# Lateral Junction Waveguide Type Photodiode for Membrane Photonic Circuits

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## Abstract

A lateral junction type photodiode grown on a semi-insulating InP substrate was realized by 3-step OMVPE growth. The responsivity of 0.27 A/W, 3 dB bandwidth of 6 GHz and 7.5 GHz at a bias voltage of 0 V and -2 V, respectively, were obtained for the stripe width of 1.4 µm and device length of 220µm. An error free transmissions up to 6 Gbps at 0 V were confirmed.

*Keywords- Photodiode, Waveguide, Lateral junction, Membrane photonic circuits.*

## I. INTRODUCTION

Higher computing performance has been achieved due to the progresses of device densities and operation speed by scaling down CMOS transistor size to follow Moore's law. However, further performance improvement will be limited by both power consumption due to heat generation [1] of the global metal interconnect and operation speed due to the RC delay [2]. To solve this problem, a lot of works on an optical interconnection that replaces the electric wiring have been pursued [3]-[5]. Moreover, the optical interconnection is expected to have low electromagnetic noise property.

To realize the optical interconnection on LSI, low power consumption and compact optical active devices such as lasers, amplifiers, and detectors are needed. For this demand, we have proposed a membrane distributed-feedback (DFB) laser, which consists of a thin (~ 150 nm-thick) semiconductor core layer including active regions with grating sandwiched by low-index polymer cladding layer [6]. The membrane structure has a strong optical confinement into the core layer and allows lasing operation with very low threshold. So far, a low threshold optical pump power (0.34 mW) with a stable single-mode operation was demonstrated under room-temperature continuous-wave (RT-CW) condition [7]. With the aim of realizing injection-type membrane lasers, a lateral current injection (LCI) structure [8] was adopted and RT-CW operation of LCI buried-hetero structure (BH) lasers with 400-nm-thick GaInAsP core layer grown on a semi-insulating (SI) InP substrate has been demonstrated [9],[10]. This membrane structure is also attractive for waveguide type photodiodes because the device length can be shortened due to its high optical confinement structure compared with previously reported photodetectors with a lateral junction [11], hence higher speed operation due to a feature of low capacitance will be expected.

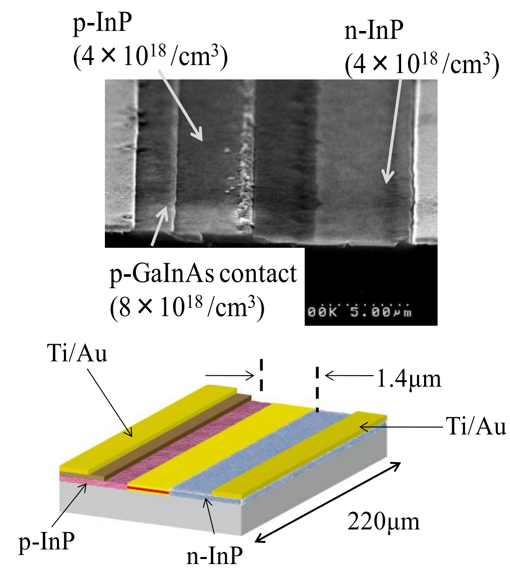


Fig. 1 The schematic structure and the cross sectional SEM view of the device.

In this paper, we would like to present fundamental properties of a lateral junction waveguide type photodiode with thin current injection layer thickness.

## II. DEVICE STRUCTURE AND FABRICATION

The schematic structure and the cross sectional SEM view of the fabricated device structure are shown in Fig. 1 and the fabrication process are shown in Fig. 2. An initial wafer with undoped GaInAsP core layers consisting of five quantum-wells (QWs, $Ga_{0.22}In_{0.78}As_{0.81}P_{0.19}$, 6 nm thick), barriers ($Ga_{0.26}In_{0.74}As_{0.49}P_{0.51}$, 10 nm thick) and optical confinement layers (OCLs, $Ga_{0.21}In_{0.79}As_{0.46}P_{0.54}$), were prepared by organo-

