Extended Abstracts of the 2017 International Conference on Solid State Devices and Materials, Sendai, 2017, pp407-408

Membrane-based GaInAs/InP waveguide-type p-i-n photodetector fabricated on Si substrate using Benzocyclobutene bonding

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Abstract

A GaInAs/InP waveguide-type p-i-n membrane photodetector bonded on Si substrate has been demonstrated as a strong candidate of on-chip optical interconnection. A responsivity of 0.95 A/W was estimated with device length of 30 μm and this value is higher than our previously reported devices.

1. Introduction

On-chip optical interconnection has been holding worldwide attention in recent years because of its noticeable potentiality for solving the fundamental limitations of electrical interconnects in the global wire layer of LSIs [1]. To be competitive with near-future electrical global interconnects, ultralow power consumption optical devices with extremely small footprint are strongly required. A membrane-structure-based in-plane photonic platform has been proposed for fulfilling such demand. The membrane structure consists of a thin semiconductor core layer sandwiched by low refractive-index dielectric materials such as SiO_2 or Benzocyclobutene (BCB), can provide significantly strong optical confinement of the active region of the laser source or the absorption region of the waveguide-type photodetector (PD) as two fundamental optical devices in the on-chip photonic integrated circuit, leading to the miniaturization and low energy cost of the device. In this case, lateral p-i-n structure will be required for electrical pumping and photocurrent collection.

Several steps of study of membrane-type PDs have been conducted in the past few years, including the GaInAsP/InP multi-quantum-well (MQW) and bulk-GaInAs/InP absorption layer based LCI-PD on SI-InP substrate [2,3]. Also, a membrane MQW-PD formed on Si substrate has been demonstrated recently as a component of the monolithic integrated circuit [4]. In this work, we demonstrated a membrane bulk-GaInAs/InP waveguide-PD with higher responsivity and shortened device length compared to the former devices and the measured responsivity showed higher value compared with the previous demonstrations mentioned above.

2. Device structure and experiment result

Figure 1 shows the schematics of the GaInAs/InP p-i-n waveguide type membrane PD bonded on Si substrate. A GaInAs bulk is sandwiched by *n*-InP and *p*-InP side clad with a top 100-nm *p*-InP clad and 50-nm bottom *u*-InP clad (exactly the same layer structure with the membrane laser except for the active region), which also forms a lateral p-i-n junction. The PD is connected with a 155-nm GaInAsP (λ_g = 1.2 μm)-core-layer channel waveguide using a butt-joint built-in (BJB) structure in consideration of the integration with other membrane devices.

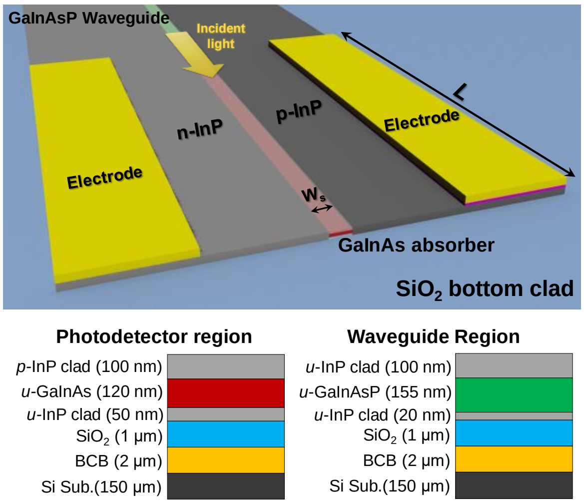

Fig. 1. Schematics of GaInAs/InP p-i-n waveguide-type membrane PD bonded on Si substrate.

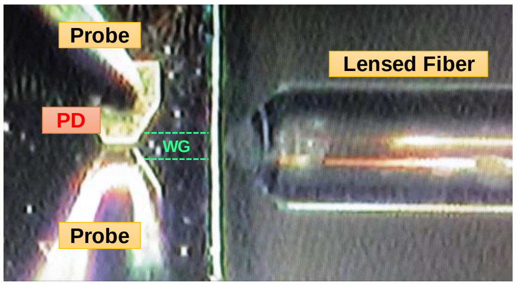

Fig. 2. CCD image of the device measurement setting

Figure 2 shows the measurement setting of the fabricated device. TE-polarized light from a spherical-lensed single-mode polarization-maintaining fiber is incident into the passive GaInAsP waveguide connected with the PD. Therefore, the measured responsivity of the PD based on this setting can be described as the following Eq. (1):

$$R_{ex} = \eta_f \cdot \eta_{wg} \cdot \eta_c \cdot \eta_i \cdot \frac{q}{h\nu} \cdot \left(1 - e^{-\xi \alpha L}\right) \qquad (1)$$

Where R_{ex} is the measured responsivity, η_f is the coupling efficiency between fiber and the waveguide, η_{wg} is the attenuation rate due to the propagation loss in passive waveguide, η_c is the coupling efficiency between the waveguide and the PD, η_i is the internal quantum efficiency, q is the electron charge, h is the Planck constant, v is the frequency of light, ξ is the optical confinement factor, α is the absorption coefficient of GaInAs and L is the absorption length. In this work, devices with different stripe width W_s of the GaInAs absorber and different absorption length have been assessed with a fixed wavelength of 1.55 µm.

