

Low-Noise Sb-Based APD with Long-Range Detection and Resistance to Sunlight Interference

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Self-driving taxis are beginning to become popular in major cities. In the future, autonomous driving is expected to expand mainly in logistics and enter our everyday lives more closely. ToF-LiDAR, which is an essential sensor for autonomous driving, is required to achieve both a longer detection range and laser safety, as well as stronger environmental robustness in outdoor settings. Although the 1550-nm band is advantageous for laser safety, its detection range has so far been limited by the lack of low-noise photodetectors. Therefore, we developed a low-noise avalanche photodiode (APD) using an antimony (Sb)-based material in the multiplication layer. In this work, we report results from a comparative evaluation of detection distance and sunlight resilience, considering system SNR, between the existing 905-nm band and the 1550-nm band equipped with the Sb-APD.

Keywords: APD, Sb, LiDAR

1. Introduction

Time-of-Flight Light Detection and Ranging (ToF-LiDAR)*¹ has been used for obstacle detection and self-localization. With increasing demand for automated driving at higher speeds and deployment in residential areas, the need to extend the detection range while complying with laser eye safety standards is expected to grow.

Highly cost-efficient 905-nm devices are widely used for ToF-LiDAR. To extend the detection range of 905-nm band systems, an optical output exceeding the Class 1 eye-safety limits⁽¹⁾ is required. Meanwhile, in the wavelength range of 1300 nm or more, the laser safety requirements are less stringent, enabling a higher optical output within the Class 1 limits.⁽²⁾ For 1550-nm band systems, high-optical-output systems using a high-optical-quality, high-optical-output fiber laser as a transmitter have been applied in practice. Regarding photodetectors, avalanche photodiodes (APDs)*² using indium phosphide (InP) and indium aluminum arsenide (InAlAs), which are materials with high intrinsic noise, for the multiplication layer*³ are commonly employed, imposing a limit on long-range detection. By contrast, it has been reported that antimony (Sb)-based materials are characterized by low noise compared to the abovementioned materials.⁽³⁾⁻⁽⁹⁾ Thus, Sb-based materials are expected to be applied in practice.

Against this backdrop, we previously developed an APD using aluminum gallium arsenide antimonide (AlGaAsSb), an Sb-based composite material, for the multiplication layer (Sb-APD).^{(10),(11)} In this report, with a view to applying this technology to ToF-LiDAR, we present the results of comparison of the signal-to-noise ratio (SNR) with an APD using silicon (Si) for the multiplication layer (Si-APD), which is used in 905-nm band systems, and evaluation of the resistance to solar interference—an advantage of 1550-nm band systems over 905-nm band systems—using a simulated solar light source to assess its impact on the SNR.

2. Device Characteristics

2-1 Current-voltage and multiplication gain-voltage characteristics

A typical APD features a structure in which the absorption layer is isolated from the multiplication layer. This structure lowers the electric field applied to the absorption layer, thereby reducing the dark current. In the layer configuration reported in this paper, indium gallium arsenide (InGaAs) was used for the absorption layer, and $\text{Al}_{0.85}\text{Ga}_{0.15}\text{As}_{0.56}\text{Sb}_{0.44}$, which was lattice-matched with InP, was used for the multiplication layer. For production, the layers were deposited on a semi-insulating InP substrate by molecular beam epitaxy*⁴ and were then formed by a general process flow with an active area diameter of 200 μm .⁽¹²⁾ Figure 1 shows the characteristics of the photocurrent, dark current (primary axis), and multiplication gain*⁵ (secondary axis) against applied voltage. The threshold voltage of the photocurrent is approximately 31 V, and the breakdown voltage*⁶ is approximately 56 V. The dark current is 30 nA or less up to the vicinity of the breakdown voltage. The results showed a multiplication gain far

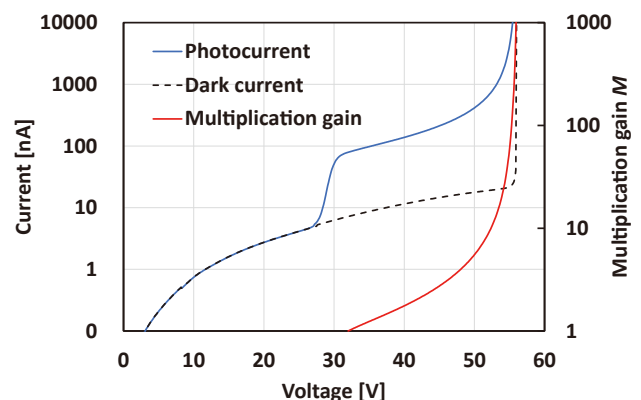


Fig. 1. Current-voltage and gain-voltage characteristics

exceeding 100. Temperature dependence of the multiplication gain is shown in Fig. 2. The breakdown voltage temperature coefficient at a multiplication gain of 100 is 16 mV/°C. This shows that the operating voltage varies only slightly with temperature compared to the temperature coefficients of approximately 50, 100, and 1,000 mV/°C reported on APDs using InAlAs, InP, and Si for the multiplication layer.

