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10 Gbps Operation of Top Air-Clad Lateral Junction Waveguide-Type Photodiodes

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Toward on-chip photonic integrated circuits (PICs) based on a membrane structure, a lateral junction waveguide-type photodiode fabricated on semi-insulating (SI-) InP substrate was successfully demonstrated. A responsivity of 0.39 A/W was obtained by adopting a bulk GaInAs absorption layer. In addition, a narrow stripe width of 0.85 µm was chosen for the realization of high-speed operation. As a result, a 3 dB bandwidth of 8.8 GHz at a bias voltage of −2 V was attained for a device length of 380 µm, and a clear eye opening was obtained up to 10 Gbps.

One of the promising solutions to overcome the problems of future large scale integrated circuits (LSI), such as global-wire signal delay and power dissipation, is an introduction of optical interconnections as a substitute for global electrical wiring. For the realization of an on-chip optical interconnection, low power consumption optical devices with a small footprint are strongly required.[1)] We proposed a membrane distributed feedback (DFB) laser, which consists of thin semiconductor core layers between low refractive index cladding layers such as benzocyclobuten (BCB) or SiO_2. Because the membrane structure has strong optical confinement within the core layer, the membrane DFB laser is feasible for low power consumption operation and short cavity length.[2)] A low threshold operation of 0.34 mW for a membrane DFB laser was demonstrated under continuous-wave (CW) optical pumping at room temperature.[3)] In order to realize electrically pumped membrane lasers, a lateral-current-injection (LCI) structure[4)] was adopted, and moderate performance was confirmed for LCI-type lasers prepared on a semi-insulating (SI)-InP substrate.[5–8)] Recently, an LCI membrane DFB laser prepared with a BCB bonding process was demonstrated with a relatively low threshold current of 11 mA.[9)]

Furthermore, we proposed membrane photonic integrated circuits (PICs) consisting of an LCI-membrane-DFB, an InP-based wire waveguide, and other semiconductor components as a candidate for an in-plane photonic platform with extremely low-power consumption.[10)] For the realization of in-plane PICs based on a membrane structure, a lateral junction waveguide-type membrane photodiode having a relatively thin core layer in common with the membrane laser is suitable for monolithic integration with the membrane DFB laser. Because the device length can be reduced owing to strong optical confinement, the membrane structure is also advantageous for waveguide-type photodiodes. In a step towards realization of a membrane-type photodiode, a lateral junction waveguide-type photodiode on SI-InP substrate was previously demonstrated using a GaInAsP quantum-well absorption layer.[11)] Here, we report the 10 Gbps operation of a GaInAs/InP lateral junction waveguide-type photodiode fabricated on a SI-InP substrate, which has a bulk GaInAs absorption layer and a narrow stripe width for high-speed operation. Figure 1 shows the schematic diagram of the fabricated lateral junction waveguide-type photodiode. As can be seen, the lateral junction

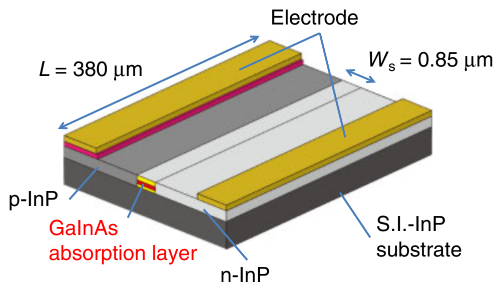

Fig. 1. (Color online) Schematic structure of a lateral junction waveguide-type photodiode on an SI-InP substrate.

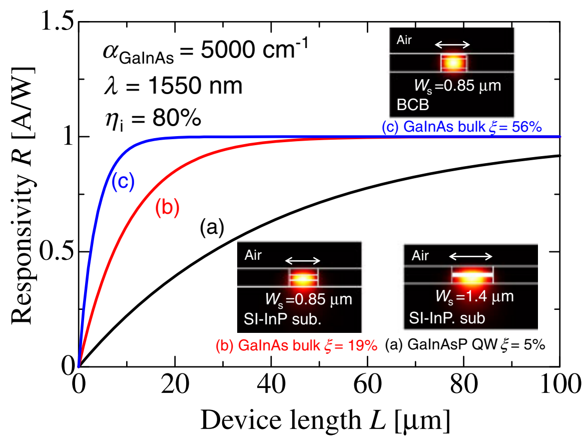

Fig. 2. (Color online) Responsivity dependence on the device length.

