Integration of Membrane-based DFB Laser and PIN Photodiode on Si Substrate toward On-chip Interconnection

Daisuke Inoue[1], Takuo Hiratani[1], Takahiro Tomiyasu[1], Yuki Atsuji[1], Tomohiro, Amemiya[2], Nobuhiko Nishiyama[1], and Shigehisa Arai[1,2]
[1] Dept. of Electrical and Electronic Engineering, Tokyo Institute of Technology
[2] Quantum Nanoelectronics Research Center, Tokyo Institute of Technology
2-12-1 O-okayama, Meguro-ku, Tokyo 152-8552, Japan
Phone: +81-3-5734-2555, e-mail: inoue.d.ac@m.titech.ac.jp

***Abstract*—Membrane DFB lasers and photodiodes were monolithically integrated on Si substrate. A threshold current of 280 µA was obtained. A photocurrent of 3 µA was obtained for the laser output of 3 µW.**

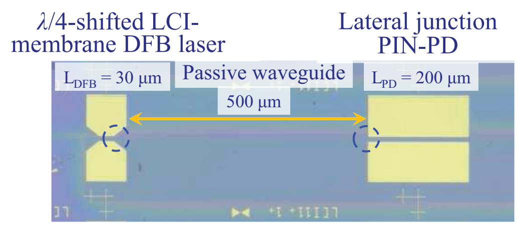
I. Introduction

On-chip optical interconnection is attractive for future LSI technology. Current copper global interconnects limit future Si LSI circuits performance by its RC delay and heat generation. However optical devices in on-chip optical interconnect are required to operate with ultra-lower energy consumption and smaller device size than conventional optical devices for long-haul communications. Especially energy cost of the transmitter is required to be significantly less than 100 fJ/bit [1]. We have been investigating membrane (100–300-nm-thick III-V semiconductor) DFB lasers for the light source of on-chip optical interconnection on a Si substrate [2]. Since, the membrane structure offers strong optical confinement for semiconductor core layer due to the large index difference between a core semiconductor layer and low index cladding materials. This leads to large optical modal gain and enables to fabricate compact lasers based on strongly index-coupled DFB structure. Therefore, ultra-low threshold operation of laser can be expected by using this membrane structure. We previously reported sub-mA threshold operation of lateral-current-injection (LCI) membrane DFB laser with butt-jointed built-in (BJB) waveguides bonded on a Si substrate [3]. However, an integration of LCI-membrane DFB laser and photodiode (PD) has not been demonstrated.

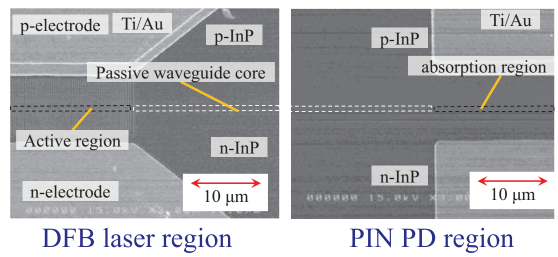
In this paper, we present monolithic integration of the LCI-membrane DFB laser and lateral junction PIN-PD by BJB structure bonded on a Si substrate. The 30-µm-long $\lambda/4$-shifted LCI-membrane DFB laser operated at a threshold current of 280 µA which is lower than previous report [3]. The laser output coupled into 500-µm-long BJB waveguide was successfully detected by 200-µm-long PIN-PD.

II. Device Structure and Fabrication Process

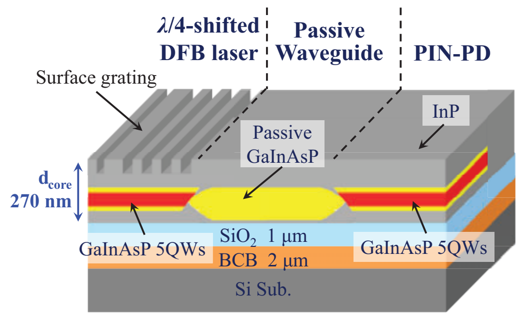
Figs. 1(a)-(c) show optical microscopic image, scanning electron microscopic (SEM) image, and schematic diagram of fabricated device respectively. As shown in Fig. 1 (a), the LCI-membrane DFB laser and lateral junction PIN-PD were connected by a passive BJB waveguide. These devices have a same stripe width of 0.7 µm, which satisfies single-transverse-mode condition. The PIN-PD has MQWs absorption layer which is the



(a) Optical microscopic image



(b) SEM images of top view.



