Large-optical-aperture Top-illuminated 50-Gbaud PIN-PD with High 3-dB Bandwidth at a Low Bias of 1.5 V

Takashi Toyonaka, Hiroshi Hamada, Shigehisa Tanaka, Masatoshi Arasawa, Ryu Washino, Yasushi Sakuma and Kazuhiko Naoe

Lumentum Japan, Inc., 4-1-55 Oyama, Chuo-ku, Sagamihara, Kanagawa, Japan
Author's e-mail address: takashi.toyonaka@lumentum.com

Abstract: High 3-dB bandwidth of 28 GHz at 1.5 V was demonstrated by introducing a capacitance-control layer into a high-responsivity top-illuminated PIN-PD with large optical-aperture diameter of 20 µm for 50-Gbaud operation.

OCIS codes: (230.5170) Photodiodes, (040.5160) Photodetectors, (060.4510) Optical communication.

1. Introduction

Recently, 400-Gb/s (4×100 Gb/s) transceiver (TRV) using 50-Gbaud 4-level pulse-amplitude modulation (PAM4) format has been attracting much interest as the next-generation system to meet the significant growth of data traffic in client networks [1]. In regard to the previous 100-Gb/s (4×25 Gb/s) TRV, a PIN-photodiode (PIN-PD) with a large optical-aperture diameter of 20 µm is applied [2, 3] because of the need for balanced optical alignment of 4 channels. The PIN-PD for a 50-Gbaud operation requires low capacitance and high-speed operation (high-frequency response) in addition to high responsivity. Therefore, a PIN-PD with small capacitance, achieved by reducing the optical-aperture diameter to 12 or 16 µm, has been commercialized. However, because of their small optical tolerance, it becomes difficult to apply these small optical-aperture PIN-PDs to existing optical-assembly equipment for 100-Gb/s (4×25 Gb/s) TRV. As an alternative, a lens-integrated back-illuminated PIN-PD has been proposed, however, its cost is disadvantageous because it must be flip chip bonded on a specified carrier. For these reasons, a top-illuminated 50-Gbaud PIN-PD with an optical-aperture diameter as large as 20 µm is highly desirable.

In this work, we demonstrate a top-illuminated PIN-PD with large optical-aperture diameter of 20 µm for 50-Gbaud operation for the first time. In order to achieve both large aperture and high-speed operation, we introduced capacitance-control layer (CCL) into PIN-PDs designed for high responsivity, and successfully confirmed a high 3-dB bandwidth of 28 GHz at a low bias voltage of 1.5 V.

2. Design concept and device structure

We previously fabricated a PIN-PD with undoped-absorption-layer thickness (Da) of 0.62 µm and optical-aperture diameter (Φ) of 16 µm. The measured capacitance and 3-dB bandwidth of the PIN-PD were 98 fF and 28 GHz, respectively. Figure 1 shows the BER characteristics for 50-Gbaud PAM4 operation. Receiver sensitivity at BER of 2×10^{-4} is less than -5 dBm at 85°C, which is considered to be sufficiently applicable to 50-Gbaud PAM4 operation. However, the PIN-PD with Φ of 16 µm or less is difficult to apply to existing optical assembly equipment for 100-Gb/s (4×25 Gb/s) TRV, which assumes the use of a PIN-PD with Φ of 20 µm. So we designed a top-illuminated 50-Gbaud PIN-PD with Φ of 20 µm targeting a capacitance of less than 98 fF and 3-dB bandwidth of no less than 28 GHz.

Figure 2 shows calculated dependence of capacitance and 3-dB bandwidth of a top-illuminated PIN-PD on optical-aperture diameter. The diameter of the PN junction was assumed to be 5 µm larger than that of its optical-aperture considering width of a ring electrode and process margin, and wiring capacitance was assumed to be 25 fF. As for the dependence of carrier velocity on electric field, we used that of [4]. The black solid line and dotted line indicate calculated capacitance and 3-dB bandwidth of the previously fabricated PIN-PD. The black circles and diamonds indicate measured capacitance and 3-dB bandwidth, and agree well with the calculated values. At Φ of 20 µm, the capacitance exceeds 120 fF and 3-dB bandwidth is 23 GHz or less due to the CR limitation, hence the PIN-PD with Φ of 20 µm is not applicable to 50-Gbaud operation.

On the other hand, the red solid line and dotted line indicate calculated capacitance and 3-dB bandwidth with Da of 1 µm in Fig. 2, respectively. Even at Φ of 20 µm, capacitance can be reduced to less than 90 fF, which due to the increasing of Da. However, 3-dB bandwidth is limited to 23 GHz, because hole velocity decreases due to decrease of electric field in the thick absorption-layer as well as carrier traveling length increases, resulting in the carrier transition time increases. For this reason, it cannot be applied to 50-Gbaud operation simply by increasing Da.

