Low-Threshold Operation of LCI-Membrane-DFB Lasers with Be-doped GaInAs Contact Layer

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Abstract **— One of the promising candidates to solve a problem of a performance limitation of LSI is replacing electrical global wirings by on chip optical interconnections. We proposed and realized lateral-current-injection (LCI) type membrane DFB lasers for this purpose. In this paper, we report a new type LCI membrane DFB laser by introducing Be-doped GaInAs contact layer to the initial wafer structure so as to make simple fabrication of p-contact. As the result, a threshold current of as low as 3.8 mA, which was much lower than the previously reported value of 11 mA, was obtained for the stripe width of 1.5 μm and the cavity length of 250 μm.**

Index Terms **— GaInAsP/InP, lateral current injection, membrane structure, quantum-well laser, semiconductor laser.**

I. Introduction

The performance of the LSI will soon expected to confront the limitation due to ohmic heating, RC delay, power consumption, and crosstalk in the global wiring. Alternatively, photonic integrated circuits (PICs) in LSI are very intriguing approaches to address the problems confronted in the electrical global wiring [1], and an ultralow power consumption laser is strongly required for such optical interconnections. As a criterion for PICs to be successfully integrated into LSI, meanwhile, the acceptable optical pulse energy of the light source is set to be 100 fJ/bit or less [2]. To meet this strict requirement, micro-cavity lasers such as vertical-cavity surface emitting lasers VCSELs), microdisk lasers, and photonic crystal (PC) lasers have been reported as very low power consumption light sources [3]-[5]. Recently, very low pulse energy operations (less than 100 fJ/bit) of PC lasers [6],[7] and VCSEL [8] were demonstrated.

As a promising candidate for the light source, we proposed and demonstrated a GaInAsP/InP membrane distributed feedback (DFB) laser consisting of a thin semiconductor core layer sandwiched by low-index claddings such as air, benzocyclobutene (BCB), or SiO_2. The membrane structure produces a large refractive-index difference between the core layer and the cladding layers and supports strong optical confinement to the active region, leading to ultralow power consumption. In our previous report, low threshold (irradiated power: 0.34 mW) under room temperature continuous wave (RT-CW) optical pumping was successfully demonstrated [9],[10].

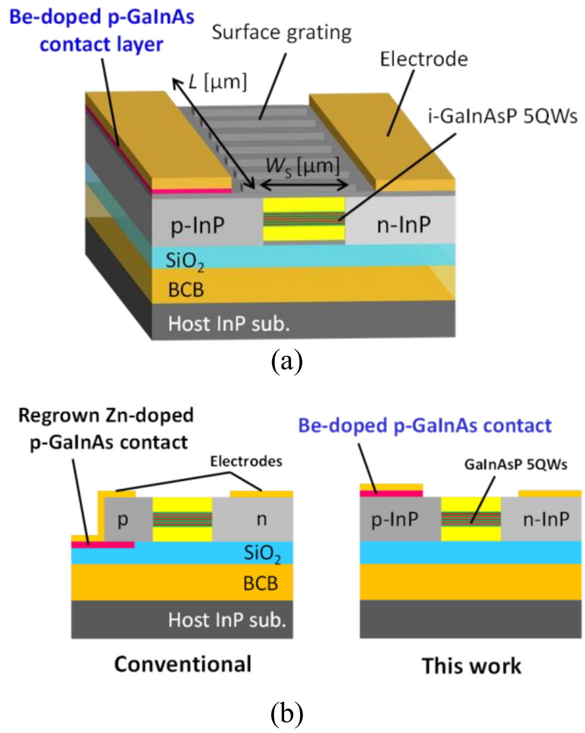

Fig. 1 Schematic structure of the LCI-membrane laser with Be-doped contact layer. (a) overall view of a device. (b) comparison of cross sectional view with that of a conventional LCI-membrane laser.

Toward an injection-type membrane laser, a lateral current injection (LCI) structure [11] was introduced and an injection-type GaInAsP/InP membrane DFB laser was demonstrated by using BCB adhesive bonding [12]. Recently, room-temperature pulsed operation with threshold current of 11 mA was realized for LCI-membrane-DFB lasers with InP surface grating [13], however, the threshold current was much higher than the expected value from the theory. In this research, new initial wafer structure consisting of a Be-doped GaInAs contact layer was introduced to achieve lower threshold operation of LCI-membrane-DFB lasers and to simplify the fabrication process.