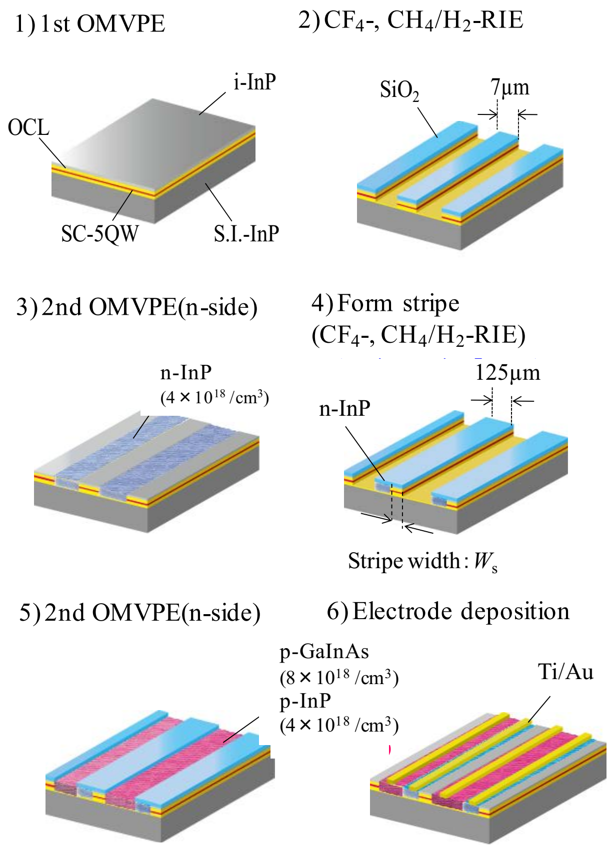


Fig. 2 Fabrication processes of the lateral junction waveguide type photodiode

metallic vapor-phase-epitaxy (OMVPE) on an Fe-doped SI-InP substrate. The total GaInAsP layer thickness was 380 nm. Then, the lateral junction structure was fabricated by reactive-ion-etching (RIE) and 2-step OMVPE selective area growth [12]. First, a mesa stripe structure with 7-µm-wide and 380-nm-high was formed with a $SiO_2$ mask. After removing plasma damaged sidewall by sulfuric acid based solution, n-InP ($N_D = 4 \times 10^{18}$ /cm$^3$) was selectively regrown at the side of the mesa as a cladding layer. Next, by etching the part of the wide mesa and the one side of the buried n-type layer in the similar way, narrow (1.4-µm-wide) stripes were formed. Then, p-InP ($N_A = 4 \times 10^{18}$ /cm$^3$) cladding and p-GaInAs contact layers were regrown in a similar way. After that, the part of the GaInAs contact layer near the stripe edge was removed by sulfuric acid solution to reduce optical absorption. Finally, Ti/Au electrode was deposited on both the p-GaInAs contact and the n-InP sections with spacing of 16 µm.

## III. Experimental Results and Discussion

As cleaved device with the length and the stripe width of 220 µm and 1.4 µm, respectively, was used for measurements. The spectral response of the photocurrent was measured by using tunable lasers, which can be scanned from 1420 nm to 1620 nm,

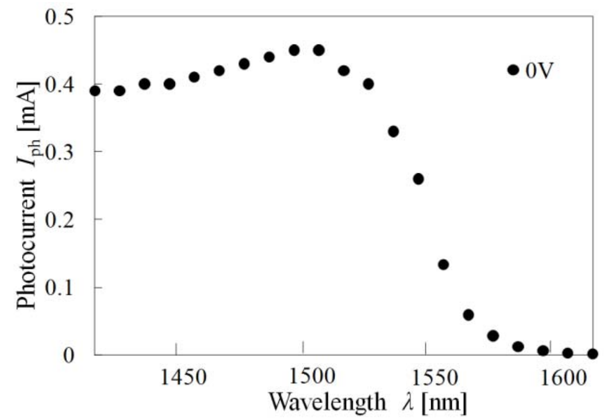


Fig. 3 Input power dependence ofphotocurrent.

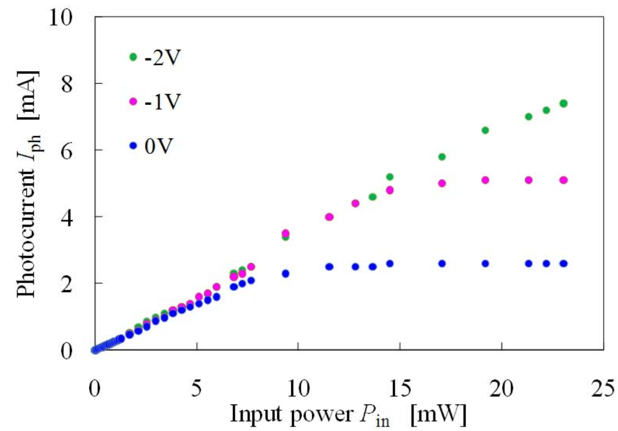


Fig. 4 Input light intensity dependence of photocurrent.

