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Japanese Journal of Applied Physics **50** (2011) 020206 **RAPID COMMUNICATION**

DOI: 10.1143/JJAP.50.020206

Lateral Junction Waveguide-Type Photodiode Grown on Semi-Insulating InP Substrate

Tadashi Okumura[1], Daisuke Kondo[1], Hitomi Ito[1], SeungHun Lee[1],
Tomohiro Amemiya[2], Nobuhiko Nishiyama[1], and Shigehisa Arai[1,2]

[1] *Department of Electrical and Electronic Engineering, Tokyo Institute of Technology, Meguro, Tokyo 152-8552, Japan*
[2] *Quantum Nanoelectronics Research Center, Tokyo Institute of Technology, Meguro, Tokyo 152-8552, Japan*

Received July 20, 2010; accepted December 3, 2010; published online February 7, 2011

A lateral junction waveguide-type GaInAsP/InP photodetector was fabricated on a semi-insulating InP substrate by two-step organometallic vapor-phase epitaxy (OMVPE) regrowth. Responsivities of 0.9 A/W at 1500 nm and 0.27 A/W at 1550 nm were obtained. A 3-dB bandwidth of 6 GHz and 6-Gbps error-free operation under non-bias conditions were achieved with a stripe width of 1.4 μm and a device length of 220 μm.

Photonic integrated circuits (PICs) with low power consumption and a highly functional optical network have attracted considerable interest in the fields of communication and device research.[1)] The optical linking instead of conventional electrical wire for data transmission is promising for realizing high speed computing system like chip to chip or board to board communication in near future.[2)] For example, it is believed that very soon the limiting factor for very large-scale integration (VLSI) will be wiring, and not logic devices. Signal delay, power consumption, crosstalk, and other factors will present serious problems in designing the entire system. In order to apply semiconductor photonic devices to an optical interconnection with a short length, a low-power-consumption driving technology and a small footprint could be important requirements.[3)] High-index-contrast waveguides have attracted considerable attention for use in compact and low-power PICs that have a high degree of integration.[4,5)]

We proposed semiconductor membrane-based waveguide devices with strong optical-field confinement in the core layers along the vertical direction to achieve low threshold and high efficiency operation as well as relatively small footprint.[6)] Low-threshold-power (0.34 mW) operation of a membrane distributed feedback (DFB) laser was confirmed under room-temperature continuous-wave (RT-CW) optical pumping.[7)] However, an electrical drive system for membrane-based photonic devices has not been realized thus far because low index cladding layer materials such as dielectric or air are insulator, we cannot inject current through such cladding layers with a conventional vertical pn junction structure in the membrane layers. Since the lateral current injection (LCI) structure, reported for devices with thick (1 μm) current-guiding layers,[8)] appears promising for membrane-based photonic devices, we introduced an LCI buried heterostructure (BH) into a thin-core (only 400 nm) GaInAsP laser grown on a semi-insulating (SI) InP substrate.[9)] Thus far, RT-CW operation has been demonstrated with a threshold current of 11 mA and a differential quantum efficiency of 33%. Toward the PICs with the membrane-based photonic devices, a lateral junction waveguide-type photodiode, which consists of similar structures and is suitable for monolithic integration with membrane lasers, will be desired. Although a 1-Gbps eye opening with a thick current-guiding LCI structure has been reported,[10)] further investigation and improvement of device characteristics is required for high-speed on-chip optical interconnection.

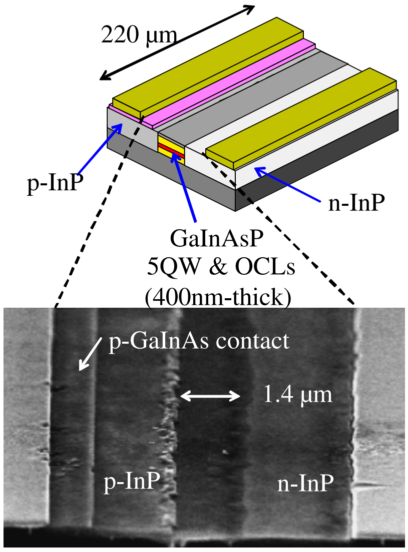


Fig. 1. (Color online) Schematic structure and SEM top view of fabricated device.

In this letter, we report the fundamental properties of a lateral junction waveguide-type photodiode with thin current injection layer.