(c) Schematic diagram of cross section.
Fig. 1 Structure of the fabricated device.

same as active layer of the laser section. A $\lambda/4$ phase-shift region was introduced in the DFB laser for reducing the total cavity length as well as for a stable single-mode operation. An initial wafer consisted of etch stop layers (300-nm-thick GaInAs and 100-nm-thick InP), p^+-GaInAs contact layer (N_A = 8 × 10^{18} cm^{-3}, 50 nm), and 270-nm-thick core layer, which were grown on an n-InP (100) substrate by gas source MBE. The core layer included GaInAsP 5QWs (λ_g = 1520 nm), 50-nm-thick undoped InP cap layer, and 100-nm-thick p-doped InP cap layer. The fabrication process of the device is described below. First, island mesa structure of the active region covered with SiO_2 mask was formed by reactive-ion-etching and selective wet etching. Then, a GaInAsP passive

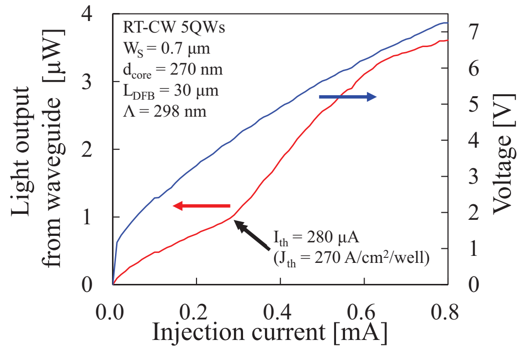


Fig. 2 Light output and voltage-current characteristics of λ/4-shifted membrane DFB laser.

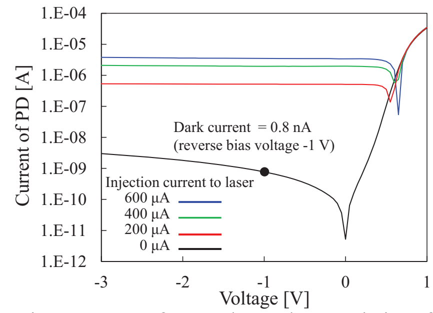


Fig.3 Current of PD-voltage characteristics of under various injection currents to the laser.

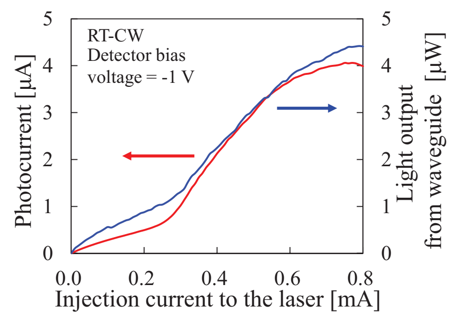


Fig.4 Photocurrent-injection current to laser characteristics.

waveguide core layer (λ_g = 1220 nm) was grown by OMVPE selective-area-growth. Subsequently, two-step regrowth of n- and p-InP layers for the lateral PIN junction structure, a BCB wafer bonding on a Si substrate, and an electrode formation were conducted [4]. Finally, a surface grating was formed by an electron beam lithography. Then the substrate was cleaved into bar form at the passive waveguide section.

III. Measurements

The light output was measured from a facet cleaved at the waveguide section with its length of approximately 500 μm so as to compare with a photocurrent detected by the PIN-PD. Fig. 2 shows light-current and voltage-current characteristic of the λ/4-shifted membrane DFB laser with a cavity length L_{DFB} of 30 μm and a stripe width W_s of 0.7 μm under a room-temperature continuous-wave (RT-CW) condition. A threshold current I_{th} of 280 μA and an external differential quantum efficiency η_d of 1% (waveguide output) were obtained. A threshold current density J_{th} was 1350 A/cm^2 (270 A/cm^2/well), which was approximately 3 times higher than that of longer cavity (100 μm) device. This poor threshold current as well as low η_d may be attributed to a leakage current between the DFB and the passive waveguide sections since η_d = 22%/facet was obtained for membrane Fabry-Perot cavity lasers [4].

The lasing wavelength was 1536 nm, and a sub-mode suppression ratio (SMSR) of 30 dB was obtained at a bias current of 700 μA. The stopband width was observed to be 35 nm from a lasing spectrum of another device with a cavity length of 100 μm, which corresponds to the refractive index-coupling coefficient κ of approximately 1600 cm^{-1}, hence the grating coupling strength of the device with L_{DFB}= 30 μm is κL= 4.8.

Next, a photocurrent of the PIN-PD monolithically integrated with the DFB laser through 500 μm long BJB passive waveguide was measured. The responsivity of the PIN-PD was separately measured to be 0.8 A/W by coupling an external light source with the assumption of a lensed fiber coupling efficiency of 2.3%. Fig. 3 shows current versus voltage characteristics of the PD under various injection currents to the DFB laser. A dark current of the PD was 0.8 nA at a bias voltage of -1 V.

Fig. 4 shows the photocurrent versus injection current to the DFB laser with the bias voltage to the PD of -1 V, where the blue and red lines indicate light output characteristic of the DFB laser and the photocurrent, respectively. In this measurement, both n-side electrodes were set to be common ground, and the isolation resistance between the p-side electrodes of the laser and the photodiode was approximately 80 MΩ. At the laser threshold current of 280 μA, the kink of photocurrent was observed and a photocurrent of approximately 3 μA for the light output of the DFB laser of around 3 μW indicates quite high coupling between these devices as well as high quantum efficiency of the PIN-PD.

IV. Conclusion

For on-chip optical interconnection, we demonstrated monolithic integration of λ/4-shifted LCI-membrane DFB laser and lateral junction PIN-PD by BJB structure bonded on Si substrate. The 30 μm-long λ/4-shifted membrane DFB laser operated with a threshold current of 280 μA under a RT-CW condition. The light output of laser coupled into BJB waveguide was successfully detected by integrated PIN-PD.

Acknowledgment

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