and a polarization controller to couple TE-polarized light as shown in Fig. 3. The input power coupled to the waveguide was estimated to be around 0.85 mW with consideration that the output power of 2 mW from lensed fiber and -3.7 dB coupling loss between the fiber to the device. Figure 4 shows input power dependence of photocurrent, $I_{ph}$, at a bias condition of 0 V, -1 V, and -2 V, where $I_{ph}$ was obtained by subtracting the dark current from the total current. The dark current at -2 V was 660 nA which is not sufficiently low for the device size. From these values the responsivity of the device is estimated to be 0.27 A/W at the wavelength of 1550 nm, which is around 1/5 of typical GaInAs/InP photodiode [13], because the initial wafer was designed for 1.55 µm wavelength laser, hence the absorption coefficient at this wavelength is low as shown in Fig 3. Design modifications for photodiode, such as GaInAs bulk material as an absorption material instead of 1.55µm QWs or using anti-reflection coating, will be required for higher responsivity.

The frequency response of the device is shown in Fig 5. An electrical signal from a network analyzer was converted into a light signal with a network performance tester in which a LN modulator and a DFB laser were built, then the light signal was converted into an electrical signal with the lateral junction

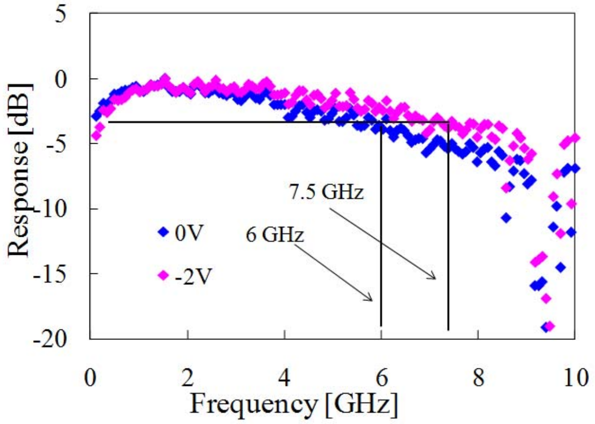


Fig. 5 Frequency response of the waveguide type lateral junction photodiode at bias voltages of 0 and -2 V.

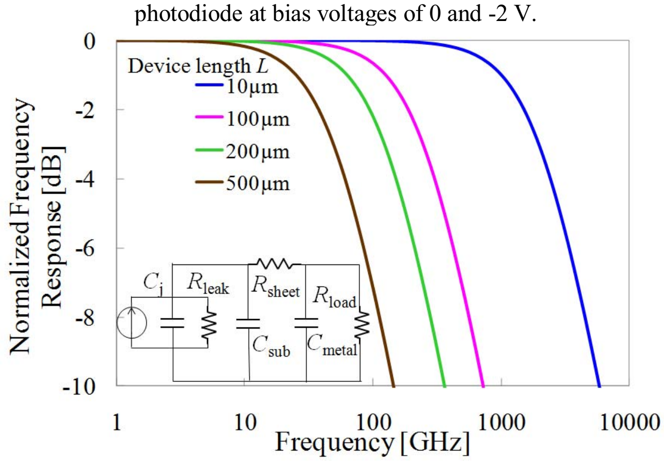


Fig. 6 Frequency response of 1 μm wide waveguide device in terms of RC limitation.

photodiode. The signal calibration of $S_{21}$ characteristics of the network analyzer has been done under the consideration of electrical cable characteristics. Current-voltage conversion was just done by internal 50-ohm impedance in the network analyzer. The low response at low frequency side (< 1 GHz) might be due to the impedance mismatching between the device and submount. The 3dB bandwidth was observed to be 6 GHz at non-bias condition and 7.5 GHz at the bias condition of -2 V when it was measured from the peak response. The speed of the device was limited by the transit time of holes in the GaInAsP OCL or by RC time constant because of relatively long distance between electrodes and thin (380 nm) carrier transport channel.

Figure 6 shows the calculated frequency response for several device lengths limited by only the RC time constant. The intrinsic response is modeled as a current source in parallel with a junction capacitor and resistance derived from leakage current. The diode series resistance, parasitic capacitances in the substrate and metal [14], and load resistance form the external circuit. From this calculation, more than 40 GHz bandwidth is expected even for the device length longer than 500 μm. On the other hand, the

