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Low-threshold-current Operation of Lateral Current Injection Membrane Distributed-feedback Laser Bonded on Si

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***Abstract*—Toward realization of an ultralow-power-consumption semiconductor light source for on-chip optical interconnection, we have been investigating the lateral current injection (LCI) membrane distributed feedback (DFB) laser. This time, we realized membrane DFB laser with 158 nm core thickness and demonstrated room-temperature continuous-wave (CW) operation with a threshold current of 390 µA for the cavity length of 360 µm and the stripe width of 0.2 µm, which is lowest value ever reported in a DFB lasers on a Si substrate.**

Keywords— membrane laser; lateral current injection; strong optical confinement; optical interconnects; DFB laser; EB lithography

I. INTRODUCTION

It is predicted that the progress of the processing speed and integration of large scale integrated circuits (LSIs) will soon confront limitation associated with RC delay and large power dissipation in the electrical global wiring. In order to solve these problems, an introduction of optical interconnection instead of the electrical interconnection has been extensively studied. For instance, in semiconductor light sources for on-chip optical interconnections, the available power dissipation for the on-chip light source is estimated to be less than 100 fJ/bit [1].

To realize such light source, we proposed and demonstrated a GaInAsP/InP membrane distributed feedback (DFB) laser consisting of a thin semiconductor core layer sandwiched by low refractive-index claddings such as air, benzocyclobutene (BCB), and SiO_2. Since the membrane structure has a large refractive-index difference between the core layer and the cladding layers and supports strong optical confinement into the active region, it leads to ultralow power consumption operation [2]. Previously, an optically pumped membrane laser with low threshold pump power 0.34 mW under room temperature continuous wave (RT-CW) was demonstrated [3]. Toward an injection-type membrane laser, a lateral current injection (LCI) structure [4] was introduced and an injection-type GaInAsP/InP membrane DFB laser was demonstrated [5]. An internal quantum efficiency of GaInAsP/InP LCI lasers was improved by covering the top surface with 50 nm thick InP cap layer [6]. Recently, RT-CW operation with a threshold current of 3.5 mA was realized for LCI membrane Fabry-Perot (FP) cavity lasers [7].

This time, we would like to report a RT-CW operation of a GaInAsP/InP LCI membrane DFB laser with the core thickness of 158 nm. The threshold current of 390 µA and a differential quantum efficiency of 3.1 % from the front facet were obtained. This threshold current was the lowest value ever reported in DFB lasers on a Si substrate.

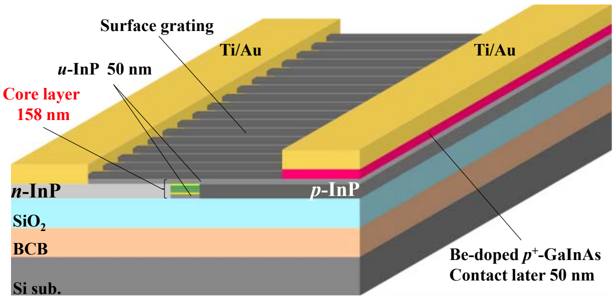

Fig. 1 Schematic structure of the membrane laser with Be-doped contact layer.

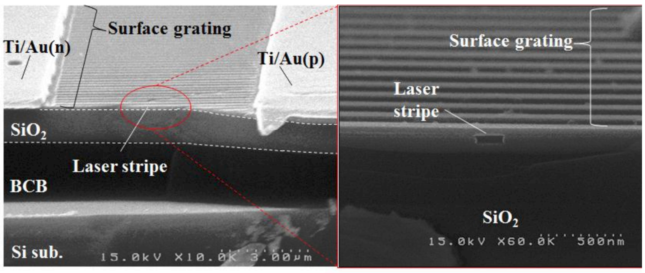

Fig. 2 A cross sectional SEM view of the fabricated device.

II. DESIGN AND FABRICATION

Fig. 1 shows the schematic structure of the fabricated LCI membrane DFB laser. Top and bottom cladding layers were composed of air (n = 1) and SiO_2 (n = 1.45), respectively. The device was fabricated as follows. Firstly, an initial wafer with a Be-doped p^+-GaInAs ($N_A = 8 \times 10^{18}$ /cm^3) contact layer was prepared on an n-InP substrate by gas-source molecular-beam-epitaxy (GSMBE); the core layer consists of three 1% compressively-strained (CS) $Ga_{0.22}In_{0.78}As_{0.81}P_{0.19}$ 3QWs (6 nm thick each) with -0.15% tensile-strained (TS) $Ga_{0.26}In_{0.74}As_{0.49}P_{0.51}$ barriers (10 nm thick each), which emit at 1.55-µm-band. The total thickness of the core layer including 50-nm-thick undoped-InP cap layers is 158 nm. The optical confinement factor ξ is estimated more than 0.7 %/well. Secondly, the LCI structure was fabricated by two-step organo-metallic-vapour-phase-epitaxy (OMVPE) selective area regrowth. A 7-µm wide mesa was formed by CH_4/H_2 reactive ion etching (RIE) and the n-InP ($N_D = 4 \times 10^{18}$ /cm^3) was

