GaAs-based low-power phototransceivers and phototransceiver arrays, in which the low-resistance interconnect between the phototransistor and the resonant cavity LED is achieved with a tunnel junction (TJ) [12], [13]. The novel *vertical* integration scheme simplifies processing and makes the area of the optoelectronic integrated circuit (OEIC) very small (0.002mm^2).

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II. Epitaxial Growth and Fabrication

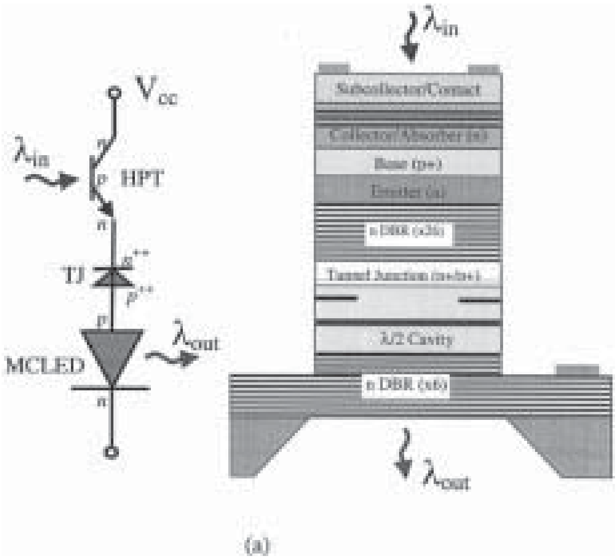
The equivalent circuit of the phototransceiver is shown in Fig. 1(a). The input optical signal is detected by the phototransistor in which the absorbing region is placed in a resonant cavity to improve the responsivity. The amplified photocurrent of the HPT drives the RCLED, which emits at a different wavelength. The optical gain of the phototransceiver is determined by the product of the phototransistor responsivity and current gain and the differential quantum efficiency of RCLED. As shown in Fig. 1(b), the TJ provides a low resistance contact between n-doped emitter layer of the HPT and p-doped layer of the RCLED, through the distributed Bragg reflector (DBR) layers, which provide an optical isolation interface between the input and the output lights.

The heterostructure was grown in a single step by molecular beam epitaxy (MBE), and is shown in Fig. 1(b). The layers are designed such that the light-absorbing multiple-quantum wells (MQWs) in the HPT and emitting quantum well (QW) in the RCLED are placed at the antinodes of the optical field of the incident light and emitting light, respectively. The QW absorption peak occurs at 980 nm, which coincides with the resonant frequency of the bottom DBR mirror. The base region is chosen to have a thickness of 100 nm and a p-doping (with Be) of 10^{18} cm^{-3}. The TJ was realized by degenerate C (p^{++}) and Si (n^{++}) doping. A ring contact is formed on the surface of the phototransistor (collector up) to enable photoexcitation. Mesa sizes of individual devices vary from 50 to 100 μm in diameter. The aperture size (window opening) is defined by the area within the top ring contact; this varies in the range of 40–90 μm.

III. Single Element Phototransceiver Characteristics

The optical gain and DC characteristics of the fabricated MQW-HPTs, without antireflection coating, were measured with a HP4145 parameter analyzer using an 850-nm laser and a tapered optical probe. The devices have low dark current ($\sim$1 nA) and reasonably high breakdown voltage (>6 V). The responsivity and the photocurrent of a typical HPT as a function of input power (850 nm) are shown in Fig. 2(a). The scanning electron microscope (SEM) microphotograph of a single phototransceiver is shown in the inset. As observed from the measured data, the device exhibits relatively high optical gain G at low input power ($G \sim 1$ A/W at $\mathrm{P_{in}} = 1$ μW).