We newly introduced CCL to a top-illuminated PIN-PD with Φ of 20 μm for 50-Gbaud operation to achieve both capacitance and 3-dB bandwidth with the target values mentioned above simultaneously. The CCL is a wide-band-gap layer which was proposed to reduce the capacitance with slightly increasing the carrier transition time [5]. Moreover, a back-illuminated PIN-PD with wide 3-dB bandwidth at a low bias voltage has been reported by introducing wide-band-gap carrier collection layer [6]. The high-speed PD design with a wide-band-gap carrier collection layer is much difficult for top-illuminated PIN-PD than back-illuminated PIN-PD because the PN junction area of top-illuminated PIN-PD is expanded due to the ring electrode fabrication, which affects its capacitance. Therefore, we optimized both the thickness and electric field of the absorption-layer and CCL for the top-illuminated PIN-PD to meet the target of capacitance and 3-dB bandwidth for 50-Gbaud operation while keeping responsivity over 0.8 A/W. Figure 3 shows a schematic cross sectional layer structure of the fabricated top-illuminated 50-Gbaud PIN-PD with a CCL. Its mesa structure consists of a p-type contact layer, an InGaAs absorption-layer, a field-control layer, and a CCL. Electric field of the CCL is controlled appropriately by optimizing dopant concentration of the field-control layer. Thicknesses of the absorption-layer and CCL are optimized to maximize the frequency response while keeping responsivity over 0.8 A/W. To minimize the mesa diameter equal to PN junction diameter, the ring electrode was precisely formed by self-alignment process technique. The mesa structure is buried with semi-insulating InP and covered with an insulating film for stable non-hermetic operation. A broadband AR coating provides low reflectivity and high optical return loss over a wavelength range from 1264 to 1338 nm. We fabricated two types of PIN-PD, one with a CCL and another without a CCL (for reference).

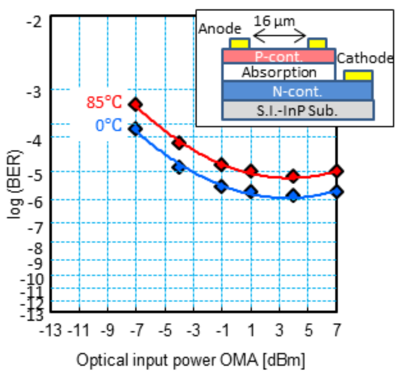

Fig. 1. The BER characteristics of the fabricated PIN-PD with Da of 0.62 μm and Φ of 16 μm

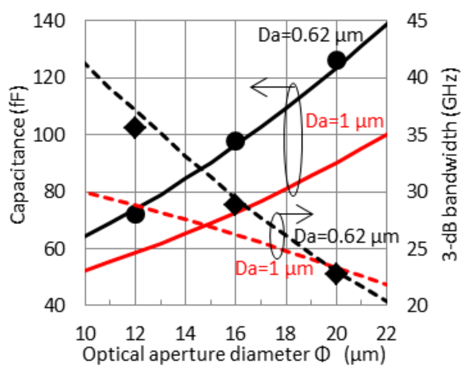

Fig. 2. Calculated dependence of capacitance and 3-dB bandwidth on optical-aperture diameter

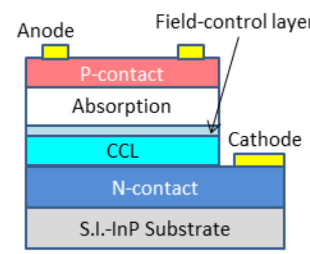

Fig. 3. Schematic cross sectional layer structure of a top-illuminated 50-Gbaud PIN-PD of this work

3. Experimental results and discussion

The fabricated PIN-PDs (one with a CCL and one without a CCL) showed high responsivity over 0.8 A/W at a wavelength of 1.3 μm. Figure 4 shows the frequency responses of the PIN-PD with Φ of 20 μm. The blue solid line and black dotted line indicate the PIN-PD with a CCL and the PIN-PD without a CCL, respectively. The average optical input power was +5 dBm and the reverse bias voltage supplied to the PD was as low as 2.0 V. Thanks to CCL, the 3-dB bandwidth was improved from 23 to 28 GHz. Figure 5 shows dependence of the capacitance and 3-dB bandwidth on optical-aperture diameter. Blue circles and diamonds indicate measured capacitance and 3-dB bandwidth of the PIN-PD with a CCL, and black circles and diamonds indicate measured capacitance and 3-dB bandwidth of the PIN-PD without a CCL. Dotted lines indicate calculated values, and the measured values agree well with the calculated values. In the case of the PIN-PD with a CCL, capacitance was reduced to 83 fF and 3-dB bandwidth was increased to 28 GHz simultaneously with Φ of 20 μm. These values are sufficient for 50-Gbaud operation as described above.

In consideration of adopting a 3.3-V power supply and the voltage drop inside a TIA, stable operation under 2-V bias is required. To confirm the capability of the fabricated PIN-PD with a CCL to operate at low bias and high optical input power, the 3-dB bandwidth against applied PD bias voltage at optical input power of +5 dBm was measured. Figure 6 shows dependences of 3-dB bandwidth of the fabricated PIN-PDs with Φ of 20 μm on bias voltage. Blue circles and black diamonds indicate the PIN-PD with a CCL and the PIN-PD without a CCL, respectively. As shown in the figure, frequency response of the PIN-PD with a CCL does not degrade even at 1.5 V.