The schematic structure and a scanning electron microscope (SEM) top view of the fabricated device are shown in Fig. 1. First, a 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, $Ga_{0.21}In_{0.79}As_{0.46}P_{0.54}$, 145-nm-thick OCLs on both sides), was prepared by organometallic vapor-phase epitaxy (OMVPE) on an Fe-doped SI-InP substrate. Then, the lateral junction structure was fabricated by reactive ion etching (RIE) and two-step OMVPE selective area growth, using a previously reported method.[9)]

A cleaved device with a length and a stripe width (W_s) of 220 and 1.4 μm, respectively, was used for measurements. Under the assumption confinement factor of a 5% into the five-QWs and an absorption coefficient of $5000\,cm^{-1}$ at a wavelength of 1500 nm, most of the light input propagating in this waveguide could be absorbed. Figure 2 shows the voltage–current characteristic after the device was mounted on a AlN sub-mount for high-speed measurement. The differential resistance at the forward bias region of 34 Ω is mainly due to the sheet resistance of the p-InP layer. The

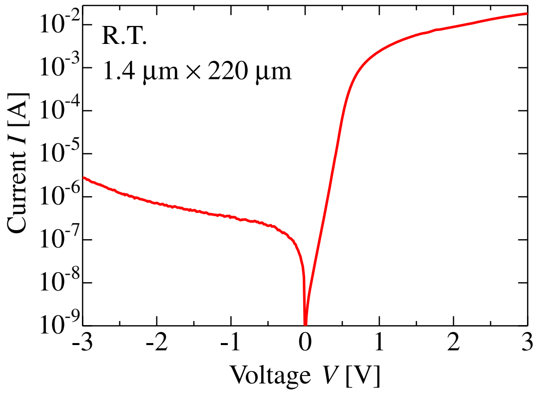


Fig. 2. (Color online) Measured I–V curve of lateral junction waveguide-type diode.

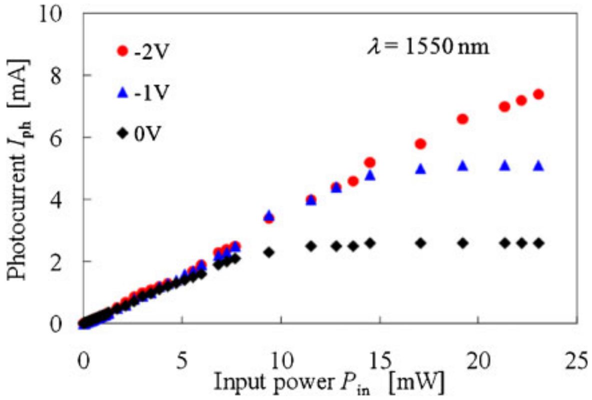


Fig. 4. (Color online) Photocurrent against incident power at 1500 nm for different bias voltages.

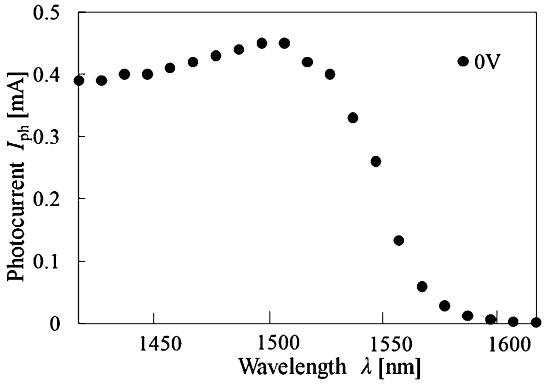


Fig. 3. Spectral response of photocurrent for input power P_{in} of 0.85 mW.

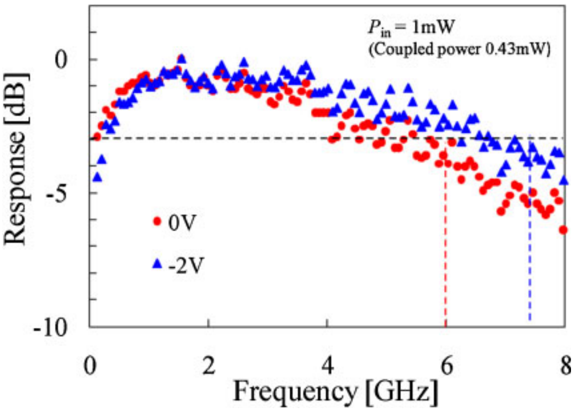


Fig. 5. (Color online) Frequency response of lateral junction waveguide-type photodiode at bias voltages of 0 and −2 V.

dark current at −2 V was 660 nA (220 mA/cm^2), which is not sufficiently low for the device size.