The cuurent versus voltage (I–V) characteristics for the RCLEDs measured through the TJ, exhibit turn-on voltages $\sim$0.8 V, reverse breakdown voltages $>$10 V, and leakage



λ/2	Contact	GaAs	0.1398 μm	n+	3×10^{18}	
2λ	Collector/ Absorber	GaAs	0.0690 μm	n	5×10^{16}	
		$In_{0.2}Ga_{0.8}As$	0.0080 μm	n	5×10^{16}	
		GaAs	0.1300 μm	n	5×10^{16}	X2
		$In_{0.2}Ga_{0.8}As$	0.0080 μm	n	5×10^{16}	X2
		GaAs	0.1300 μm	n	5×10^{16}	
	Base	GaAs	0.1 μm	p+	1×10^{18}	
λ	Emitter	$Al_{0.3}Ga_{0.7}As$	0.09 μm	n	5×10^{17}	
		$Al_{0.3}Ga_{0.7}As$	0.2051 μm	n	3×10^{18}	
λ/4	DBR	GaAs	0.0699 μm	n	2×10^{18}	X26
λ/4	DBR	$Al_{0.8}Ga_{0.2}As$	0.0803 μm	n	2×10^{18}	X26
λ/4	Tunnel junction	GaAs	0.0624 μm	n++	$>3\times10^{18}$	
		GaAs	0.0075 μm	P++	$>1\times10^{20}$	
λ/2	Cavity including confinement layers	AlGaAs graded	0.0100 μm	p	1×10^{18}	
		$Al_{0.98}Ga_{0.02}As$	0.0240 μm	p	1×10^{18}	
		$Al_{0.66}Ga_{0.34}As$	0.0180 μm	i	------	
		AlGaAs graded	0.0120 μm	i	------	
		GaAs	0.0100 μm	i	------	
		$In_{0.15}Ga_{0.85}As$	6 nm	i	------	
		GaAs	0.0100 μm	i	------	
		AlGaAs graded	0.0120 μm	i	------	
		$Al_{0.88}Ga_{0.12}As$	0.0480 μm	i	------	
λ/4	DBR	GaAs	0.0699 μm	n	2×10^{18}	X6
λ/4	DBR	$Al_{0.8}Ga_{0.2}As$	0.0803 μm	n	2×10^{18}	X6
N+ GaAs (100) substrate and buffer						

(b)

Fig. 1. (a) Equivalent circuit and schematic. (b) Heterostructure grown by MOCVD for the vertically integrated phototransceiver.

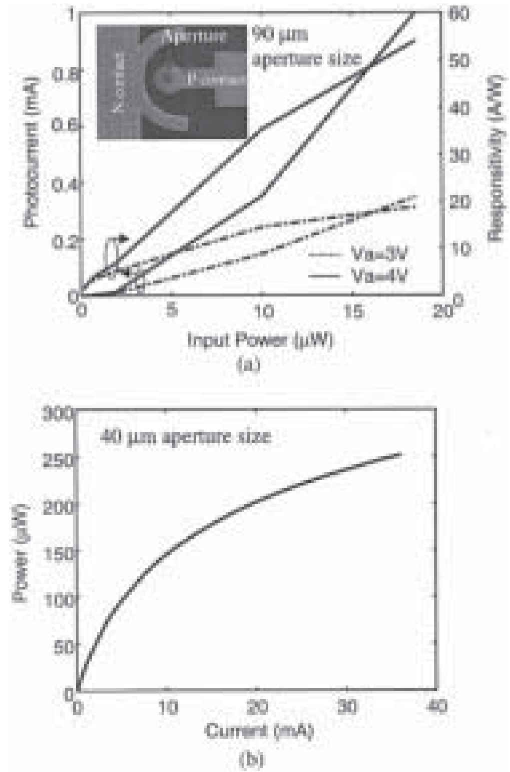


Fig. 2. (a) Photocurrent and responsivity a MQW-HPT of 90-μm aperture size, with inset showing the SEM photomicrograph of a fabricated phototransceiver. (b) Measured *L–I* characteristics of a RCLED with an aperture size of 40μm.

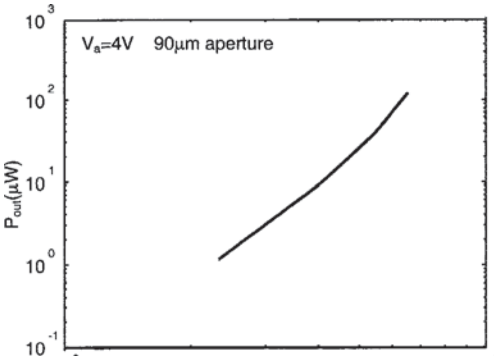


Fig. 3. Measured transfer characteristics of a vertically integrated phototransceiver with an aperture size of 90μm.

currents <1 nA. Both a low resistance TJ and a high-quality diode are evident from such characteristics. Shown in Fig. 2(b), is the light output versus current (L–I) characteristics of a RCLED with an aperture size of 40 μm. The maximum output power is 250 μW for an injection current of 36 mA, with a slope efficiency of 2.4%.

