Monolithically integrated low-power phototransceiver incorporating InGaAs/GaAs quantum-dot microcavity LED and modulated barrier photodiode

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A low-power monolithically integrated phototransceiver, consisting of a high-sensitivity modulated barrier photodiode and a $In_{0.4}Ga_{0.6}As/GaAs$ self-organised quantum-dot microcavity light-emitting diode, is demonstrated. The modulated barrier photodiode exhibits a responsivity of 1.8×10^3 A/W, for 630 nm excitation, at an input power of 10 nW. The output wavelength is 980 nm. The phototransceiver exhibits an optical gain of 18 dB and power dissipation of 110 µW for an input power of 10 nW.

A densely packed, two-dimensional array of phototransceivers which can detect, process and transmit image signals with high sensitivity and efficiency, and dissipate little power, would be an attractive element in current image sensing applications [1 – 4]. For example, in a 200×200 element array, the phototransceiver in each pixel should detect input power as low as ~10 nW, and the electrical power consumption of each phototransceiver should not exceed 300 µW. The bandwidth is usually not an important factor in such massively parallel architectures. A modulated barrier photodiode (MBPD), sometimes called a Camel diode, has the unique property that the optical gain increases with decreasing input excitation power and it is therefore more suitable for such applications than a phototransistor [5, 6]. As a light emitter in the phototransceiver circuit, quantum-dot microcavity light-emitting diodes (QD-MCLEDs) promise narrowband resonant emission, directional output and nearly singlemode operation [7, 8]. In addition, a high wall-plug efficiency can be obtained at very low operating currents. We report here the fabrication and performance characteristics of a monolithically integrated low power phototransceiver consisting of a GaAs-based modulated barrier photodiode and a self-organised $In_{0.4}Ga_{0.6}As/GaAs$ quantum-dot microcavity LED. The phototransceivers demonstrate large optical gain and ultra-low power dissipation.

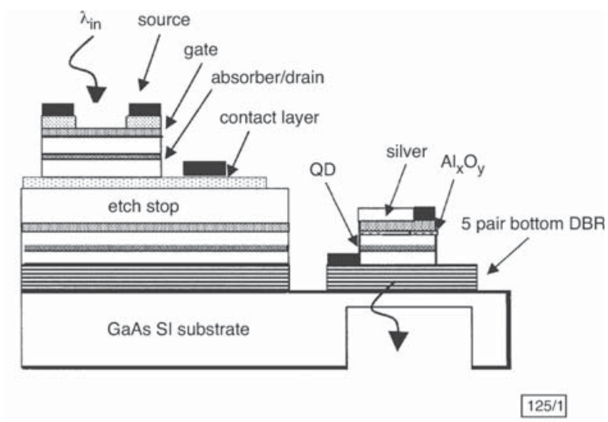

Fig. 1 *Schematic diagram showing cross-section of monolithically integrated MBPD-MCLED phototransceiver*

The phototransceiver equivalent circuit consists of the modulated barrier photodiode connected in series with the microcavity light emitting diode. The photogenerated current corresponding to the input optical signal is amplified by the gain of the MBPD and the amplified signal is retransmitted at a different wavelength by the MCLED. The heterostructure for the optoelectronic integrated circuit (OEIC) is grown by single-step molecular beam epitaxy. The MCLED utilises five periods of *n*-doped (5×10^{18} cm^{-3}) $GaAs/Al_{0.8}Ga_{0.2}As$ distributed Bragg reflector (DBR) bottom mirror, grown on a semi-insulating GaAs substrate. The active region of the MCLED consists of a single layer of $In_{0.4}Ga_{0.6}As/GaAs$ quantum dots that emit light at 980 nm. Two undoped graded superlattice spacer layers are used to sandwich the quantum-dot region and form the λ/2-cavity. The heterostructure is designed to achieve high slope efficiency, a high optical confinement factor and low drive current. The top mirror of the microcavity LED is made of 100 nm of evaporated silver. The lateral size of the MCLED is defined by oxide-confinement, produced by lateral wet oxidation of $Al_{0.98}Ga_{0.02}As$ layers. The aperture size of the MCLED varies from 8 to 20 µm. The multiquantum well (MQW) MBPD consists of 0.4 µm n^+(1×10^{19} cm^{-3}) GaAs bottom contact layer, a 120 Å p^+(4×10^{18} cm^{-3}) GaAs gate, a 0.26 µm n(1×10^{18} cm^{-3}) $Al_{0.3}Ga_{0.7}As$ source, and a 0.13 µm n^+(1×10^{19} cm^{-3}) GaAs top contact layer. The drain/absorber region of the MBPD is made of three $In_{0.2}Ga_{0.8}As/GaAs$ quantum wells. The well and barrier thicknesses are 80 and 1300 Å, respectively. The quantum well absorption peak occurs at 980 nm which corresponds to the resonant frqeuency of the bottom DBR mirror. Our objective was to compare the performance of the phototransceiver with 630 and 980 nm light, where a partially resonant cavity with the bottom DBR is formed. A 0.7 µm thick $Al_{0.75}Ga_{0.25}As$ etch stop layer, inserted between the MBPD and the MCLED, serves to isolate the devices. The monolithically integrated OEIC is fabricated by standard lithography and wet/dry etching techniques. To facilitate the detection and transmission of data, the MBPD is designed to detect input power from the front side of the wafer, and the MCLED is made to emit from the substrate side. Fig. 1 is a schematic diagram of the OEIC and Fig. 2 is a scanning electron micrograph of a section of an array.

