# Low dark current backside-illuminated photodiode for 200 Gb/s operation with 40 μm wide alignment tolerance

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**Abstract:** A backside-illuminated photodiode employing a semiconductor-buried structure is demonstrated at 200 Gb/s. The photodiode exhibited a 3dB bandwidth of 65 GHz, an effective aperture of 40 μm, and a dark current of 1 pA.

## 1. Introduction

Optical devices are required to continuously increase bit rates to cope with the drastic increase in data traffic. The standard of 200 Gb/s per wavelength is promoted, and it is expected to be applied to products of next generation [1]. Since the PAM4 method is used for a transmission distance of 2 km or less, a high-speed photodiode (PD) is required for 100 Gbaud operation.

On the one hand, a large light-receiving aperture is necessary to facilitate optical coupling and reduce fabrication cost. On the other hand, enlarging a light-receiving aperture is equivalent to enlarging the p-n junction size, which increases the capacitance and narrows the bandwidth. The previously reported aperture with a vertical-illuminated PD structure is as small as 10 μm [2]. In addition, the dark current generally increases with the p-n junction size. A large dark current degrades the reliability. Wide bandwidth has been reported for a waveguide PD structure, where the p-n junction can be easily made smaller; however, the receiving diameter is also smaller [3]. In this study, we fabricated a backside-illuminated PD employing a semiconductor-buried structure that achieves low dark current and high reliability. Furthermore, an effective light-receiving diameter of 40 μm was achieved by integrating a parabolic-shaped lens into a PD. To the best of our knowledge, this is the first PD that simultaneously combines wide bandwidth, large light-receiving diameter, and high reliability.

## 2. Device structure

Fig.1(a) shows the schematic cross section of the fabricated PD. A contact layer, InP layers, an InGaAs absorption layer, and a window layer were sequentially grown on Fe-InP substrate by metal organic chemical vapor deposition technique. The thicknesses of both the undoped InP and InGaAs absorption layers affect the capacitance and carrier transit time. Therefore, those thickness were optimized to maximize the bandwidth. The epitaxial growth layer outside of the light-receiving area was etched off and a Fe-InP layer was regrown as a replacement [4]. Zn was selectively diffused to make a p-type conductive region in the undoped InP window layer [5]. A p-type conductive region size is approximately 10 μm. A leak current of junction sidewall was reduced to adopt a buried structure with Fe-InP and selected Zn diffusion process. In addition, this buried structure enables capacitance reduction. An anode metal has functions as an anode contact metal and as a mirror metal, as a result the reflected light through the absorption layer from the input surface increases the absorption efficiency again in the InGaAs absorption layer. On the substrate side, the InP substrate was processed into a parabolic-shaped lens shape via a dry-etched technique to expand the responsivity tolerance. An anti-reflection coating was deposited on the optical input surface to suppress Fresnel reflection. Fig.1(b) presents the three-dimensional image (3D) of the integrated lens. The radius of curvature was set to 80 μm to focus the light into the InGaAs absorption layer.

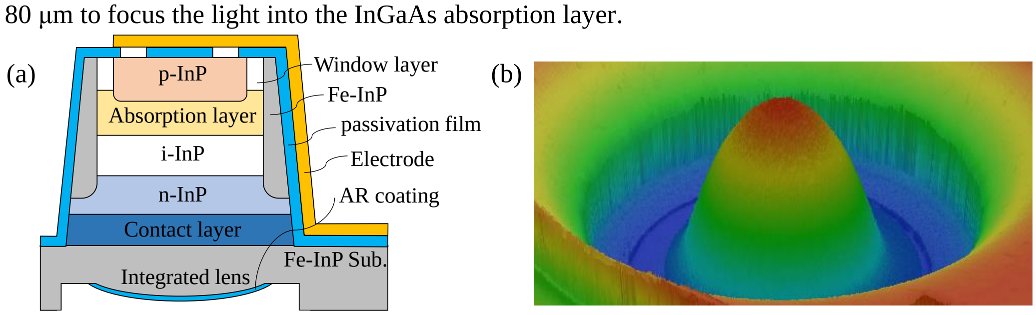


Fig. 1 Device structure (a) Schematic cross section of the PD (b) 3D image of the integrated lens