The optical input–output characteristics of the phototransceivers were measured using a GaAs laser ($\lambda = 850$ nm), a tapered optical probe, and a Ge detector. The optical gain of the OEIC is a function of input power (i.e., photocurrent), which originates from the dependence of the current gain (β) of the HPT on the collector current [14]. The measured optical transfer characteristics of a phototransceiver with a 90-μm aperture size are shown in Fig. 3. As can be seen in the figure, the circuit exhibits an optical gain of 13 dB at an input power of 5μW. The corresponding power dissipation of the circuit is 400 μW.

IV. Phototransceiver Arrays

Phototransceiver arrays have also been fabricated and characterized. The array size varied from 2×2 to 13×13, with the interelement spacing varying from 80 μm to 150 μm. The transfer characteristics of a uniformly illuminated 6×6 array (with individual phototransceiver aperture size of 40 μm and spacing of 80 μm) are shown in Fig. 4(a). The optical gain is 9 dB for

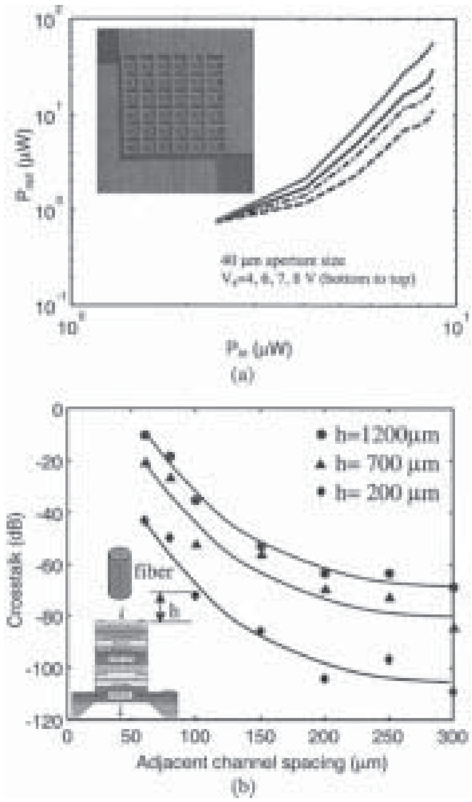


Fig. 4. (a) Optical transfer characteristics of a vertically integrated 6×6 phototransceiver array at different biasing voltages, with inset showing the SEM photomicrograph. (b) Crosstalk for different adjacent channel spacing and photoexcitation distance h.

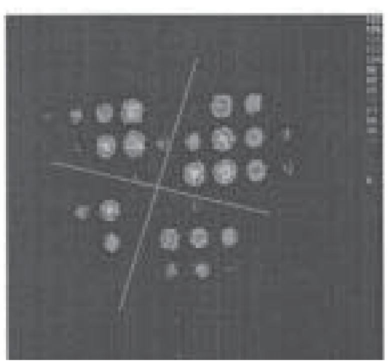


Fig. 5. An illuminated 9×9 array ($\lambda_{\rm in} = 0.63$ μm, $\lambda_{\rm out} = 0.98$ μm). Output image of a cross wire from at a voltage of 4V. Note that light output from the outer elements of the array are not seen due to a Gaussian, rather than uniform, intensity profile of the input beam.

$V_a = 8$ V and an input power of 9 μW. The uniformity of phototransceiver arrays was studied by measuring the photocurrent of the HPTs and the output intensity of the individual phototransceiver. The uniformity was within 10% for a 13×13 array. The adjacent channel crosstalk was investigated with light incident from a fiber on one channel and measuring the photocurrent developed in the HPTs of adjacent channels. The results are shown in Fig. 4(b), as a function of input fiber distance. The data indicate that the measured crosstalk, which is very small, is almost entirely optical crosstalk.

