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Butt-Joint Built-in (BJB) Structure for Membrane Photonic Integration

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Abstract—**On-chip optical interconnections have potential for replace global copper wires on LSI chips. In this work, as an integration method, an OMVPE butt-joint regrowth of 175-nm thick GaInAsP/InP was conducted toward an integration of active and passive components. In the numerical calculation, a coupling efficiency and residual reflection of designed butt-joint coupling were estimated to be 98% and -40dB, respectively. In the experimental method, we investigated the dependence of butt-joint interface morphology and regrown surface flatness on the side etch depth and the mesa angle. As a result, a flat regrown surface without degradation in crystalline quality was obtained.**

Keywords—butt-joint regrowth; OMVPE; photonic integrated circuit; membrane structure

I. INTRODUCTION

An introduction of optical interconnections to replace copper global wires is considered as a promising solution of performance limitation of Si-LSI [1]. To realize the optical interconnects, we have proposed GaInAsP/InP membrane photonic integrated circuits on Si substrate using benzocyclobutene (BCB) bonding [2]. The Membrane structure consists of a thin semiconductor core layer sandwiched by low refractive index claddings such as SiO_2, BCB, and the air. A large refractive-index difference between the thin semiconductor core layer and dielectric cladding layers leads to the strong optical confinement to the active region hence an extremely low-threshold laser with high-speed direct modulation capability is expected. In our previous researches, we have reported lateral current injection membrane lasers [3], GaInAsP wire waveguides [4] and lateral junction membrane photodetectors [5].

In order to integrate each membrane component, high coupling efficiency and low diffraction losses as well as low optical absorption at the passive region are necessary, which can be achieved with sufficient thickness controllability and surface smoothness. There has been several approaches to photonic integration, such as butt-joint built-in (BJB) structure [6], selective area growth (SAG) [7], offset quantum-well [8], and quantum-well intermixing (QWI) [9] to name just a few. However, it is difficult to fabricate with membrane structure or hard to achieve rapid band gap change at the active-passive interface. Therefore, in this work, we employed the butt-joint built-in (BJB) structure using organo-metallic vapor phase epitaxy (OMVPE) as an integration method, and demonstrated it satisfies the requirements above for membrane integration. Moreover in the calculation, the coupling efficiency and the residual reflection of the butt-joint interface was estimated with the finite difference method (FDM) and the eigen-mode expansion method (EME).

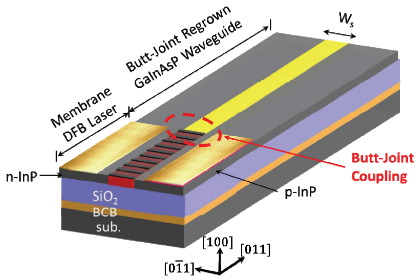

Fig.1 Schematic structure of the membrane DFB laser integrated with GaInAsP waveguide.

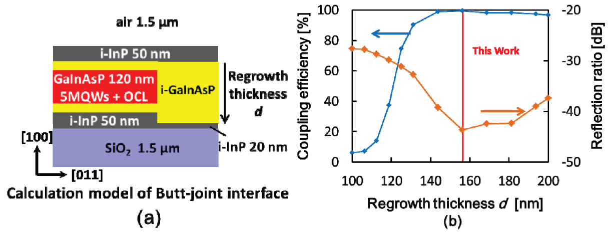

Fig. 2 Regrown GaInAsP thickness dependence of butt-joint coupling efficiency and reflection ratio.

II. NUMERICAL ANALYSIS

Figure 1 shows the schematic structure of the membrane DFB laser integrated with a GaInAsP waveguide. The BJB coupling characteristics, which are determined by the equivalent refractive-index and the mode profile difference between the active and passive regions, depend on the regrown GaInAsP/InP thickness. In order to calculate the coupling efficiency and the residual reflection of the BJB coupling, a simple simulation model was used and the simulation was carried out by the FDM and EME methods. Figure 2 (a) shows the calculation model of the BJB interface. The parameters were set as the following; the regrowth thickness of i-GaInAsP (with constant i-InP cap thickness of 20 nm) varies from 100 nm to 200 nm. The coupling efficiency and the residual reflection at each thickness were plotted on graph in Fig. 2 (b). The maximum coupling efficiency of around 98% and the minimum residual reflection of -42dB can be achieved simultaneously at the thickness of 155 nm. At this thickness, the equivalent index at the laser and passive sections are 2.66 and 2.63, respectively. The coupling efficiency decreases rapidly when regrowth thickness becomes less than 130 nm due to a decrease in the optical confinement factor in the regrown waveguide. Therefore, i-GaInAsP regrown thicker than the optimal value has little effect, whereas i-GaInAsP regrown thinner than the optimal value causes significant coupling loss.