II. Design and Fabrication

One of the causes of the high threshold operation is degradation of optical property due to impurity diffusion.

Table. 1 GaInAsP/InP epitaxial layer structure

Name	materials	Doping concentration	Thickness
Cap layer	InP	undoped	20 nm
OCL	InP	undoped	155 nm
QW(×5)	$Ga_{0.22}In_{0.78}As_{0.81}P_{0.19}$	undoped	6 nm
barrier(×6)	$Ga_{0.26}In_{0.74}As_{0.49}P_{0.51}$	undoped	10 nm
OCL	$Ga_{0.21}In_{0.79}As_{0.46}P_{0.54}$	undoped	155 nm
Etch stop layer	InP	undoped	50 nm
p contact	$Ga_{0.47}In_{0.53}As$	$8\times10^{18}/cm^3$	50 nm
Etch stop layer	InP	undoped	100 nm
Etch stop layer	$Ga_{0.47}In_{0.53}As$	undoped	300 nm

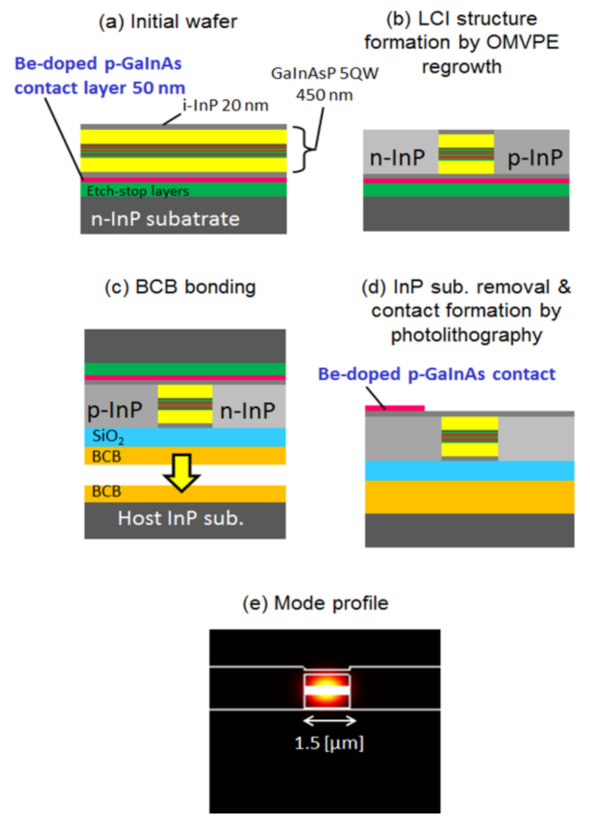

Fig. 2 (a)-(d) Fabrication process of the membrane laser with Be-doped p-GaInAs contact layer. (e) Mode profile of the designed structure for a W_S of 1.5 μm.

So far, Zn has been adopted as a p-type dopant of a GaInAs highly doped contact layer. However it has a large diffusion coefficient, leading to degradation of luminescence properties. In contrast, Be or C are well known as p-type dopants with low diffusion coefficient. Figure 1(a) shows the schematic structure of our membrane DFB laser with a Be-doped contact layer. Top and bottom cladding layers were composed of air (n = 1) and SiO_2 (n = 1.45), respectively. The core layer consisted of five 1% compressively-strained $Ga_{0.22}In_{0.78}As_{0.81}P_{0.19}$ quantum-wells (CS-5QWs, 6-nm-thick), 0.15% tensile-strained $Ga_{0.26}In_{0.74}As_{0.49}P_{0.51}$ barriers (10-nm-thick), sandwiched by optical confinement layers (OCLs, 155-nm-thick for both side). The total thickness of the core layer was 450 nm including a 50-nm-thick InP cap layer for surface passivation. As can be seen from Fig. 1(b), an introduction of Be as a p-type dopant of GaInAs contact enables electrodes to easily access to the contact due to an absence of regrowth process of the contact layer, which can simplify the fabrication process of LCI-membrane lasers.

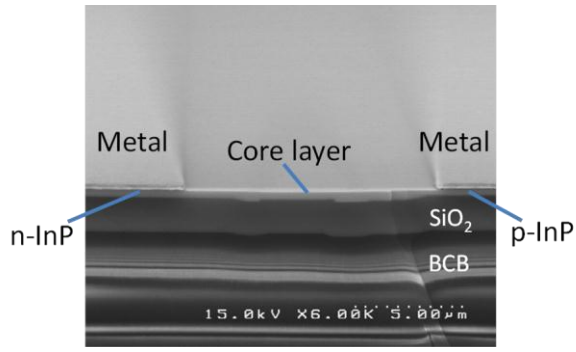

Fig. 3 Cross sectional SEM view of the fabricated device.