**3. Measurement results**

Fig.2(a) illustrates the I-V characteristics of the fabricated PD (n = 5). At an operating voltage of 2 V, the dark current is 1 pA. Additionally, the characteristic variation among samples is relatively small. To the best of our knowledge, the dark current is the smallest for PDs in the present work. Fig. 2(b) depicts the temperature dependence of the dark current. The slope of the plotted line indicates the thermal activation energy. The estimated activation energy Ea is 0.66 eV. Since the Ea is approximately equal to the band gap energy (0.68–0.74 eV) of InGaAs absorption layer, and the diffusion current is the dominant component of the dark current. Moreover, the result indicated that there is almost no leak current and generated current. This result indicates that there are few defects in the epitaxial layer and on the junction sidewall. These decent results on the dark current can be attributed to the effect of selected Zn diffusion and buried structure. Based on these results, high reliability can be expected. To confirm the long-term reliability of the buried structure, a high temperature accelerated aging test of 175 °C was performed for five PDs with same semiconductor-buried structure which has a large aperture size of 20 μm. We plotted the I-V curves of PDs at room temperature following each aging process. Fig.2(c) shows the variations of dark currents measured at 2 V. The large dark currents are stable for over 5000 hours and there was no degradation of PDs during the aging test.

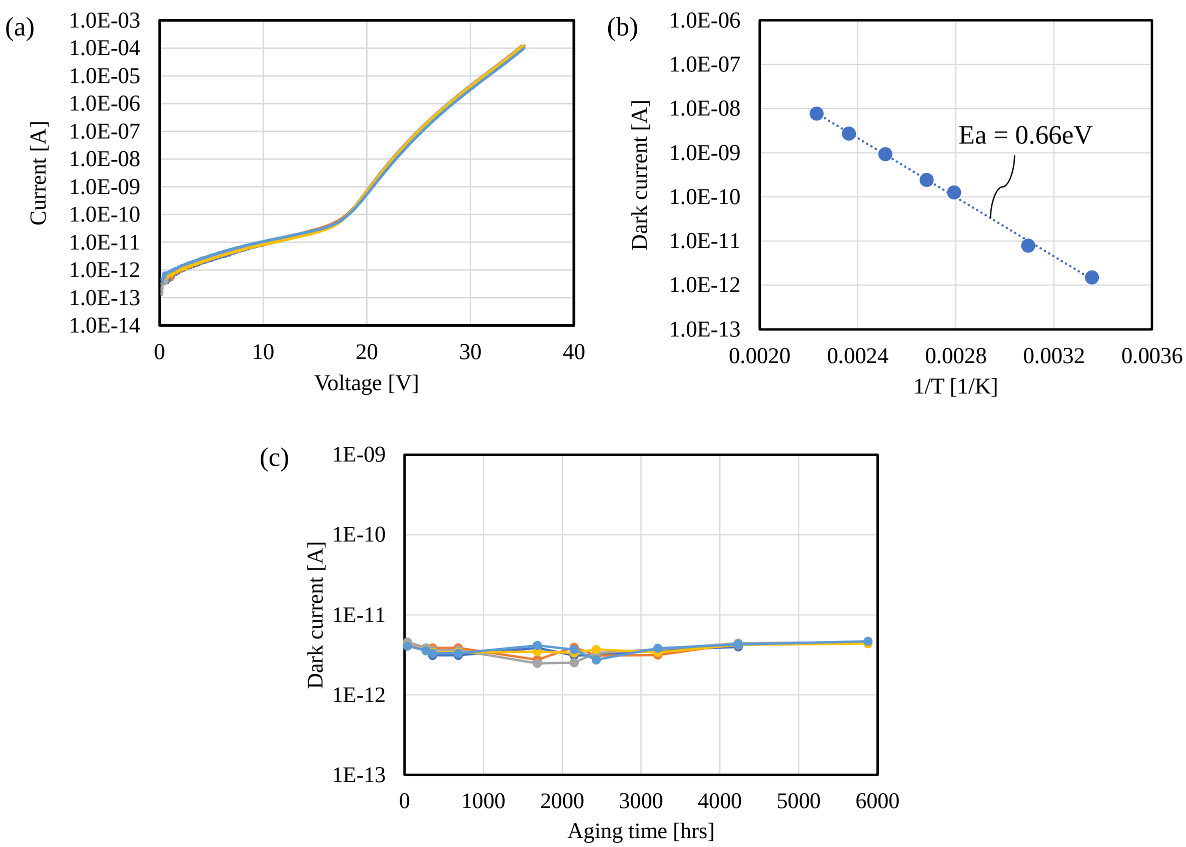


Fig.2 I-V characteristics (a) I-V curves at room temperature (b) Temperature dependence of the dark current (c) Dark currents at room temperature in high temperature accelerated aging test

Fig.3 shows a two-dimensional (2D) photocurrent profile of the fabricated PD from the back side of the PD. A focused light beam with a spot size of 3 μm scanned the back side of the PD, and the measured photocurrents are plotted as shown in Fig. 3. The optical input is -10 dBm and the bias voltage is 2 V. Fig.3(a) illustrates the 2D photocurrent profile of PD without integrated lens and Fig.3(b) shows the 2D photocurrent profile of the PD with an integrated lens. Without the integrated lens, the responsivity tolerance is approximately 10 μm, which corresponds to the junction size. By integrating the lens, the responsivity tolerance significantly expanded from approximately 10 μm to almost 40 μm while retaining a circular shape. The large effective aperture effectively facilitates optical coupling. The responsivity is 0.60 A/W at 1310 nm wavelength owing to the optimization of the thickness of the InGaAs absorption layer and mirror metal.