III. EXPERIMANTAL RESULTS AND DISCUSSION

The initial epitaxial layers consist of GaInAsP 5QWs (90 nm) sandwiched by GaInAsP optical confinement layers (15 nm) and i-InP layers (50 nm), which were grown by OMVPE on an (100) n-InP substrate. The unregrown island region was defined by photolithography, using a 50 nm SiO_2 mask. The island masks are 13 μm wide and 10 to 300 μm long, oriented in the [011] direction. Each island mask is spaced apart by 250 μm. The 50 nm i-InP surface was etched by CH_4/H_2 reactive-ion-etching (RIE), and GaInAsP core layers were etched by selective wet etching (H_2SO_4:H_2O_2:H_2O = 1:1:40 at 20°C for 11 min.). Then an InP buffer layer, undoped GaInAsP (λ_g = 1.22 μm) and an InP cap layer were grown by OMVPE. The growth conditions are summarized in Table 1. In previous studies, it was found that the BJB interface in the [011] direction has a tendency to cause an air gap between the as-grown region and regrown region. For high efficiency coupling, it is necessary to get rid of the air gaps on the BJB interface. Therefore we investigated the change in regrowth morphology at the BJB interface, by using the island mesa angle and under etch of the SiO_2 mask with wet chemical etching.

TABLE I. Growth Conditions

	Material	Thickness (nm)	Time	Growth Rate(nm/min.)	Growth Temperature (°C)
Step 1	i-InP	3	10 sec.	20	600
Step 2	i-GaInAsP	155	8 min.	19	650
Step 3	i-InP	20	1 min.	20	650

Figure 3 shows an SEM image of the regrown BJB interface observed from the <01$\bar{1}$> direction. A smooth surface and a gapless BJB coupling were achieved. The island mesa angle of 50° and the under etch depth underneath the SiO_2 mask of 160 nm were observed from this SEM picture. The deviation in surface height near the BJB interface is estimated to be less than 5 nm.

Then we evaluated the regrown GaInAsP luminescence properties by photoluminescence (PL) measurement. PL mapping was generated by stepping the 3 μm × 3 μm field of view; with the regrowth mask region in a 200-μm-wide and 200 μm-long square in the center. Figure 4 (a) and (b) show the PL peak intensity and PL peak wavelength mapping result respectively. The peak wavelengths were 1.22 μm and 1.55 μm in the regrown GaInAsP region and as-grown active region respectively. The full width at half maximum of regrown region was 49.4 meV in the measured regrown area. Compared with the bulk growth in our previous result, the value of it was 57.7 meV. From the results of the PL measurement, the quality of regrown layers near the mask can as good as that far from the mask.

IV. CONCLUSION

BJB regrowth using OMVPE was demonstrated for membrane photonic integration. According to a numerical

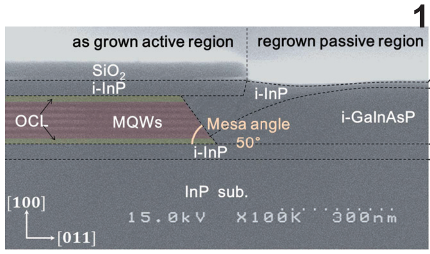

Fig. 3 SEM picture of the butt-joint interface observed from [01$\bar{1}$] direction.

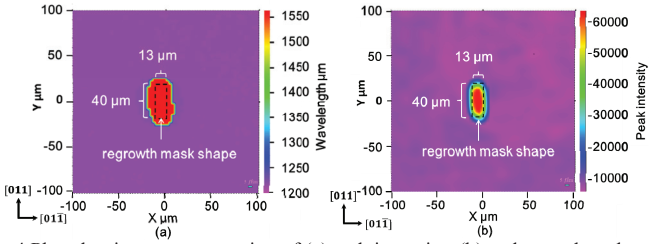

Fig. 4 Photoluminescence mapping of (a)peak intensity, (b)peak wavelength around regrowth mask (13 μm wide and 40 μm long).

calculation, a coupling efficiency of 98% and a residual reflection of -42dB can be achieved at an optimum thickness of the membrane structure. In the experiments, the gapless and flat regrowth surface were obtained with fairy good photoluminescence properties.

ACKNOWLEDGMENT

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