The device was fabricated as follows. GaInAsP/InP epitaxial layers with a Be-doped p-GaInAs contact layer, as shown in Table. 1, were grown on an n-InP substrate by gas-source molecular-beam epitaxy (GSMBE). The Be-doped contact layer was grown below the OCLs and the QWs, which was different from the previous initial wafer (Zn-doped contact was grown at the top of the wafer). The process flow is simply illustrated in Fig. 2(a)-(d). The LCI structure was fabricated by two-step organometallic vapor-phase epitaxy (OMVPE) selective area regrowth. First, a mesa stripe (7-μm-wide and 400-nm-high) was formed by reactive-ion-etching (RIE) with a SiO_2 mask, and n-InP (N_D = 4 × 10^{18} /cm^3) was selectively regrown on both sides of the mesa as a cladding layer. Next, one side of the cladding layer was etched, and p-InP (N_A = 4 × 10^{18} /cm^3) were regrown in the same way. Then, after depositing 1-μm-thick SiO_2 and 2-μm-thick BCB layers, the wafer was bonded upside down on an InP host substrate, and the BCB was hard-baked at 250°C for 1 hour under a N_2 atmosphere. Subsequently, the InP host substrate and etch-stop layers were removed by polishing and wet chemical etching. The top Be-doped GaInAs contact layer (the layer order was reversed by bonding) was then removed except for p-contact section, and Ti / Au electrodes were deposited on both p- and n-side electrodes. Finally DFB pattern was formed by electron-beam lithography (EBL) and CH_4/H_2 RIE on the InP cap layer. The depth of the InP surface grating was set to be 30 nm and corresponding index-coupling coefficient κ_i was estimated to be 150 cm^{-1}. The grating period and the equivalent refractive index for a device with a stripe width of 1.5 μm are 253.75 nm and 3.10, respectively. Figure 2(d) shows a fundamental mode profile of the designed LCI-membrane-DFB laser in case for stripe width W_S of 1.5 μm. This profile indicates that propagating light is well confined to the active region and the optical confinement factor was estimated to be 2%/well.

A scanning-electron-microscopic (SEM) image of fabricated device is shown in Fig. 3, where metal contact pads were formed by lift-off process with (10 + W_S) μm wide mask and AZ5218 photoresist. As can be seen, metal contact pads were formed approximately 5μm away from the stripe edge.

III. Experimental Results

Figure 4 shows the light output properties of an LCI-membrane-DFB laser with a Be-doped GaInAs contact layer (solid line) and a previously reported membrane laser from conventional initial wafer (dashed line). A low threshold operation of 3.8 mA and a differential quantum efficiency of 8.2%/facet were obtained under a RT-pulsed condition (1μs width and 1 kHz repetition) for a device with a cavity length of 250 μm and a stripe width of 1.5 μm. This corresponds to a threshold current density of 1.01 kA/cm^2 (203 A/cm^2/well) when the current is regarded as uniformly injected into the entire stripe region. This threshold is much lower and the output is higher than those of previously reported results [13].

The lasing spectrum was measured using a multimode fiber directly aligned to the cleaved facet. Figure 5 shows the lasing spectrum of a device at a bias current of $2I_{th}$, whose cavity length and stripe width are 250 μm and 1.5 μm, respectively. As can be seen, it showed multi-mode mode operation, not a single-mode operation under DFB mode, which may be attributed to a failure in the formation of the surface grating. From the measured resonant mode spacing of 1.32 nm, the effective refractive index of the waveguide n_{eff} is calculated to be 3.75 which is approximately 5% smaller than that of conventional (vertical current injection type) GaInAsP/InP lasers emitting at 1500-1600 nm wavelength range. Since the equivalent refractive index of this waveguide structure n_{eq} and its wavelength dispersion are calculated to be 3.03 and -0.41 μm^{-1}, respectively, n_{eff} is calculated to be 3.67, which is almost the same as that measured from the mode spacing.