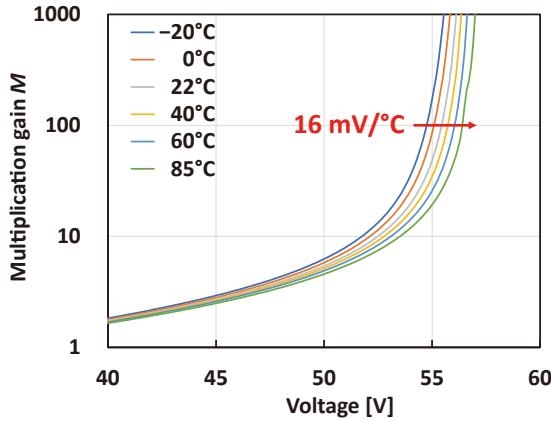


Fig. 2. Temperature dependence of gain-voltage

2-2 Evaluation of the ionization coefficient ratio

APDs amplify electrons generated via avalanche multiplication, but amplification is not uniform. Excess noise is generated due to statistical fluctuations. This excess noise factor F is expressed by equation (abbreviated as Eq.) (1) using the multiplication gain M . Here, k is the ionization coefficient ratio ($k = \beta/\alpha$) between electrons (α) and holes (β), and it is determined by the multiplication layer material. Meanwhile, the relationship between $F(M)$ and SNR can be expressed by Eq. (2).

$$F(M) = M \left[1 - (1 - k) \left(\frac{M-1}{M} \right)^2 \right] \quad \text{..... (1)}$$

$$SNR = \frac{I_p^2 M^2}{2q(I_p + I_d) M^2 F(M) B_w + N_{circuit}^2} \quad \text{..... (2)}$$

I_p is the photocurrent, I_d is the dark current, B_w is the noise bandwidth, and $N_{circuit}$ is the amplifier-induced noise. When the multiplication gain is high, the influence of the amplifier-induced noise decreases in relative terms, and the excess noise factor becomes dominant. Accordingly, the smaller the k of a material, the greater the advantage in SNR. Figure 3 shows the experimental results of the excess noise factor against the multiplication gain, as well as the fitting results of the least squares method based on Eq. (1), which are indicated by the dashed line. As shown in the figure, k of the Sb-APD is approximately 0.02. This is one order of magnitude smaller than that of InAlAs ($k: 0.2$), which is a typical long-wavelength material, as indicated by the dotted line. The value is equivalent to that of Si, indicating that the Sb-based material is characterized by low noise.

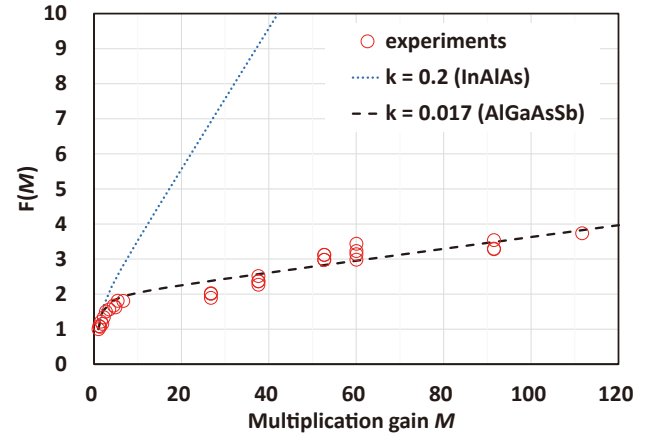


Fig. 3. Excess noise factor dependence on gain

3. Signal-to-Noise Ratio

3-1 Evaluation method

A schematic diagram of the experimental system for evaluating SNR is shown in Fig. 4. Semiconductor lasers with wavelengths of 905 nm and 1550 nm were used as transmitters for the Si-APD and Sb-APD, respectively. The pulsed laser beam (optical output power: P_t) was reflected by a reflector with a reflectance (ρ) of 10%, and the reflected light was focused onto the APD active area (optical input power: P_s) by a lens with a diameter of 1 inch (D_R), which was mounted on each APD. To eliminate incident ambient light, a 900 nm ± 25 nm bandpass filter and a 1550 nm ± 25 nm bandpass filters were mounted on the Si-APD and Sb-APD, respectively. The output current from the APDs was amplified by a transimpedance amplifier (gain: 10 k Ω) and a booster amplifier, and the output voltage was observed using an oscilloscope. The evaluation was conducted by theoretically calculating⁽¹³⁾ the propagation loss indicated in Eq. (3) and adjusting the optical pulse power input to the APDs, instead of propagation over the actual range (R). SNR was calculated as a percentage of the output amplitude against the root mean square (RMS) noise of the peak voltage indicated in Eq. (4).

