Monolithically Integrated Low-Power Phototransceiver Incorporating Microcavity LEDs and Multiquantum-Well Phototransistors

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***Abstract*—A low power GaAs-based monolithically integrated phototransceiver, consisting of a high gain phototransistor and a microcavity light-emitting diode, is demonstrated. The input and output wavelengths are 0.85 and 0.98 μm, respectively. The phototransceiver exhibits an optical gain of 7 dB and power dissipation of 400 μW for an input power of 1.5 μW. The small signal modulation bandwidth is 80 MHz.**

***Index Terms*—Low power, microcavity, monolithic integration, phototransceivers.**

I. Introduction

IMAGE sensor technologies being envisioned at the present time will utilize advances in optics, optoelectronics, and micromechanical components [1]. For example, in an adaptive optoelectronic eye, the essential components are a steerable micromachined microlens and microprism array, followed by image detection, optoelectronic parallel processing and finally, electronic processing. The microlens size essentially decides the pixel size. A densely packed, two-dimensional (2-D) array of phototransceivers that can detect, process, and transmit image signals with great adaptability and efficiency is an essential element in such applications. However, unlike the requirements of conventional lightwave WDM-based networks, very stringent power handling and dissipation requirements have to be met [1]. For example, in an image sensor having a 100×100 element array, the phototransceiver in each pixel should be capable of detecting input power as low as $\sim$1 μW, and the electrical power consumption of each phototransceiver should not exceed 500 μW. Each pixel may consist of three input colors (i.e., phototransceivers) and therefore, the phototransceivers, with a single-wavelength output, generally have different input and output wavelengths. On the other hand, the bandwidth is usually not an important factor in such massively parallel architectures. There is therefore a need to develop low power phototransceivers. Since micromachined optics will limit the speed of image collection on a focal plane array to $<$ 10 MHz. The overall bandwidth of the system can be enhanced in a subsequent stage using time-division multiplexing. Two-dimensional arrays of vertical-cavity surface-emitting lasers (VCSELs), operating with ultra low threshold current, large quantum efficiency, low-beam divergence, and very low power dissipation can be used for this application [2], [3]. On the other hand, microcavity light-emitting diodes (MCLEDs) provide very high wall-plug efficiency, comparable to VCSELs at low current levels [4]–[6]. The monolithic integration of high sensitivity heterojunction phototransistors (HPTs) and VCSELs or MCLEDs in a phototransceiver is therefore very attractive for adaptive sensor technologies. Monolithically integrated phototransceivers that emit light with wavelength transparent to the GaAs substrate ($\lambda_{\rm out} > 850$ nm) are very attractive for massively parallel applications. Three-dimensional (3-D) interconnects and massive chip-to-chip routing can be easily realized without additional electronic circuits. We report here the design and performance characteristics of GaAs-based multiquantum-well HPT/MCLED low power phototransceivers, which offer large optical gain and very low power dissipation.

II. Heterostructure and Fabrication

The phototransceiver equivalent circuit is shown in Fig. 1(a). It consists of a multiquantum-well phototransistor (MQW-HPT) and a microcavity light-emitting diode (MCLED). The photocurrent corresponding to the input optical signal is amplified by the gain of the floating-base transistor and retransmitted at a different wavelength by the MCLED. The parameters of both devices are optimized for large optical gain, small pixel size, and low power dissipation. A schematic of the OEIC, grown by one-step molecular beam epitaxy, and an SEM picture of a four-color pixel are shown in Fig. 1(b) and (c), respectively. The monolithically integrated OEIC is fabricated by standard lithography and wet/dry etching techniques. The MCLED utilizes 23 periods of undoped GaAs–AlAs DBR and three periods of n-doped (5×10^{18} cm^{-3}) GaAs–$Al_{0.8}Ga_{0.2}As$ DBR mirror, grown on a semi-insulating GaAs substrate. The active region of the MCLED consists of a single $In_{0.2}Ga_{0.8}As$–GaAs quantum well that emits light at 0.98 μm. The thickness of the barrier and well is 60 Å and 100 Å, respectively. Two undoped graded superlattice spacer layers are used to sandwich the quantum-well region and form the $\lambda/2$ cavity. The heterostructure is designed to achieve high slope efficiency and low drive current. An optional top mirror of the microcavity LED is made with a MgF–ZnSe DBR. The lateral size of the MCLED is

Manuscript received June 21, 2000; revised August 25, 2000. This work was supported by the Army Research Office (MURI program) Grant DAAG 55-98-1-0288.