Figure 6 shows a plot of the reciprocal of the measured differential quantum efficiency η_d as a function of the cavity length L and its liner approximation. An internal quantum efficiency η_i of 17% and waveguide loss α_{WG} of 5.9 cm^{-1} were obtained from the following relation,

$$\frac{1}{\eta_d} = \frac{1}{\eta_i}\left[1 + \frac{\alpha_{WG}L}{\ln(1/R)}\right]. \quad (1)$$

The internal quantum efficiency η_i was much lower than that of our conventional DH lasers ($\eta_i \sim 70\%$) and also that of LCI lasers prepared on semi-insulating InP substrates ($\eta_i \sim 40\%$) [15]. This is due to a large amount of carrier leakage in OCLs and carrier recombinations at dielectric-semiconductor interfaces, both of which originate from the LCI structure. Hence an effective threshold current for radiative recombinations is estimated to be 1/2 of measured values. Fortunately, we already reported some unique core structures suited for LCI-membrane lasers and can expect their highly-efficient operations with η_i of around 70% [16], [17], threshold current of 1/3-1/4 lower value can be expected by adopting these core structures.

By introducing a thinner core layer (~200 nm) and shorter cavity structure (~50 μm) as well as the matching of peak gain and the Bragg wavelengths, LCI-membrane-

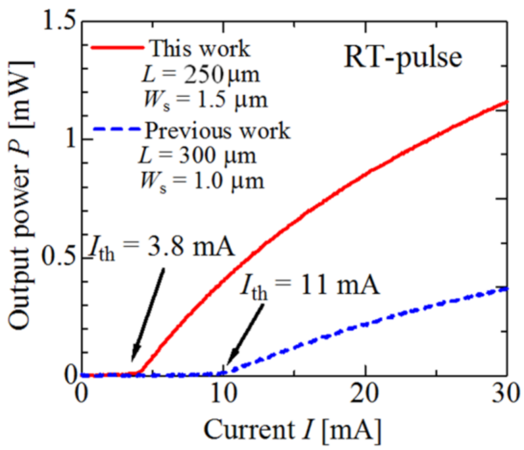

Fig. 4 Lasing characteristics of the membrane laser.

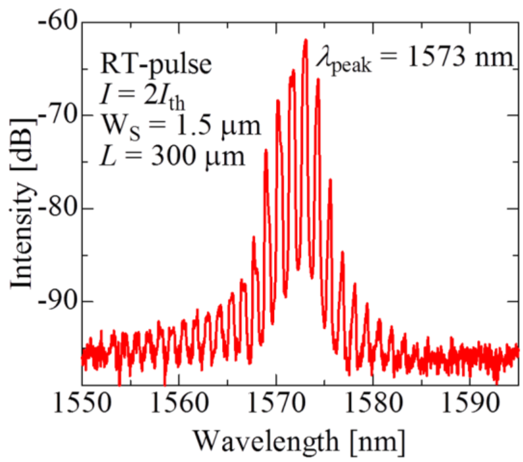

Fig. 5 Lasing spectrum of the membrane laser.

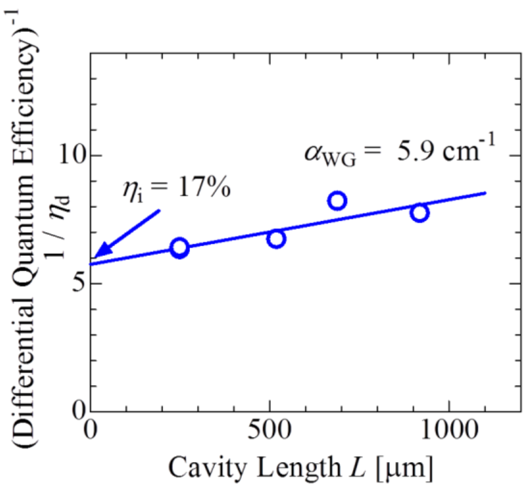

Fig. 6 Reciprocal of differential quantum efficiency as a function of the cavity length.

DFB laser will achieve a single-mode operation together with ultralow threshold current.

IV. Conclusion

As a step toward a realization of an photonic integrated circuits in LSI, we investigated the LCI-membrane-DFB laser with wire Be-doped p-GaInAs contact layer. As the result, a threshold current of 3.8 mA and a differential quantum efficiency of 8%/facet were obtained for the cavity length of 250 μm and stripe width of 1.5 μm. In addition, an internal quantum efficiency and a waveguide loss were evaluated to be 17% and 5.9 cm^{-1}, respectively.

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