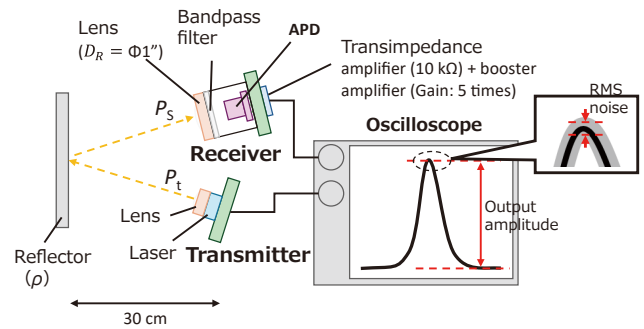


Fig. 4. SNR evaluation setup

$$P_S = \frac{\rho D_R^2 \exp(-2\sigma R)}{4R^2} P_t \quad \text{..... (3)}$$

$$SNR = \frac{\text{Output amplitude}}{\text{RMS noise at peak output}} \quad \text{..... (4)}$$

3-2 Evaluation results

The optical input power to the APD was set to 25 nW, 39 nW, and 70 nW for both the Si-APD and the Sb-APD. For a transmitter with a pulse width of about 7 ns in the 905-nm wavelength band, the maximum permissible optical output power compliant with the Class 1 eye-safety limits is 28 W, which is equivalent to the optical input power after propagation over 135 m, 105 m, and 80 m when the optical output power is converted based on Eq. (3). Similarly, in the 1550-nm wavelength band, this is equivalent to the propagation range of 250 m, 200 m, and 150 m for the 100 W optical output power within the Class 1 limits. In the evaluation, an SNR of 17.8 dB or more, which is required for the detection probability of 99.9% at a multiplication gain of 100, was used as the criterion. The results of theoretical calculation and measurement-based evaluation of SNR versus multiplication gain are presented in Figs. 5 and 6. Since the Sb-APD has higher light sensitivity than the Si-APD, its absolute value of SNR is high, offering an advantage of approximately 3 dB over the Si-APD at a multiplication gain of 100. Furthermore, SNR exceeded 17.8 dB even at the detection range of 200 m. Notably, in the region with a high multiplication gain where shot noise*7 is dominant,

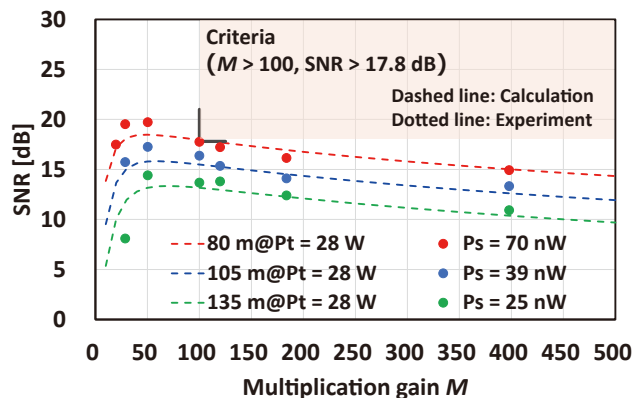


Fig. 5. SNR dependence on gain of the Si-APD

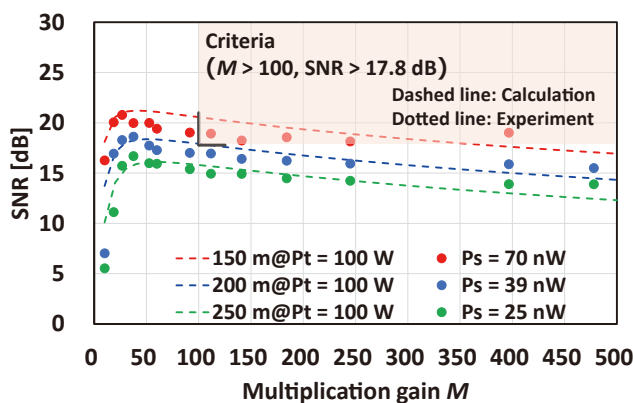


Fig. 6. SNR dependence on gain of the Sb-APD

SNR deteriorates sharply in APDs with existing InP and InAlAs multiplication layers whose excess noise factor is high. By contrast, the Sb-APD provided results demonstrating characteristics equivalent or superior to those of the Si-APD.