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Publisher Item Identifier S 1041-1135(00)10491-4.

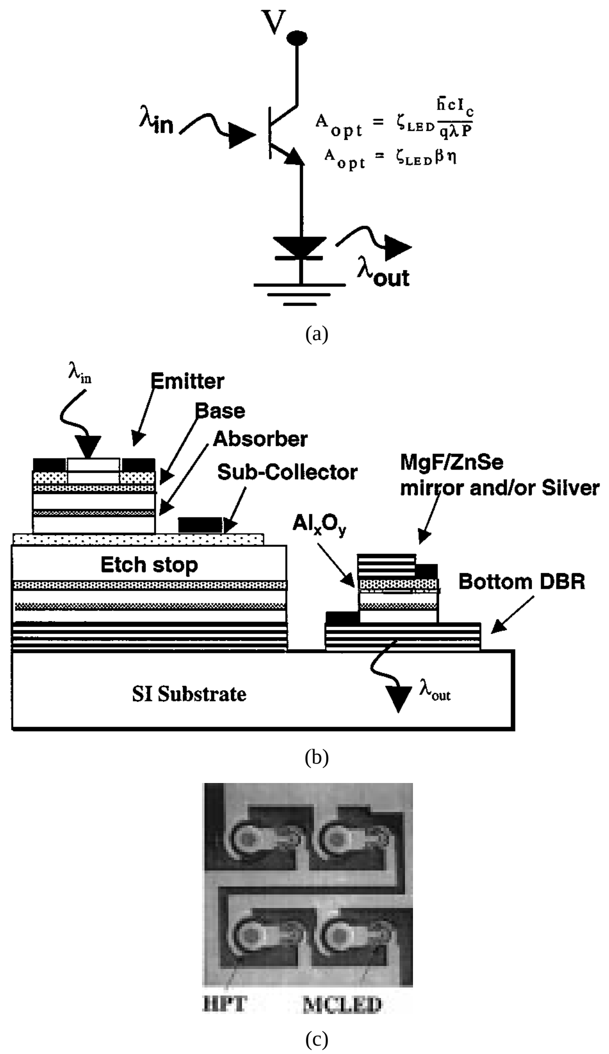

Fig. 1. (a) Equivalent circuit, (b) heterostructure cross section, and (c) SEM photomicrograph of the integrated phototransceiver.

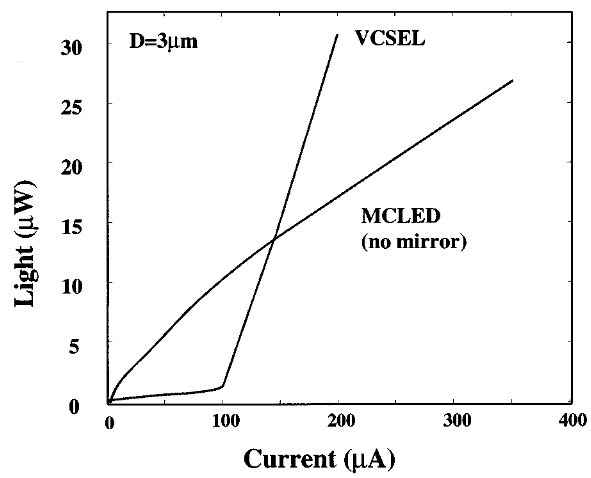

Fig. 2. Light current characteristics of 3-μm aperture oxide-confined MCLED and VCSEL.

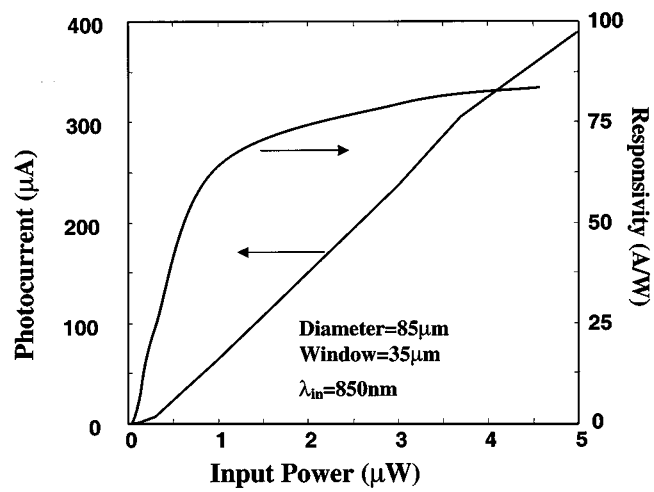

Fig. 3. Photocurrent and responsivity of MQW-HPT as a function of incident optical power.