The measured photocurrent I_{pd} against Input power P_{in} of a device with L = 30 µm and W_s = 0.7 µm (same as the reported laser stripe width) based on different bias voltage is shown in Fig. 3, which indicate a R_{ex} of 0.19 A/W. However, the η_f should be excluded from the R_{ex} for assessing the responsivity of device itself since the light from the laser source will be directly incident to the passive-waveguide-connected PD in the case of integrated platform. The fiber-waveguide coupling η_f is calculated to approximately 20% by using a commercial photon design suite FIMMPROP, which indicated that the responsivity of device (including η_{wg} and η_c) is 0.95 A/W. Saturation of the photocurrent due to carrier accumulation was observed under the bias condition of 0V.

Figure 4 provides the absorption-length-dependent R_{ex} with different W_s under a bias voltage of -1V. Wider stripe provide larger Γ to the GaInAs absorber as it can be seen in the mode field distribution. The theoretical curve based on Eq. (1) with an adjustable loss parameter ($\eta_f\eta_{wg}\eta_c\eta_i$), calculated Γ with different W_s, and a fixed material absorption coefficient α of 5000 cm^{-1} fit well with the experiment plots. The reduction of R_{ex} of device with W_s of 500 nm is mainly caused by the drastically decreased η_{wg} of the large mode field in the narrow waveguide, which suffers greatly from the absorption loss of heavily doped *p*-InP side clad and the scattering loss. The theoretical curve indicates that a light absorption above 90% as a sufficient value in the design of PD can be achieved with a device length of 10 µm with W_s larger than 0.7 µm.

Finally, experimental results of on-chip PDs proposed in the past years are listed in Table I for comparison. An improvement of responsivity with significantly shortened device length of our previously devices has been achieved. And a further improvement can be expected by introducing a photonic crystal (PhC) structure according to Ref [5].

3. Conclusion

Experiment results of the responsivity of GaInAs/InP LCI p-i-n membrane photodetectors with different stripe width and absorption length have been demonstrated. 0.95 A/W was estimated with a device length of 30 µm and stripe width 0.7 µm. Curve fitting of the experiment results indicated that absorption above 90% can be expected with a 10-µm device length, which is a sufficient value for on-chip interconnection.

Acknowledgements

This work was supported by JSPS KAKENHI Grant Numbers #15H05763, #17H03247, #15J11776, #16H06082, #16J11581, #17H03247 and JST CREST Grant Number PMJCR15N6.

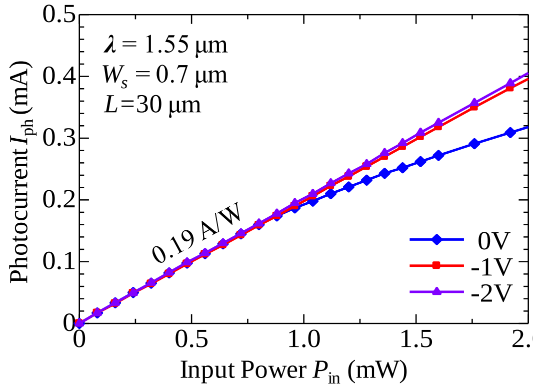

Fig. 3. Photocurrent against independent power at 1550 nm with various bias voltages.

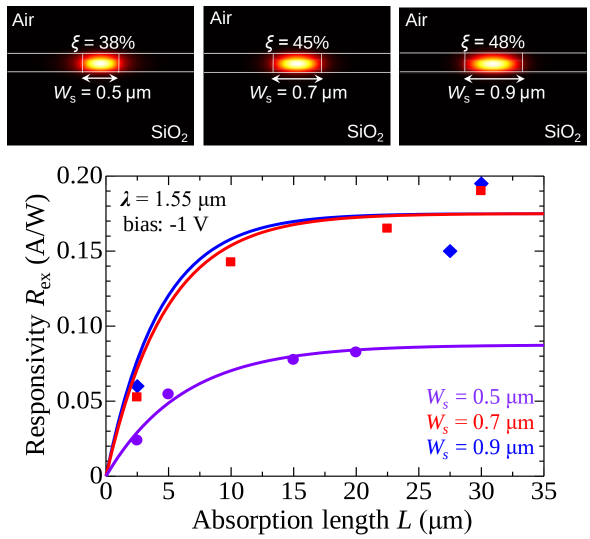

Fig. 4. Experiment plots and theoretical curve of R_{ex} against absorption length at 1550 nm with various stripe widths W_s and their mode field distributions.

Table I Comparison with previously demonstrated devices

Structure	Stripe width	Absorb length	λ	Responsivity	Ref
MQW-PD SI-InP sub.	1.40 µm	220 µm	1500 nm	0.90 A/W	[2]
			1550 nm	0.27 A/W	
GaInAs-PD SI-InP sub.	0.85 µm	390 µm	1550 nm	0.39 A/W	[3]
MQW-PD Si sub.	0.70 µm	200 µm	1550 nm	0.80 A/W	[4]
PhC-GaInAs-PD	0.40 µm	1.7 µm	1537 nm	0.98 A/W	[5]
This work	0.70 µm	30 µm	1550 nm	0.95 A/W	

References

[1] D. A. B. Miller, Proc. IEEE. **97** (2009) 1166.
[2] T. Okumura *et al.*, *Jpn. J. Appl. Phys.* **50** (2011) 020206.
[3] T. Shindo *et al.*, *Jpn. J. Appl. Phys*. **52** (2013) 118002.
[4] D. Inoue *et al.*, IEEE. J. Sel. Top. Quantum Electron. **21** (2015) 1502907.
[5] K. Nozaki *et al.*, *Optica* **3** (2016) 483.