The spectral response of the photocurrent, as shown in Fig. 3, was measured using tunable lasers and a polarization controller to couple only transverse-electric (TE)-polarized light through a lensed fiber with a coupling loss of 3.7 dB. The incident optical power, P_{in}, was fixed at 2 mW, and the P_{in} coupled to the waveguide was estimated to be around 0.85 mW. Since the device length was sufficiently long, the responsivity was estimated to be 0.9 A/W (a quantum efficiency of 72%) at 1500 nm and 0.27 A/W at 1550 nm. Figure 4 shows the incident power dependence of photocurrent, I_{ph}, at a 1500-nm wavelength, and bias conditions of 0, −1, and −2 V. Saturation of the photocurrent due to carrier accumulation was observed under the bias conditions of 0 and −1 V. Transverse-magnetic (TM)-mode response was measured to be 0.65 A/W around 1520-nm wavelength, which is lower than the responsivity for TE mode because of the compressively strained quantum wells.

High-speed measurements were performed at a 1550-nm wavelength due to the limitation of our performance tester. 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 1550-nm-wavelength DFB laser were installed, then the light signal was converted into an electrical signal by the lateral junction photodiode. The signal calibration of the S$_{21}$ characteristics of the network analyzer was performed with consideration for the characteristics of the electrical cable. Current–voltage conversion was performed at an internal impedance of 50 Ω using the network analyzer. Figure 5 shows the frequency response of the device, in which the reduction of the response on the low-frequency side (<1 GHz) might be due to a mismatch between the impedance of the device on the submount and the measurement setup. Because the submount didn't contain a 50 Ω load resistance parallel to the photodiode for an impedance matching, the output impedance at low-frequency was dominated by reverse-biased resistance (> MΩ) of the photodiode. The 3-dB bandwidth was observed to be 6 and 7.5 GHz under the bias conditions of 0 and −2 V, respectively. The speed of the device was considered to be limited by the carrier transit time (t_{tr}) in the absorption layer, because the RC time constant was not large due to lower capacitance ($C = 20$ fF), as compared to that in a vertical pn junction structure.[8,11] Figure 6 shows that the calculated bandwidth dependence is limited by the transit time of holes as a function of the applied electric field.[12] Although the bandwidth can be increased by applying the bias voltage, at a certain point the carrier velocity becomes saturated. In this calculation, the saturation velocity of holes of GaInAs was assumed to be 6.0×10^6 cm/s.[13] To obtain a bandwidth larger than 15 GHz, the width of the waveguide must be as

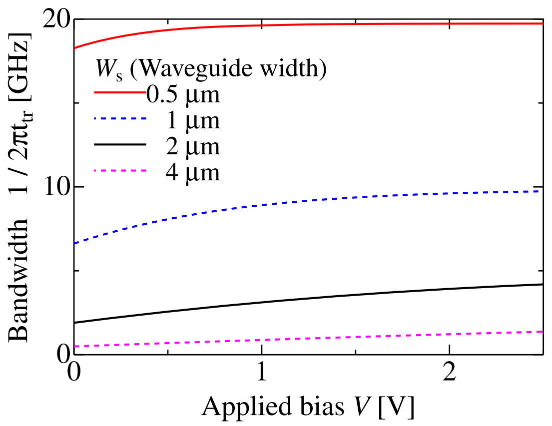
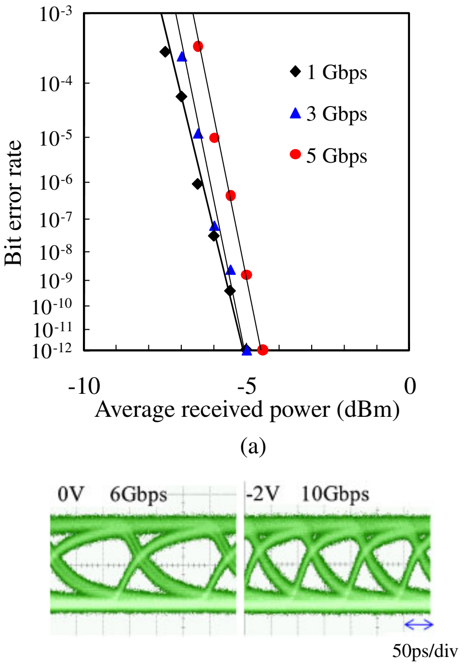


Fig. 6. (Color online) Bandwidth calculated from carrier transit time under applied electric field.