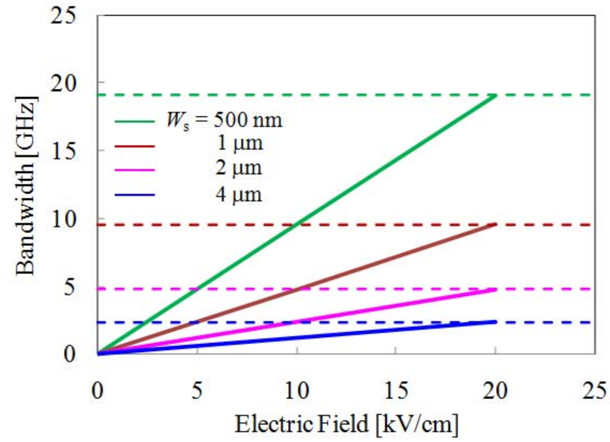


Fig. 7 Bandwidth calculated from carrier transit time under applied electric field..

bandwidth dependence on the applied electric field limited by the transit time of holes is shown in Fig. 7. Though the bandwidth can be increased by applying voltage, the carrier velocity is saturated at a point. The dashed lines show the bandwidth limitation of each waveguide width defined by the saturation velocity. In this calculation, the saturation velocity of holes in GaInAs was assumed to be $6.0\times10^{6}$ cm/s [15]. To obtain higher speed operations, one simple solution is narrowing waveguide width less than 500 nm [16]. Another solution is applying the Uni-Traveling-Carrier (UTC) structure which uses only electrons as its active carriers [17].

Figure 8 shows bit error rate (BER) measurement results and eye diagrams at 6 and 10 Gbps. Clear eye opening was obtained up to 10 Gbps when biased with -2 V. The pseudo random bit sequence (PRBS) non-return-to-zero (NRZ) signal with the word length of $2^{31}$-1 from a pulse pattern generator was converted into light signals with the performance tester and input to the photodiode, then electrical signal from the device was measured by the error detector. The horizontal axis contained the coupling loss of 3.7 dB and the loss in measurement system of -4 dB, respectively. Error free back-to-back transmissions were obtained from 1 Gbps to 6 Gbps at non-bias condition. However, the averaged received power for this measurement was so high due to its poor responsivity which can be improved by adopting an appropriate design of the device.

## IV. Conclusion

As a candidate for membrane photonic circuits, waveguide type lateral junction photodiode with considerably thin layer was realized on a SI-InP substrate. The responsivity of 0.27 A/W, 3dB bandwidth of 6 GHz at 0 V and 7.5 GHz at -2 V, and an error free detection up to 6 Gbps at 0 V were obtained for the stripe width of 1.4 μm and the device length of 220 μm. Further

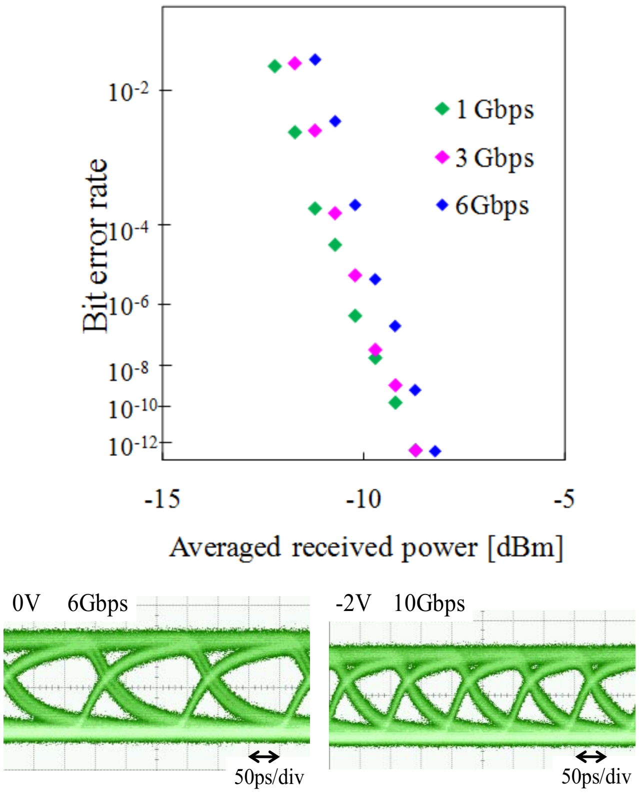


Fig. 8 BER measurements at 0Vcondition and eye patterns.

investigations for high-speed and high responsivity operation will be required.

## Acknowledgment

We would like to thank Professor Emeriti Y. Suematsu and K. Iga, Professors K. Kobayashi, K. Furuya, M. Asada, and F. Koyama, T. Mizumoto and Associate Professors Y. Miyamoto, M. Watanabe, T. Miyamoto, and H. Uenohara of Tokyo Institute of Technology for fruitful discussions. This research was financially supported by a Grant-in-Aid for Scientific Research (#19002009, #19686023, #21226010 and #08J55211) from the Ministry of Education, Culture, Sports, Science and Technology, Japan (MEXT).

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