structure was formed on the SI-InP substrate with a top air-cladding layer. In this device, the bulk GaInAs absorption layer was introduced to the core layer as a substitute for the GaInAsP multiple-quantum-wells (MQWs) used in a previous report.[11)] Whereas the stripe width of the previous device was set to be $W_s = 1.4$ µm, the narrow stripe width of $W_s = 0.85$ µm was adopted in this device toward high speed operation. The optical confinement factor ξ in the GaInAs absorption layer (100 nm thick) was estimated to be approximately 19%, which is considerably higher than that for the previously reported device consisting of an absorption layer of five QWs. Figure 2 shows the calculated responsivity of the photodiodes as a function of the device length for three different cases: (a) five GaInAsP QWs on an SI-InP substrate

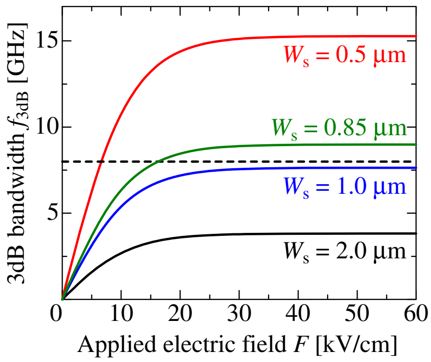

Fig. 3. (Color online) 3 dB bandwidth dependence on the stripe width of a lateral junction waveguide-type photodetector.

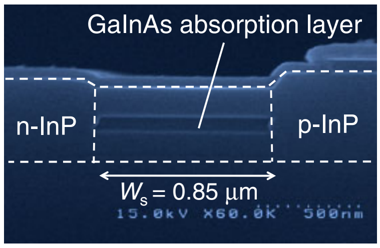

Fig. 4. (Color online) Cross-sectional SEM view of the lateral junction structure.

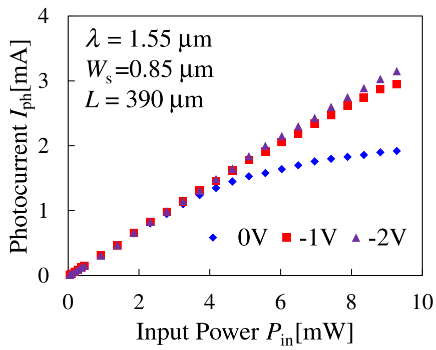

Fig. 5. (Color online) Photocurrent against independent power at 1550 nm for different bias voltages.

with stripe width W_s of 1.4 µm (optical confinement factor ξ of 5%), (b) bulk GaInAs on an SI-InP substrate with W_s of 0.85 µm (100-nm-thick absorption layer, ξ of 19%), and (c) bulk GaInAs with 200-nm-thick membrane structure with W_s of 0.85 µm (100-nm-thick absorption layer, ξ of 56%). In this calculation, the internal quantum efficiency was assumed to be 80% as a general value of commercial GaInAs photodiode. In addition, Fig. 2 shows the cross-sectional optical mode field (insets of Fig. 2). In case of the lateral junction type photodiode on SI-InP, the optical confinement factor is reduced drastically when the stripe width is reduced to less than 1 µm. However, the high optical confinement factor of 56% can be maintained in the lateral junction waveguide-type membrane photodiode [shown in Fig. 2(c)], which consists of a thin core layer between low-refractive-index cladding layers, with a total thickness of around 200 nm. Therefore, we note that the membrane structure photodiode consisting of a bulk GaInAs absorption layer can be a good candidate as a compact and efficient high-speed detector with a device length of around 10 µm.

The bandwidth dependence on the applied electric field is limited by the hole transit time in the GaInAs absorption layer and is shown in Fig. 3. In this calculation, the saturation velocity for GaInAs was set to 4.8×10^4 m/s.[12] In addition, the absorption layer was assumed to be fully depleted. The 3 dB bandwidth can be increased by applying voltage; however, the carrier velocity will saturate at a certain value. Hence, the maximum 3 dB bandwidth approaches a certain value (almost inversely proportional to the stripe width), and it was estimated to be approximately 8 GHz (dashed line) for a stripe width of 1 µm. Therefore, in order to achieve a large 3 dB bandwidth (>8 GHz) for 10 Gbps operation, a stripe width of less than 1 µm is required.[13]

Figure 4 shows the cross-sectional scanning electron microscope (SEM) view of the fabricated device with narrow stripe width of 0.85 µm. The lateral junction structure was formed using a two-step organometallic vapor phase epitaxy (OMVPE) regrowth method.[5,6] The total thickness of the core layer was designed to be 400 nm, which consists of a lower optical confinement layer (OCL; bandgap wavelength length: $\lambda_g = 1.2$ µm, 155 nm), a bulk GaInAs absorption layer (100 nm thick), and an upper OCL ($\lambda_g = 1.2$ µm, 155 nm). First, a mesa structure was formed with a SiO_2 mask and using a dry etching process. After removing the plasma-damaged sidewall, n-InP ($N_D = 4 \times 10^{18}$ cm^{-3}) was selectively regrown at both sides of the mesa structure. After etching part of the wide mesa structure and one side of the buried n-type layer in the same way, narrow (0.85 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 the same way. Finally, a Ti/Au electrode was deposited on both the p-GaInAs contact and the n-InP sections. As can be seen in Fig. 4, n-InP and p-InP were formed on the side of the core layer, and a relatively flat, top surface was confirmed.

