106-Gb/s Waveguide AlInAs/GaInAs Avalanche Photodiode with Butt-joint Coupling Structure

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Abstract: A waveguide AlInAs/GaInAs APD with the butt-joint coupling structure for 106-Gb/s PAM4 applications is demonstrated for the first time. A maximum 3-dB bandwidth of 38 GHz and high responsivity at unity gain of 0.90 A/W are exhibited at 1.55 µm.

1. Introduction

Data center interconnections for over the top (OTT) services and 5G mobile front-haul networks have accelerated the growth of the optical fiber transmission capacity. Under these circumstances, there have been a lot of demands for high-speed transmission over more than 10 km [1-2]. However, it is well known that the lack of optical power budget occurs in the case of higher bit rate transmission beyond 100 Gb/s. From the viewpoint of the component cost and power consumption, the intensity-modulation and direct detection (IMDD) system is desirable compared with the digital coherent system. Therefore, to implement a high-speed IMDD system with a reach longer than 10 km, some amplification of optical power is necessary on the receiver side. The avalanche photodiode (APD) is a preferable detector to amplify optical signals without additional power consumption or optical components [3].

While several high-speed APDs have been reported [4-7], InP-based APDs have remarkable advantages compared with silicon-germanium APDs. Owing to the optical absorption property of GaInAs, they have high responsivity over a wide spectral range from O- to L-band. With respect to the structure design, a butt-joint (BJ) coupled waveguide structure is highly promising. We have proved its effectiveness by a waveguide p-i-n PD with the BJ coupling structure which has achieved both high responsivity and wide bandwidth [8]. Besides p-i-n PDs, we have verified an InP-based 8-channel waveguide APD array featuring the BJ coupling structure for 53.12 Gb/s pulse amplitude modulation 4-level (PAM4) transmission [9]. Although it exhibited the excellent linearity under high optical input power condition and uniformity of properties between the channels, the maximum 3-dB bandwidth was only 23 GHz on account of the low multiplication-bandwidth product attributed to the InP avalanche layer.

In this paper, we demonstrate a waveguide APD with a BJ coupling structure introducing AlInAs avalanche layer for the first time. This waveguide APD has indicated not only high responsivity but also high multiplication-bandwidth product due to the material property of AlInAs. We have also revealed 106.25 Gb/s (53.12 GBaud) PAM4 operation with the receiver module using the waveguide APD.

2. Device structure and characteristics

Fig. 1 (a) shows the schematic cross-sectional view of the waveguide APD with the BJ coupling structure. A spot-

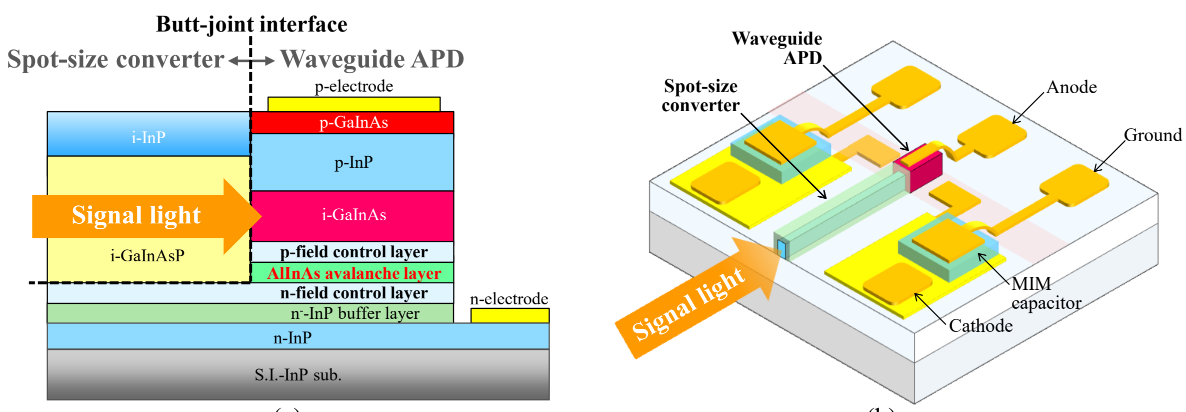
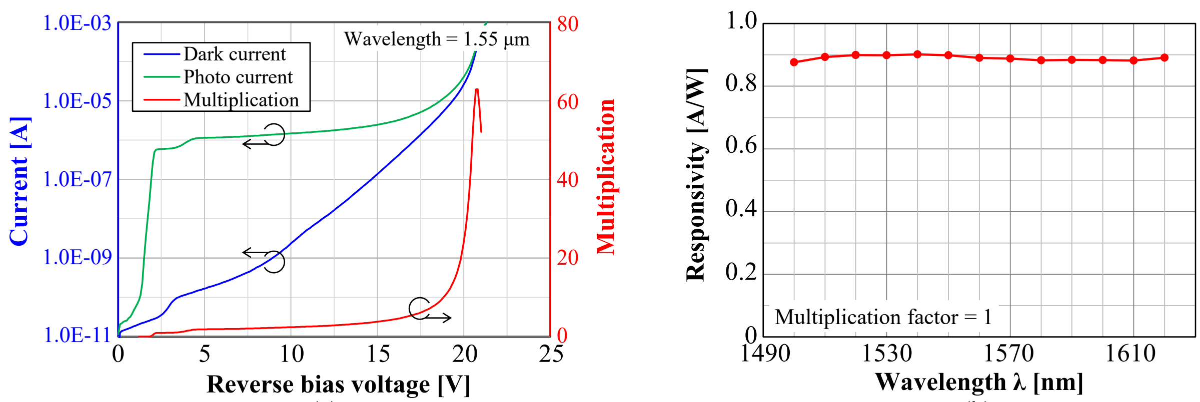