Imaging experiments were conducted with the arrays wired, bonded, and mounted on an optically transparent carrier. Illumination was provided with a 632-nm light from an He–Ne laser. The output image at 980 nm was recorded by a CCD-based near-field measurement system. Shown in Fig. 5, is the output image of a crosswire from a 9×9 array (with individual phototransceiver aperture size of 40 μm and spacing of 120 μm) for a biasing voltage of 4 V.

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REFERENCES

[1] J. Cheng, P. Zhou, S. Sun, S. Hersee, D. Myers, J. Zolper, and G. Vawter, "Surface-emitting laser-based smart pixels for two-dimensional optical logic and reconfigurable optical interconnects," *IEEE J. Quantum Electron.*, vol. 29, pp. 741–756, Feb. 1993.

[2] Y. Lu, J. Cheng, J. Zolper, and J. Klem, "Integrated optical/optoelectronic switch for parallel optical interconnects," *Electron. Lett.*, vol. 31, pp. 579–581, 1995.

[3] K. Beyzavi, D. Kim, C. Chao, P. Burrows, and S. Forrest, "A cascadable InGaAsP-InP optoelectronic smart pixel with low switching energy," *IEEE Photon. Technol. Lett.*, vol. 7, pp. 1162–1164, Oct. 1995.

[4] A. Alduino, G. Ortiz, C. Hains, B. Lu, Y. Lu, J. Cheng, R. Schneider, J. Klem, and J. Zolper, "500Mbit/s operation of a multifunctional binary optical switching fabric," *Electron. Lett.*, vol. 31, pp. 1570–1571, 1995.

[5] E. Fossum, "COMS image sensors: Electronic camera-on-a-chip," *IEEE Trans. Electron. Devices*, vol. 44, pp. 1689–1698, Oct. 1997.

[6] R. Milano, P. Dapkus, and G. Stillman, "An analysis of the performance of heterojunction phototransistors for fiber optic communications," *IEEE Trans. Electronic Devices*, vol. ED-29, pp. 266–273, Feb. 1982.

[7] J. Blondelle, H. Neve, P. Demeester, P. Daele, G. Borghs, and R. Baets, "16% External Quantum Efficiency from Planar Microcavity LED's at 940nm by Precise Matching of Cavity Wavelength," *Electron. Lett.*, vol. 31, pp. 1286–1288, 1995.

[8] H. Neve, J. Blondelle, R. Baets, P. Demeester, P. Daele, and G. Borghs, "High efficiency planar microcavity LED's: Comparison of design and experiment," *IEEE Photon. Technol. Lett.*, vol. 7, pp. 287–289, Mar. 1995.

[9] D. Deppe, D. Huffaker, T. Oh, H. Deng, and Q. Deng, "Low-threshold vertical-cavity surface-emitting lasers based on oxide-confinement and high contrast distributed Bragg reflectors," *IEEE J. Select. Topics Quantum Electron.*, vol. 3, pp. 893–904, June 1997.

[10] O. Qasaimeh, W. D. Zhou, P. Bhattacharya, D. Huffaker, and D. Deppe, "Monolithically integrated low-power phototransceiver incorporating microcavity LED's and multiquantum well phototransistors," *IEEE Photon. Technol. Lett.*, vol. 12, pp. 1683–1685, Dec. 2000.

[11] ——, "Monolithically integrated low-power phototransceiver incorporating InGaAs/GaAs quantum dot microcavity LED's and modulated barrier," *Electron. Lett.*, vol. 36(23), pp. 1955–1957, 2000.

[12] J. B. Boucart *et al.*, "Metamorphic DBR and tunnel-junction injection: A CW RT monolithic long-wavelength VCSEL," *IEEE J. Select. Topics Quantum Electron.*, vol. 5(3), pp. 520–529, May/June 1999.

[13] J. Wierer, D. Kellogg, and N. Holonyak, "Tunnel contact junction native-oxide aperture and mirror vertical-cavity surface-emitting lasers and resonant-cavity light-emitting diodes," *Appl. Phys. Lett.*, vol. 74, pp. 926–928, 1999.

[14] O. Qasaimeh, W. D. Zhou, P. Bhattacharya, D. Huffaker, and D. Deppe, "Monolithically integrated low-power phototransceivers for optoelectronic parallel sensing and processing applications," *J. Lightwave Technol.*, vol. 19, pp. 546–552, Apr. 2001.