defined by oxide-confinement, produced by wet oxidation of $Al_{0.98}Ga_{0.02}As$ layers. This aperture size D varied from 3 to 30 μm. The MQW-HPT consists of 4175 Å n^+ (3×10^{18} cm^{-3}) GaAs subcollector, a 1000 Å p^+ (1×10^{18} cm^{-3}) GaAs base, a 1810 Å n(5×10^{17} cm^{-3}) $Al_{0.3}Ga_{0.7}As$ emitter, a 890 Å n^+ (3×10^{18} cm^{-3}) $Al_{0.3}Ga_{0.7}As$ sub-emitter, and a 1390 Å n^+ (3×10^{18} cm^{-3}) GaAs contact layer. The collector-absorber of the HPT is made of 3 $In_{0.2}Ga_{0.8}As$/GaAs quantum wells that detect input light in the wavelength range of 0.7–0.98 μm. The well and barrier thickness are 80 Å and 1300 Å, respectively. The MQW enhances the absorption coefficient of the absorber and increase the sensitivity (quantum efficiency) of the phototransistor. A 0.42-μm-thick etch stop layer, inserted between the HPT and the MCLED, serves to isolate the devices.

III. Experimental Results

Fig. 2 shows the output light current (L–I) characteristics of a 3-μm aperture MCLED with 26 pairs of GaAs–AlAs bottom DBR and no top mirrors. Also shown for comparison is the L–I characteristics of a 3 μm aperture VCSEL fabricated from the same structure. The top mirror of the VCSEL is made of six pairs of ZnSe–MgF DBRs. It is seen that at low drive currents the light output of the MCLED is higher than that of the VCSEL. Below 100 μA, the differential quantum efficiency of the MCLED is 7%. Therefore, an efficient MCLED is suitable for the realization of a low power OEIC, without having to fabricate DBR mirrors.

The responsivity and the dc characteristics of the fabricated MQW-HPTs, without antireflection coating, were measured using a GaAs laser ($\lambda = 850$ nm), a tapered optical probe and HP4145 parameter analyzer. The fabricated MQW-HPTs have a diameter of 85 μm and window opening of 35 μm. The dark current of the phototransistor is $\sim$ nA, and the breakdown voltage is larger than 5 V. The offset voltage is very close to zero, indicating symmetric BE and BC junctions. The measured photocurrent and responsivity of the MQW-HPT, as a function of input power, are shown in Fig. 3. As can be seen in the figure, the devices operate with a high optical gain at low input power ($\Re > 60$ A/W at $P_{\text{in}} = 1$ μW). The current gain β of heterojunction phototransistors, neglecting surface recombination can be expressed as

$$\beta = \frac{I_c}{I_{\text{scr}} + I_{rb}} = \frac{\beta_{\max}}{1 + kI_c^{-1+1/n}} \tag{1}$$

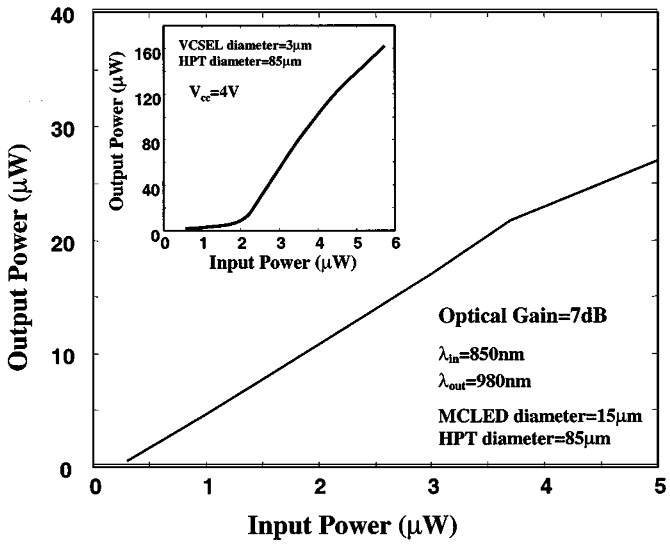

Fig. 4. Optical input–output characteristics of the monolithically integrated phototransceiver incorporating a MCLED. The inset shows the input–output characteristics of the OEIC incorporating a VCSEL.