Fig. 1. Schematic diagrams of (a) cross-sectional view and (b) three-dimensional view of the waveguide APD.

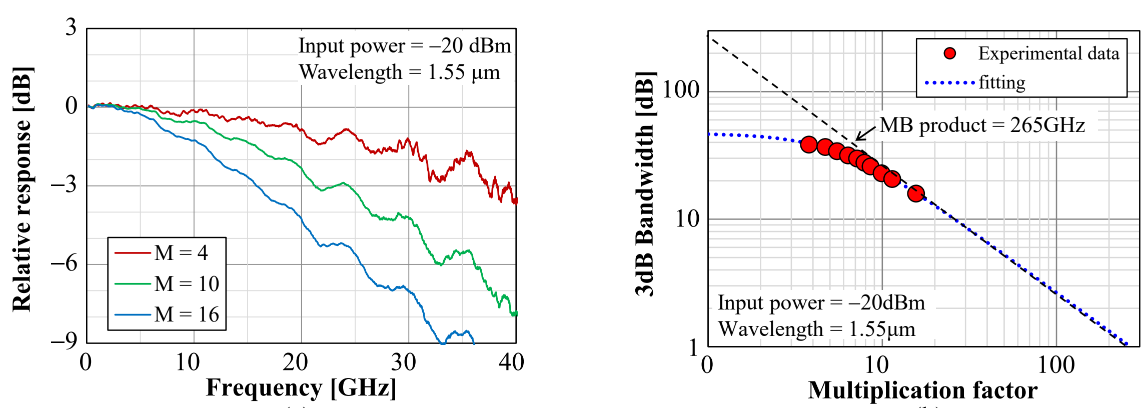
size converter (SSC) comprising an i-GaInAsP core formed by the BJ regrowth process is directly connected with the waveguide APD, which yields high optical coupling efficiency at the interface. In this structure, optical signal is efficiently absorbed in the thin GaInAs absorber designed to shorten the carrier transit time, due to a highly confined optical mode and long propagation length along the waveguide. Hence, BJ coupled waveguide APDs perform not only wide bandwidth given by the short carrier transit time but also high responsivity, compared with conventional surface illuminated APDs. In order to increase multiplication-bandwidth product, an AlInAs avalanche layer, which has a high ionization coefficient rate, was newly introduced. Its thickness was designed to be less than 100 nm to shorten the avalanche build-up time. Fig. 1 (b) shows a schematic diagram of three-dimensional view of a waveguide APD. A buried waveguide of the SSC was formed through regrowth processes to enhance optical coupling efficiency with an optical fiber and suppress the polarization dependent loss (PDL) for IMDD operation. In addition, metal-insulator-metal (MIM) capacitors were integrated by using InP-based monolithic integration technology to eliminate external capacitors in receiver modules.



(a) (b)

Fig. 2. (a) The dark current, photo current and avalanche multiplication versus reverse bias voltage and (b) spectral responsivity at unity gain of the fabricated waveguide APD.