(a)

(b)

Fig. 7. (Color online) BER characteristics under (a) non-bias condition and (b) eye patterns for 6 and 10 Gbps.

narrow as 500 nm.[14)] Another solution for extending the bandwidth is the application of a uni-traveling-carrier (UTC) structure that uses only electrons as its active carriers.[15)]

Figure 7 shows the bit error rate (BER) measurement results under a non-bias condition for 1, 3, and 6 Gbps and eye diagrams at 6 and 10 Gbps. A clear eye opening was obtained at up to 10 Gbps when biased with −2 V. The pseudo random bit sequence (PRBS) non-return-to-zero (NRZ) signal with a word length of $2^{31} - 1$ from a pulse pattern generator was converted into light signals using the performance tester and input to the photodiode, after which the electrical signal from the device was measured by the error detector. The horizontal axis still contained the coupling loss of 3.7 dB between the fiber and the waveguide. Though the averaged received power for this measurement was so high due to its poor responsivity, error-free back-to-back transmissions were obtained from 1 Gbps at the coupled input power of −8.7 dBm to 6 Gbps at −8.2 dBm under a non-bias condition. By adopting an appropriate design for the device, an improvement of the high received power and a reduction in the device size could be realized.

In conclusion, a lateral junction waveguide-type photodiode with a thin current injection layer was fabricated on an SI-InP substrate. A 3-dB 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 achieved. Further analysis and refinements are required for high-speed operation with high responsivity for application to membrane photonic circuits.

Acknowledgments We would like to thank Professors Emeritus Y. Suematsu and K. Iga, K. Furuya, and K. Kobayashi for their continuous encouragement. We are also grateful to Professors M. Asada, F. Koyama, T. Mizumoto, Y. Miyamoto, M. Watanabe, T. Miyamoto, and H. Uenohara of the Tokyo Institute of Technology and T. Maruyama of Kanazawa University for their fruitful discussions. This research was partially supported by Grants-in-Aid for Scientific Research (Nos. 19002009, 21226010, 21860031, 22360138, 08J55211, and 09J08757) and JSPS-FIRST from the Ministry of Education, Culture, Sports, Science and Technology, Japan (MEXT). The first author acknowledges the Japan Society for the Promotion of Science (JSPS) for its research fellowship for young scientists.

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1) G. Chen, H. Chen, M. Haurylau, N. A. Nelson, D. H. Albonesi, P. M. Fauchet, and E. G. Friedman: Integration—VLSI J. **40** (2007) 434.
2) A. V. Krishnamoorthy and K. W. Goossen: IEEE J. Sel. Top. Quantum Electron. **4** (1998) 899.
3) D. A. B. Miller: Proc. IEEE **97** (2009) 1166.
4) T. Tsuchizawa, K. Yamada, H. Fukuda, T. Watanabe, J. Takahashi, M. Takahashi, T. Shoji, E. Tamechika, S. Itabashi, and H. Morita: IEEE J. Sel. Top. Quantum Electron. **11** (2005) 232.
5) R. Katouf, N. Yamamoto, A. Kanno, N. Sekine, K. Akahane, H. Sotobayashi, T. Isu, and M. Tsuchiya: Appl. Phys. Express **1** (2008) 122101.
6) T. Okamoto, N. Nunoya, Y. Onodera, S. Tamura, and S. Arai: Electron. Lett. **37** (2001) 1455.
7) S. Sakamoto, H. Naitoh, M. Otake, Y. Nishimoto, S. Tamura, T. Maruyama, N. Nishiyama, and S. Arai: IEEE J. Sel. Top. Quantum Electron. **13** (2007) 1135.
8) K. Oe, Y. Noguchi, and C. Caneau: IEEE Photonics Technol. Lett. **6** (1994) 479.
9) T. Okumura, H. Ito, D. Kondo, N. Nishiyama, and S. Arai: Jpn. J. Appl. Phys. **49** (2010) 040205.
10) S. Murata, M. Arai, and K. Oe: IEEE J. Sel. Top. Quantum Electron. **8** (2002) 1366.
11) S. Gevorgian, H. Berg, H. Jacobsson, and T. Lewin: IEEE Microwave Mag. **4** (2003) 60.
12) J. M. T. Pereira: Int. J. Comput. Math. Electr. Electron. Eng. **26** (2007) 1114.
13) K. Brennan: Appl. Phys. Lett. **51** (1987) 995.
14) M. W. Geis, S. J. Spector, M. E. Grein, R. T. Schulein, J. U. Yoon, D. M. Lennon, C. M. Wynn, S. T. Palmacci, F. Gan, F. X. Kärtner, and T. M. Lyszczarz: Opt. Express **15** (2007) 16886.
15) T. Ishibashi, S. Kodama, N. Shimizu, and T. Furuta: Jpn. J. Appl. Phys. **36** (1997) 6263.