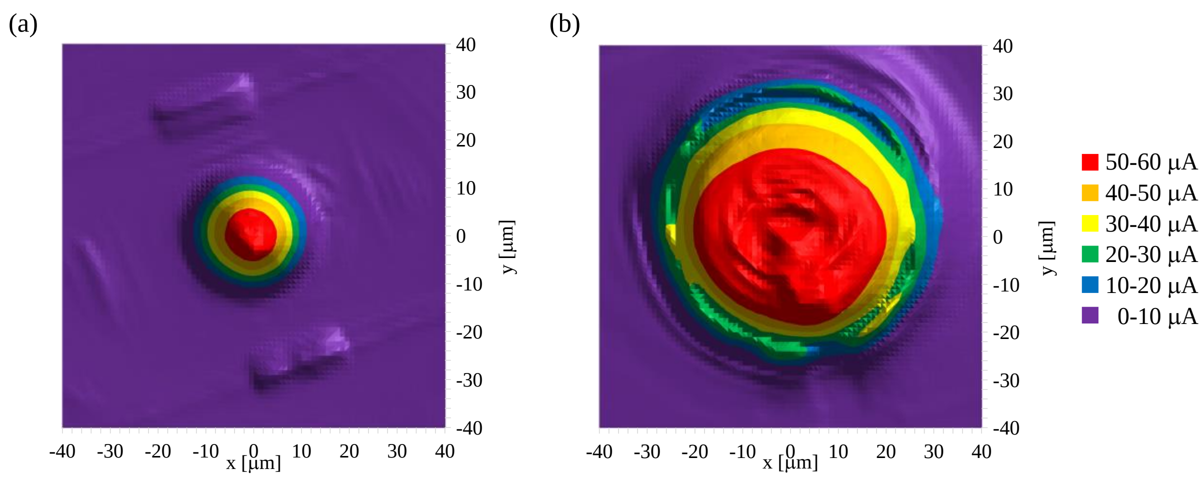


Fig.3 2D photocurrent profiles of the PDs (a) Without integrated lens (b) With integrated lens

The capacitance of the fabricated PD is 45 fF. It is sufficiently low because of the Fe-InP buried structure and the optimized thicknesses of the InP and InGaAs layers. Fig.4 illustrates the small signal frequency response of the fabricated PD with an integrated lens measured by directly probing the PD. The optical input is 0 dBm and the bias voltage is 2 V. The dashed line is the fitting curve. The 3dB frequency bandwidth is 65 GHz, which is sufficiently wide to achieve 200 Gb/s operation of the receiver.

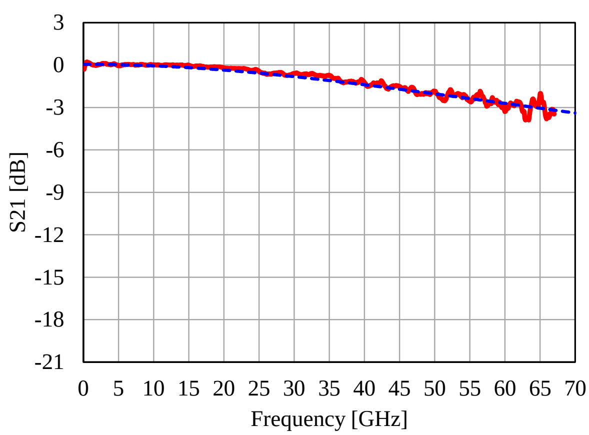


Fig.4 Frequency response of the fabricated PD

## 4. Conclusion

We demonstrated a backside-illuminated PD employing a semiconductor-buried structure for 200 Gb/s per wavelength operation. The fabricated PD exhibited a 3dB frequency bandwidth of 65 GHz at 2 V. An effective aperture of 40 µm was achieved by integrating a parabolic-shaped lens on the backside of the PD. Furthermore, the PD has an excellent dark current of 1 pA and high reliability owing to the adopted semiconductor-buried structure. The fabricated PD simultaneously realizes high bandwidth, effective larger aperture, and high reliability. In summary, it is ideal for industrial equipment for 200 Gb/s operation.

## 5. References

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