For the purpose of examining effectiveness of the BJ coupling structure, fabricated waveguide APD chips were evaluated mainly at a wavelength of 1.55 μm at which the absorption coefficient of GaInAs is smaller than that of 1.31 μm. Fig. 2 (a) shows bias voltage dependence on a dark current, photo current and avalanche multiplication of a fabricated waveguide APD. We have observed the multiplication characteristics without edge-breakdown, in which maximum multiplication factor has been more than 60 at a breakdown voltage of 21 V. Owing to the thin-film AlInAs avalanche layer, the temperature dependence of breakdown voltage has been as small as 11.7 mV/K. The wavelength dependence on responsivity at unity gain of a waveguide APD evaluated with a 3-μm-diameter beam focused by lenses is shown in Fig. 2 (b). The high responsivity of approximately 0.9 A/W has been achieved over



(a) (b)

Fig. 3. (a) optical/electrical frequency response and (b) multiplication factor versus 3-dB bandwidth: experimental data (circle), multiplication component which is intrinsic avalanche build-up time (dash line) and curve fitting in experimental data (dot line) of the waveguide APD.

the C- and L-band with the optimally designed SSC.

The optical/electrical frequency responses of the waveguide APD under the optical input power of −20 dBm at the intrinsic multiplication factors of 4, 10 and 16 are shown in Fig. 3 (a). The intrinsic multiplication factors have been estimated from the measured multiplication-voltage characteristics. By the introduction of the AlInAs avalanche layer, we have successfully obtained a maximum 3-dB bandwidth of 38 GHz at a multiplication factor of 4. Fig. 3 (b) shows the multiplication factor versus 3-dB bandwidth. The multiplication-bandwidth product has been estimated to be 265 GHz from intrinsic avalanche build-up time extracted by fitting experimental data on a theoretical multiplication factor versus 3-dB bandwidth curve.

3. Receiver performance for 106.25 Gb/s PAM4 operation

In order to evaluate the performance of 106.25 Gb/s (53.12 GBaud) PAM4 operation, a receiver module consisting of the waveguide APD and a transimpedance amplifier (TIA) was assembled. Fig. 4 shows the photomicrograph of the fabricated waveguide APD chip. Before the assembly, PDL of the APD chip at a wavelength of 1.31 μm has been evaluated. Thanks to SSC, it has been less than 0.25 dB and small enough to avoid the influence of polarization rotation. A 3-dB bandwidth of the module under the high optical input power of −5 dBm has been measured to be more than 35 GHz at a multiplication factor of 3. The 1.31-μm optical signal for the 106.25 Gb/s PAM4 operation was generated by pseudo random bit sequence with the length of 2^{15}-1 (PRBS15Q). The extinction ratio of the signal was 5.6 dB and transmitter and dispersion eye closure for PAM4 (TDECQ) was 1.7 dB. Eye diagrams after back-to-back transmission and applying 11-tap feed forward equalizer (FFE) at a multiplication factor of 2.5 under the optical modulation amplitude (OMA) of −12, −4 and +4 dBm are shown in Fig. 5. The clear eye-opening under high optical input power condition has been successfully observed thanks to the high linearity of the InP-based waveguide APDs.

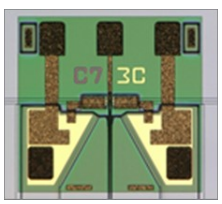
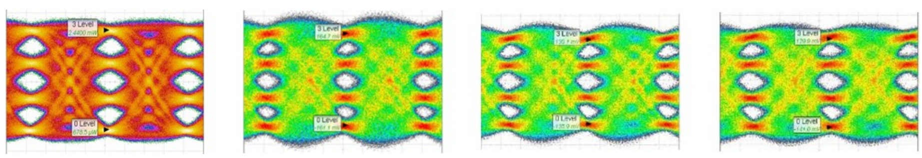


Fig. 4. Photomicrograph of the fabricated waveguide APD.



(a) (b) (c) (d)

Fig. 5. Output waveforms of (a) optical signal and electrical signal of the receiver module with the waveguide APD at back-to-back transmission under OMA of (b) −12, (c) −4 and (d) +4 dBm.

4. Conclusion

We have demonstrated the AlInAs/GaInAs waveguide APD with the BJ coupling structure for the first time. By introducing AlInAs avalanche layer to the BJ coupled waveguide PD structure, the fabricated APD has achieved the remarkably high responsivity in a wide spectral range and wide bandwidth of 38 GHz at a multiplication factor of 4. In addition, the receiver modules employing the waveguide APD have indicated the high performance for 106.25 Gb/s PAM4 operation. From these result, we have revealed that the waveguide APD is very promising for high bit rate transmission over more than 10 km in IMDD systems.

5. References

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