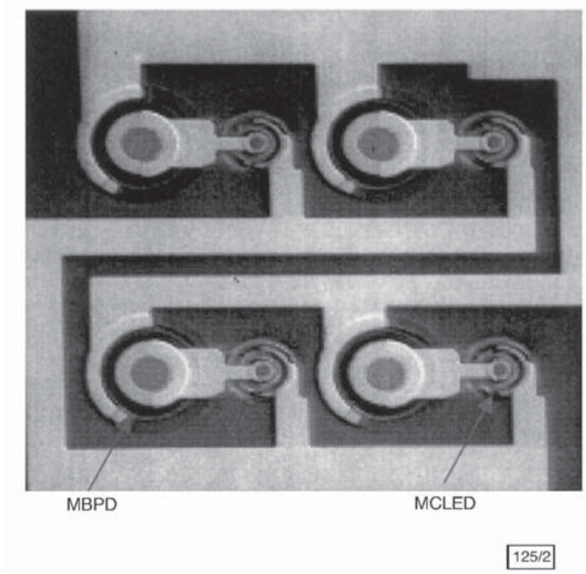

Fig. 2 *SEM photomicrograph of four-element array of phototransceivers*

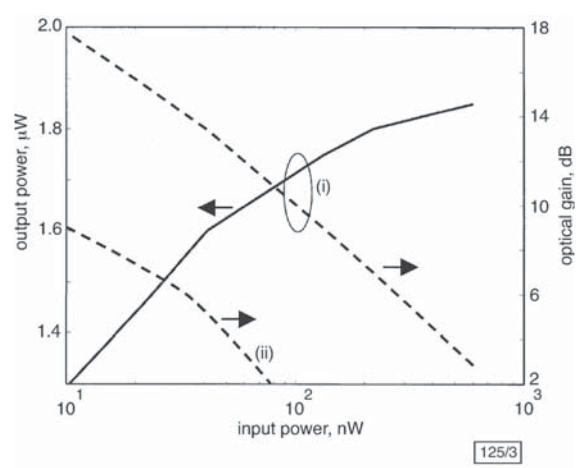

Fig. 3 *Optical input-output characteristics of monolithically integrated phototransceiver*

$V_{cc} = 8$ V, $\lambda_{out} = 980$ nm
(i) $\lambda_{in} = 630$ nm
(ii) $\lambda_{in} = 980$ nm

The light-current (L-I) characteristics of substrate-emitting MCLEDs of different aperture size were measured. Devices with aperture size of 15 µm demonstrate differential quantum efficiency of ~3% at injection currents < 100 µA. The responsivity and DC characteristics of the MQW-MBPDs, without anti-reflection coating, were measured using an HeNe laser (λ = 630 nm), a tapered optical probe and HP4145 parameter analyser. The devices have a diameter of 53 µm and window opening of 33 µm. The dark current of the MBPD is ~20 µA at V_{cc} = 8 V and the breakdown voltage is larger than 12V. The photocurrent increases from 20 to 180μA as the input optical power increases from 10nW to 100μW. The responsivity, $\Re$, of the device is > 1.8×10^3 A/W at an incident power of 10nW and monolithically decreases to 2A/W at 100μW incident power. This is a unique feature of modulated barrier photodiodes.

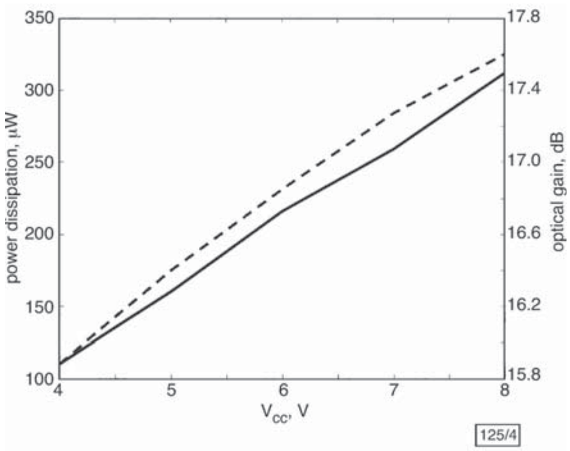

Fig. 4 *Optical gain and power dissipation as function of bias for 10nW input power*

P_{in} = 10nW
λ_{in} = 630nm
λ_{out} = 980nm
– – – – G
——— P_{diss}

The input-output characteristics (λ_{in} = 630nm and λ_{out} = 980nm) of the monolithically integrated phototransceiver are shown in Fig. 3. The measured data are obtained for V_{cc} = 8V. Also shown are the gains of the phototransceiver for 630 and 980nm photoexcitation light. It should be noted that a reasonable optical gain is obtained at 980nm input light. We believe that the small absorption in only three quantum wells is compensated by the resonance effect at 980nm provided by the bottom DBR. Conversely, the circuit demonstrates an optical gain of 17.6dB for 630nm light at an input optical power as low as 10nW which is very satisfactory for the applications envisaged. The optical gain can be further increased by using anti-reflection coating on the MBPD. The measured power dissipation (P_{diss}) and optical gain (G), as a function of V_{cc}, are shown in Fig. 4 for P_{in} = 10nW. The total power consumption in the circuit is 312μW for an input optical excitation power of 10nW and V_{cc} = 8V. It is evident that there is a trade-off between P_{diss} and G. For V_{cc} = 4V and P_{in} = 10nW, the optical gain and power dissipation of the circuit are 15.8dB and 110μW, respectively. The power dissipation of the OEIC may be further reduced by reducing the dark current of the MBPD. Several advantages stem from this integration scheme which include simplicity of processing, array fabrication and increased reliability due to reduced power consumption.

Acknowledgment: The work is supported by the Army Research Office (MURI programme) under grant DAAG 55-98-1-0288.

6 September 2000
Electronics Letters Online No: 20001352
DOI: 10.1049/el:20001352

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