GaInAsP/InP Membrane Lasers for On-chip Applications

(Invited paper)

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ABSTRACT

Toward the practical use of on-chip optical interconnection in LSIs, we developed an ultralow-power DR laser made in an InP-based membrane on a silicon substrate. The device showed a low threshold current of 0.21 mA, a high differential quantum efficiency of 32 %, and a maximum light output of 0.5 mW. Demonstration of data transmission confirmed a small energy cost of 93 fJ/bit at 20 Gbps operation.

Keywords: Semiconductor laser, III-V semiconductors, Optical interconnection, Photonic integrated circuits.

1. AIMING FOR ON-CHIP OPTICAL INTERCONNECT

Silicon LSIs have rapidly advanced their performance by increasing the degree of their integration. In consequence, the interconnection delay of inter-block data communication (especially between CPU and memory) in a chip is becoming a dominant limiting factor on LSI performance, which is known as an ‘interconnect bottleneck’. To overcome this problem, several potential countermeasures have been proposed. Especially the on-chip optical interconnection is very promising because it has less transmission delay and electromagnetic interference.

A laser is a key device for this purpose and has to satisfy several requirements for on-chip operation. First, it must be compatible with a silicon platform. Second, it must operate with low driving energy. Considering various factors, the allowable driving energy for on-chip data communication has been estimated to be 100 fJ/bit or less [1]. Thirdly, the laser must produce sufficient light output for high-speed communication with a low bit error rate (BER). For example, light output is needed to be 0.16 mW or more for 10 Gbps transmission with BER of 10⁻⁹ or less, a GaInAs PIN photodetector, and an intra-chip link loss of 5dB. To meet these requirements, we have developed a distributed-reflector laser (DR laser) made in a GaInAsP membrane on a silicon platform. The details are described below.

2. STRUCTURE OF MEMBRANE DR LASER WITH LOW POWER CONSUMPTION

The point of our idea is to make the core of waveguides (active region of lasers) in a form of a GaInAsP/InP membrane sandwiched between air and SiO₂ layers (see Fig. 1(a)). Strong optical confinement can be achieved in the core because the refractive indices of air and SiO₂ are far smaller than that of III-V semiconductors. This enables laser operation at very low input power as compared to ordinary semiconductor lasers [2]. We made actual devices on a SiO₂/Si substrate. Typical structural parameters of the device were: 32-μm-long distributed feedback (DFB) region, 50-μm-long distributed Bragg reflector (DBR), 296-nm grating period, and 0.7-μm grating stripe.

Fig. 1. (a) Structure of membrane distributed-reflector (DR) laser, (b) Cross sectional SEM image near p-electrode and quantum-well (QW) gain region.
width. The active region consists of five GaInAsP strained quantum wells sandwiched by InP layers with a total thickness of 270 nm. Figure 1(b) shows part of the cross section of the device.

Figure 2 shows the energy cost as a function of the length of the DFB region, calculated for various values of the index coupling coefficient, assuming 10-Gbps operation and 0.16-mW light output power. Other structural parameters were set equal to the typical values mentioned above. As DFB length decreases, the energy cost increases because of increases in differential resistance and threshold current of the device. And as DFB length increases, the energy cost again increases because of a decrease in differential quantum efficiency and an increase in threshold current. There is therefore an optimal DFB length that minimizes the energy cost. The optimal DFB length depends on the index-coupling coefficient, but the minimum energy cost is almost the same value. For the index-coupling coefficient of 1000 cm⁻¹, the energy cost can be reduced to 52 fJ/bit, using 50-μm DBR length.

3. STATIC CHARACTERISTICS OF FABRICATED MEMBRANE LASERS

Figure 3 shows the light output and bias voltage characteristics of the DR laser, measured under room-temperature continuous-wave (RT-CW) condition. The threshold current I₀ was 0.21 mA (threshold current density J₀ = 820 A/cm²). The light output increased linearly with injection current, showing an external differential quantum efficiency of 32% for injection current I < 1.5 mA and a maximum power conversion efficiency (wall-plug efficiency), ηPC, at an output power 0.16 mW of 12.2% [3]. They were slightly improved to ηal of 36% and ηPC of 14.6% in a different device [4].

4. DYNAMIC OPERATION OF MEMBRANE LASERS

From the small-signal modulation response, we obtained the relaxation oscillation frequency f₁ and 3dB bandwidth f₁/₂ as a function of the square root of injection current. Figure 4 shows the result. The slope of f₁ curve (i.e. modulation current efficiency factor) and that of f₁/₂ were 12 and 15 GHz/mA½, respectively.

We demonstrated high-speed direct modulation of the DR laser at a data rate of 20 Gbps. Figure 5 shows the bit error rate (BER) as a function of average received power after amplification by an EDFA. Bias current for the DR laser were set to 1.06 mA (bias voltage = 1.76 V). The minimum BER of 6.4×10⁻¹⁰ was obtained at an average
received power of -4.8 dBm. This result shows the feasibility of using the membrane DR laser as an ultralow-power light source for on-chip optical interconnections. Inset in Fig. 5 shows the 20-Gbit/s eye diagram measured at an average received power of -4.8 dBm, where eye opening can be confirmed. Noise was moderately suppressed because the absorption region at the rear of the laser prevented signal reflection back to the cavity. The energy cost was 93 fJ/bit. To the best of our knowledge, it is the lowest value reported for membrane-based DFB and DR lasers.

5. COMPARISON OF VARIOUS DFB/DR LASERS MADE ON SI SUBSTRATE

The performance of our membrane laser is summarized in Table I, compared with those of other DFB lasers and DR ones made on Si substrate. DFB lasers hybrid-coupled with Si waveguides have too energy cost for on-chip application. In contrast, lasers combined monolithically with InP/GaInAsP waveguides can achieve low energy cost, and especially our device (bottom in the table) has achieved the minimum value of energy cost. DR lasers (DFB lasers combined with DBR) have a relatively high differential-quantum-efficiency (DQE) because DBR suppresses the unnecessary reflection of light, and our device has achieved the highest DQE. We expect that the energy cost of our device can be lowered down to 50 fJ/bit at 20 Gbps by improving the device structure, especially around the electrodes, to reduce the parasitic resistance of the device.

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