Figure 5 shows the incident power dependence of photocurrent, I_{ph}, at a 1550 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 V. Taking into account the coupling efficiency of a lensed single-mode fiber, the responsivity of the fabricated device was estimated to be approximately 0.37 A/W at a wavelength of 1550 nm, which is 37% greater than the value of 0.27 A/W for the previously reported device with an MQW absorption layer.[11] However, this value is relatively low compared with that of general commercial devices. In the lateral junction type photodiode, the surface recombination on the interface between semiconductor and air on the top of the stripe thought to be cause of the low internal quantum efficiency η_i. In case of the lateral current injection laser, the thicker InP cap layer[7] or the uniformly distributed quantum well structure[8] were proposed in order to suppress the surface recombination on the top of the stripe. These structures can be also applied for the lateral junction type photodiode toward enhancement of the responsivity more than 70%. The frequency responses of the fabricated device with bias voltage of 0, −1, −2, and −4 V is shown in Fig. 6. An electrical signal from a network analyzer was converted

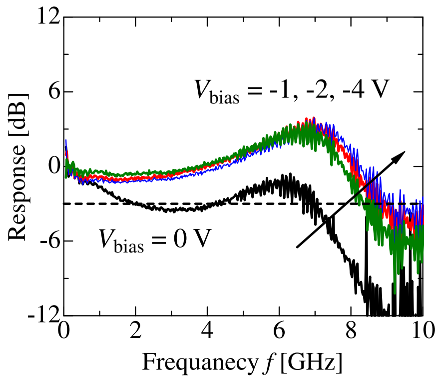

Fig. 6. (Color online) Frequency response with various bias voltages.

into a light signal with a network performance tester, in which an LN modulator and a DFB laser were built. Then, the light signal was converted into an electrical signal with the fabricated lateral junction photodiode mounted on an alumina sub-mount with a co-planar circuit. The frequency response peaking and ripple at around 7 GHz in Fig. 6 might be due to an impedance mismatch between the device and the sub-mount. Because such peaking and ripple were not observed in the frequency response of previously reported devices,[11)] these were not attributed to lateral junction structure. The roll-off around 3 GHz with bias current of 0 V is caused from the carrier transit time in the core layers, and improved with applying the bias voltage. The 3 dB bandwidth was observed to be 1.9 GHz at the non-bias condition and 8.8 GHz at the bias voltage of −2 V. Because the 3 dB bandwidth was 6 GHz at a bias voltage of −2 V in the previously reported device with a stripe width of 1.4 µm, we confirmed that the reduction in the stripe width resulted in a faster response. The 3 dB bandwidth was considered to be limited by the carrier transit time in the GaInAs absorption layer, because the RC time constant was thought to be small owing to the lower capacitance (<0.1 pF), compared to that in a vertical pn-junction structure.[4,14)]

Figure 7 shows the eye diagram at 10 Gbps operation. 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 and input into the fabricated device. As seen in Fig. 6, a clear eye opening at 10 Gbps at a bias voltage of −2 V was observed. Due to its poor responsivity and small photocurrent, the relatively large-noise level was observed on the in measured eye diagram. By adopting an appropriate design for the device, an improvement of the high received power could be realized. Furthermore, a reduction of the device size less than 10 µm could also be expected by introducing the membrane structure.

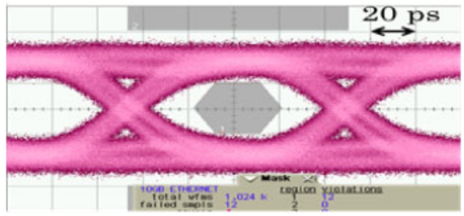

Fig. 7. (Color online) Eye diagram at 10 Gbps ($V_{bias} = -2$ V).

In summary, a narrow-stripe lateral junction waveguide-type photodiode with a bulk GaInAs absorption layer was demonstrated in order to realize high-speed operation. By adopting the bulk GaInAs absorption layer, a responsivity of 0.39 A/W was obtained. A 3 dB bandwidth of 8.8 GHz at a bias voltage of −2 V was realized for a stripe width of 0.85 µm and a device length of 380 µm, and a clear eye opening was obtained up to 10 Gbps.

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