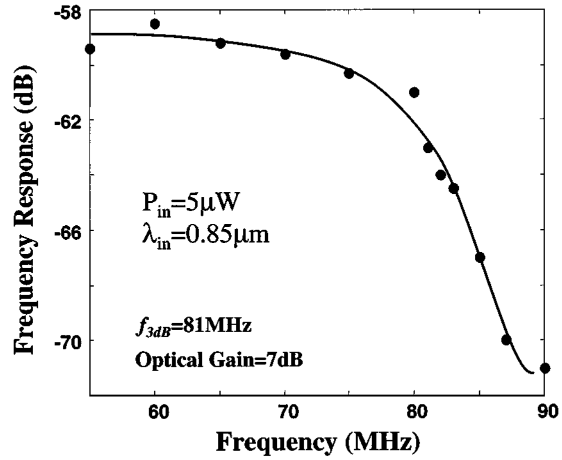

Fig. 5. Frequency response of the monolithically integrated circuit.

where

$I_{\rm scr}$ recombination current in the base-emitter space charge region;

$I_{\rm rb}$ recombination current in the neutral base region $\beta_{\max} = I_c/I_{\rm rb}$;

n ideality factor of the phototransistor;

k constant derived from the ratio of $I_{\rm scr}/I_{\rm rb}$.

At low current $\beta \sim I^{1-1/n}$, and at high current $\beta = \beta_{\max}$. The ideality factor of the MQW-HPT is 1.3, estimated by fitting the measured data with the above expression.

The input–output characteristics ($\lambda_{\rm in} = 850$ nm and $\lambda_{\rm out} = 980$ nm) of the monolithically integrated phototransceiver are shown in Fig. 4. The measured data are obtained for $V_{cc} = 4$ V. The circuit incorporates a 15-μm MCLED aperture with no top mirrors and has a 7% differential efficiency. As can be seen in the figure, the circuit demonstrates an optical gain of ~7 dB at an input optical power as low as 1 μW, which is very satisfactory for the applications envisaged. The optical gain of a phototransceiver is expressed as $G_{\rm op} = \Re \times \gamma$, where γ is the slope efficiency of the MCLED. The optical gain can be further increased by optimizing the device parameters (base doping and thickness of MQW-HPT and QW design of MCLED) and by using AR coating for the HPT. The total power consumption in the circuit is 400 μW for an input optical excitation power of 1.5 μW, which is also quite low. The circuit power dissipation may be further reduced by either increasing the current gain of the phototransistor or by reducing the turn-on voltage of the MCLED. For sake of comparison, a VCSEL-based phototransceiver was fabricated with the same heterostructure. The top mirror is realized with six pairs of 1790 Å MgF/830 Å ZnSe. The measured input–output characteristics of the circuit are shown in the inset of Fig. 4. As can be seen, the VCSEL-based OEIC exhibits an optical gain of 10 dB at an input power of 2.5 mW. The corresponding power dissipation of the circuit is 760 mW. It is evident that the MCLED-based OEIC demonstrates low power dissipation and high optical gain at input powers less than 2 mW, which are necessary for the envisioned application.

The frequency response of the monolithically integrated phototransceiver was measured using a high speed single-mode edge-emitting GaAs laser ($\lambda = 880$ nm) and HP8593A spectrum analyzer. The laser was modulated with a HP8350 sweeper oscillator and coupled onto a single mode fiber. The measured bandwidth of the photoreceiver, which is limited by the RC time constant of the HPT, was 80 MHz. The frequency response of the monolithically integrated circuit is shown in Fig. 5. Several advantages stem from this integration scheme which include simplicity of processing, array fabrication, and increased reliability to reduce power consumption.

IV. CONCLUSION

A low power GaAs-based monolithically integrated phototransceiver, consisting of a high gain phototransistor and a microcavity light-emitting diode has been designed, fabricated, and characterized. The OEIC demonstrates an optical gain of 7 dB and dissipates 400 μW for an incident power of 1.5 μW.

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