4. Resilience to Sunlight Interference

4-1 Evaluation method

Sunlight has a broad wavelength spectrum and reduces SNR as noise. The irradiance reaching the Earth's surface is attenuated by the atmosphere. It is 0.76 W/m²/nm at a wavelength of 905 nm and 0.26 W/m²/nm at a wavelength of 1550 nm.⁽¹⁴⁾ Accordingly, sunlight-induced SNR reduction of 1550-nm band systems is expected to be lower than that of 905-nm band systems. Thus, we conducted an experiment to evaluate the influence of sunlight interference on SNR using a solar simulator. Figure 7 shows a schematic diagram of the measurement setup. For the configuration, a solar simulator (the HAL-320W manufactured by Asahi Spectra Co., Ltd.) was added to the SNR evaluation setup shown in Fig. 4. An evaluation was conducted based on the worst-case simulation of perpendicular incidence on the APD.

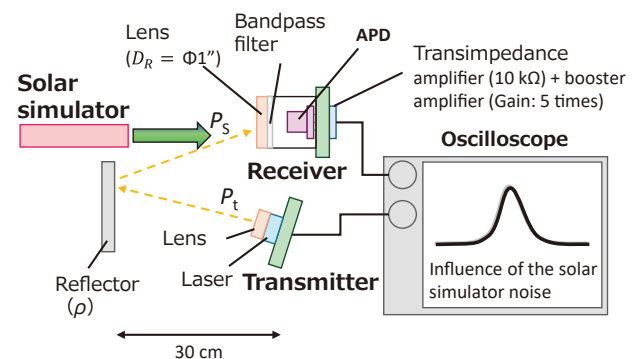


Fig. 7. Sunlight immunity evaluation setup

4-2 Evaluation results

Figure 8 shows the evaluation results of the SNR dependence of detection range of the Sb-APD and Si-APD under 1-sun illumination conditions (1,000 W/m²), which simulated the midsummer direct sunlight conditions. The optical output power was set to the maximum output within the Class 1 eye-safety limits, and the multiplication gain of each APD was set to approximately 100. The detection range with an SNR of 17.8 dB or more is 28 m for the Si-APD and 72 m for the Sb-APD. The results show that the range can be extended approximately 2.5 times.

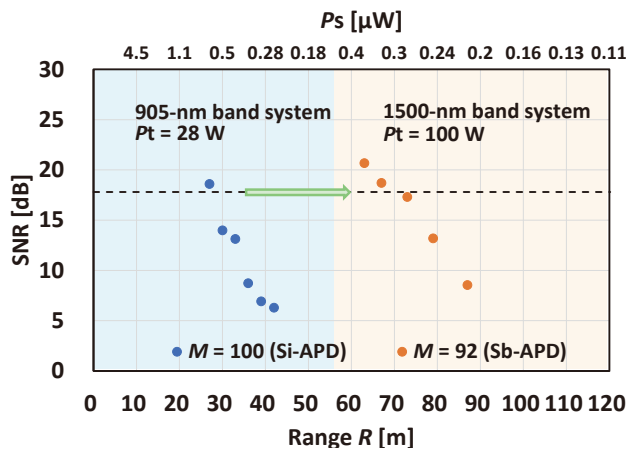


Fig. 8. Range dependence of SNR for an Si-APD and an Sb-APD under 1-sun illumination conditions

5. Conclusion

We developed a low-noise Sb-APD using AlGaAsSb for the multiplication layer and InGaAs for the absorption layer and evaluated the performance of a 1550-nm band system as a ToF-LiDAR sensor. Compared to a 905-nm band system using an Si-APD, SNR with a multiplication gain of 100 is approximately 3 dB higher. We also confirmed that an SNR of 17.8 dB or more for a detection range of 200 m can be attained in combination with a transmitter with optical output power of 100 W. We also evaluated the SNR robustness under the direct illumination conditions of 1-sun irradiance and confirmed that a detection range approximately 2.5 times that of a 905-nm system can be attained. Accordingly, the combination of a high output transmitter and an Sb-APD for 1550-nm ToF-LiDAR systems is expected to achieve long-range detection and further expand outdoor applications while ensuring eye safety.

Technical Terms

- *1 ToF-LiDAR: Time-of-Flight Light Detection and Ranging: A ranging method based on the time between emitting a laser pulse toward a target and receiving the reflected pulse.
- *2 APD: Avalanche Photodiode: A type of optical sensor that converts light into electricity. The device has an internal function for amplifying signals.
- *3 Multiplication layer: A layer in the APD configuration that amplifies photo-generated electrons via avalanche multiplication.
- *4 Molecular Beam Epitaxy: A technique to deposit atoms onto a substrate one layer at a time in an ultra-high vacuum. This is one of the crystal growth techniques to produce high-quality films.
- *5 Multiplication gain: Percentage of photocurrent amplified by an APD.
- *6 Breakdown voltage: Threshold voltage that can consistently trigger the APD avalanche multiplication.
- *7 Shot noise: Noise generated by statistical fluctuations of photo-generated electrons.

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