Figure 7 shows the comparison between measured 3-dB bandwidth of fabricated PIN-PD with a CCL and calculated 3-dB bandwidth of conventional PIN-PDs. The conventional PIN-PDs were assumed to have Da of 0.7, 0.9, 1.0, and

1.1 µm and no CCL layer. As for conventional PIN-PDs with Φ of 20 µm, the 3-dB bandwidth is limited to 25 GHz or less. Open and closed squares indicate reported values. Their detailed structures are unknown and bias voltages vary from 2 to 5 V, but they are within the range of the calculation for conventional PIN-PDs. On the other hand, the developed PIN-PD with a CCL and Φ of 20 µm demonstrated 3-dB bandwidth of 28 GHz, which exceeds the bandwidth limitation limited by optical-aperture.

In addition, we conducted reliability tests of high temperature operation life test (175°C, 2,000 hours) and dump heat test at normal bias voltage (85°C, 85 %, 2,000 hours), and confirmed stable operation of the PIN-PDs with no degradation in dark current.

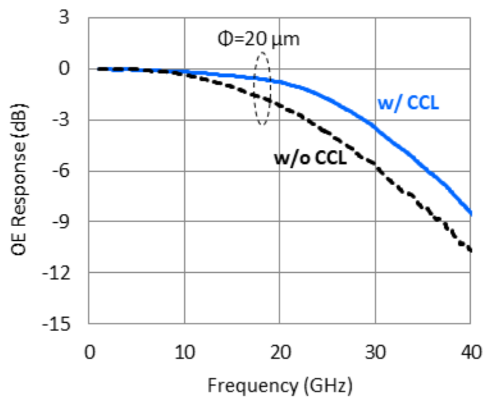

Fig. 4. Frequency response of the fabricated PIN-PDs

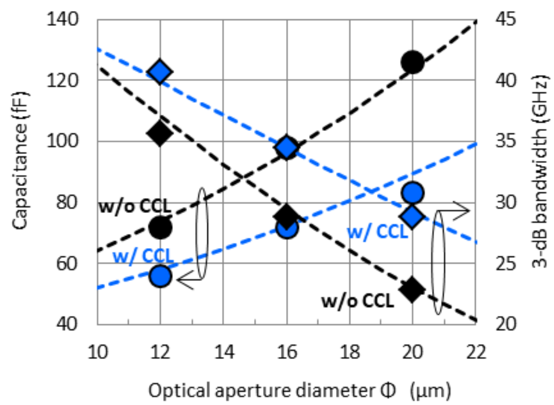

Fig. 5. Dependence of capacitance and 3-dB bandwidth of the fabricated PIN-PDs on optical-aperture diameter

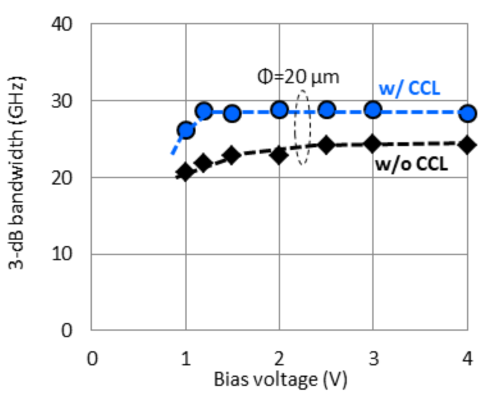

Fig. 6. Dependences of 3-dB bandwidth of the fabricated PIN-PDs on bias voltage

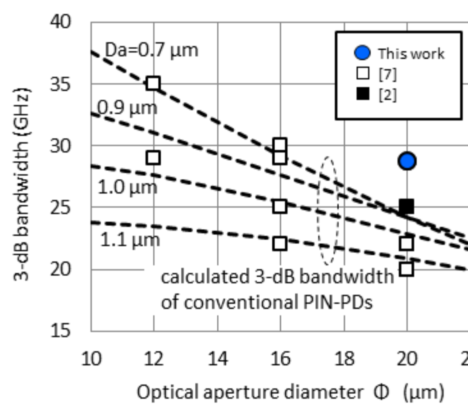

Fig. 7. Comparison between measured 3-dB bandwidth of fabricated PIN-PD with a CCL and calculated 3-dB bandwidth of conventional PIN-PDs

4. Conclusion

A top-illuminated 50-Gbaud PIN-PD with optical-aperture diameter of 20 µm was demonstrated for the first time. We newly introduced capacitance-control layer into large optical-aperture PIN-PD to realize both low capacitance and high 3-dB bandwidth, and achieved high responsivity of over 0.8 A/W, low capacitance of 83 fF and high 3-dB bandwidth of 28 GHz simultaneously. We also confirmed its low bias voltage operation at as low as 1.5 V with optical input power of +5 dBm. To our knowledge, this top-illuminated PIN-PD has the largest optical-aperture, so far reported, that is applicable to 50-Gbaud operation

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