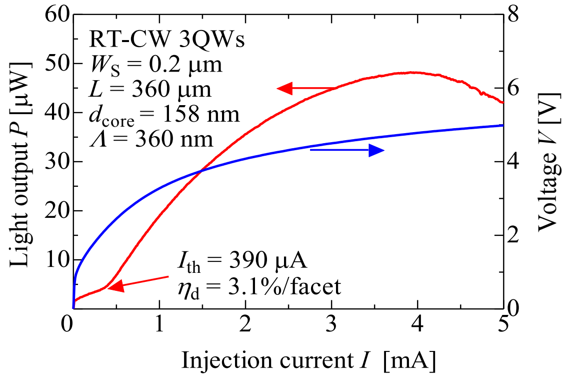

Fig. 3 Light output and $V-I$ characteristics.

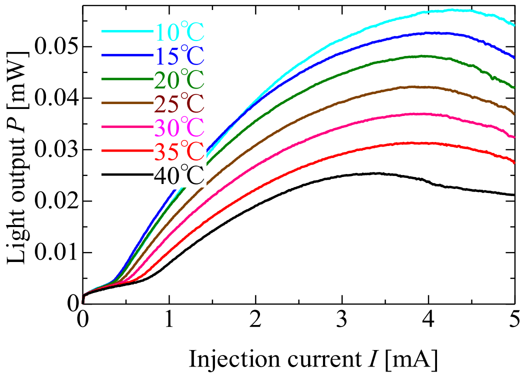

Fig. 4 L-I characteristics at various temperatures ranging from 10 to 40°C.

selectively regrown at both sides of the mesa as a cladding layer with a SiO_2 mask. After etching the part of the mesa and the one side of the *n*-type cladding layer, the *p*-InP (N_A = 1 × 10^{18} /cm^3) was regrown in the same way. Then, 1-μm-thick SiO_2 bottom cladding layer was deposited on the wafer. Meanwhile, 2-μm-thick BCB was spin-coated onto the Si host substrate and it was thermally pre-cured for its polymerization in N_2 environment at 210°C. The wafer and host substrate were bonded with a bonding pressure of about 25 kPa at 130°C, and completely solidified by hard-curing at 250°C under N_2 atmosphere. Subsequently, the *n*-InP substrate and etch-stop layers were removed by polishing and wet chemical etching. A part of the top Be-doped p^+-GaInAs contact layer near the stripe edge was removed by wet chemical etching. Then, Ti/Au electrodes were evaporated on the *n*-InP and *p*-InP regions. Finally, surface grating patterns were formed with an electron beam lithography (EBL), where the depth of the surface grating was assumed to be 30 nm and index-coupling coefficient κ was estimated to be 2300 cm^{-1}. Fig. 2 shows a cross-sectional SEM view of the fabricated device.

III. Experimental Results

The light output and voltage–current (V-I) characteristics of the LCI membrane DFB laser with the core thickness of 158 nm are shown in Fig. 3. The cavity length and the stripe width were 360 μm and about 0.2 μm, respectively. As can be seen, the threshold current of 390 μA and the differential quantum efficiency (DQE) of 3.1%/facet were obtained under a RT-CW condition, whereas the LCI membrane FP laser operated with the threshold current of 1.4 mA for the cavity length of 440 μm. The poor DQE can be attributed to long cavity length with high κ (2300 cm^{-1}) of the grating. Even though the rise-up voltage was confirmed to be around 0.8 V, the bias voltage at the threshold of around 2 V may be attributed to the thin (50 nm) undoped-InP layer below the p^+-GaInAs layer. The light output-current (L-I) characteristics at various temperatures ranging from 10 to 40ºC are shown in Fig. 4. As the next step, we try to realize a LCI membrane DFB laser with very short cavity of around 20 μm and demonstrate ultralow threshold operation of the LCI membrane DFB laser below the threshold current of 100 μA.

IV. Conclusion

The LCI membrane DFB laser with 158 nm core thickness was realized and a RT-CW operation with the threshold current of 390 μA and external quantum efficiency of 3.1%/facet was achieved for the cavity length of 360 μm and the stripe width of 0.2 μm. These results indicate ultralow threshold operation of the LCI membrane DFB laser with very short cavity.

Acknowledgment

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