Evaluation of the Long-Term Reliability of Open-Tube Diffused Planar InGaAs/InP Avalanche Photodiodes under a Hybrid of Thermal and Electrical Stresses

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Abstract: The long-term reliability of open-tube diffused planar InGaAs/InP APDs was investigated via accelerated life testing in this study. For the proposed life testing scheme, both thermal and electrical stresses were applied simultaneously to reduce the testing periods while maintaining statistical significance. Additionally, the Eyring model was used to extrapolate the activation energy. To determine the optimum life testing conditions, high-temperature storage tests, preliminary accelerated life tests, and main accelerated life tests were conducted. From the test results, the mean-time-to-failure was utilized to verify the suitability of the Eyring model. The proposed testing scheme, which utilizes a hybrid of accelerated stress factors, allows us to estimate the device reliability within an acceptable testing period, minimizing the time to market.

Keywords: avalanche photodiodes; linear-mode avalanche photodiode; breakdown voltage; dark current; accelerated life test; activation energy; high-temperature storage test; mean time-to-failure; minimum survival time

1. Introduction

For years, planar InGaAs/InP avalanche photodiodes (APDs) have been widely used for optical communication, because APDs based on this material have good photon detection efficiency at a 1550 nm wavelength, which is interesting for being eye-safe and exhibiting low levels of dark current [1]. When it comes to eye-safe wavelengths, planar InGaAs/InP APDs are preferred over Si-based APDs for applications in optical communications. Because eye safety requirements are emerging for the automotive technology industry, the wavelength of sensors has been changed to 1550 nm. Thus, InGaAs/InP APDs are attracting much attention due to their receiver sensitivity at the C-band wavelength. Recently, they have been used as single-photon detectors in versatile applications, such as in quantum key distribution (QKD) networks, light detection and ranging (LiDAR), also called laser detection and ranging (LADAR), and optical time-domain reflectometry (OTDR) [2–7]. QKD is a technology that uses quantum physics to secure the distribution of symmetric encryption keys. It works by sending photons, which are “quantum particles” of light, across an optical link [2,3]. LiDAR technology uses the time-of-flight (TOF) methodology for acquiring 3-dimensional (3D) images to make a precise measurement of distance [4,5]. OTDR is another type of measurement technique that provides the loss characteristics of an optical link along its entire length to determine the length-dependent loss [6,7].

APDs operate in two different modes: the linear mode and Geiger mode. Linear-mode (LM) APDs operate below the breakdown voltage and the avalanche gain can be obtained approximately between 10 and 100. For this reason, a pre-amplifier is required...
for LM APDs. In LM APDs, the intensity of the output photocurrent is proportional to the intensity of the input optical power. In addition, for communication networks, such as OTDR, the measurement and analysis of the fraction of reflected light can be readily accomplished using LM APD [6,7]. Geiger-mode (GM) APDs, specifically single-photon avalanche diodes (SPADs), operate above the breakdown voltage and the avalanche gain is larger by approximately millions of times, implying that single-photon detection or long-range distance measurements are feasible [8]. However, the operating speed of each chip of a GM APD is slow; thus, they cannot be utilized for high-speed scanning operations. For this reason, LM APDs have been in the spotlight for scanning laser detection and ranging (LADAR) systems due to their faster operating speeds compared with GM APDs and their lower operating voltage that is below the breakdown voltage.

When it comes to photodetectors for optical communications, anticipating the device lifetime is essential in verifying its reliability. With the developments made in the technology of fabricating planar InGaAs/InP APDs, device reliability has shown remarkable enhancements. Previous studies have focused on the noise of APDs, such as the dark count rate (DCR) or after-pulse characteristics, whereas the reliability of APDs has not been discussed [8–10]. However, not only are the noise characteristics, but also the reliability is conclusive for operating APDs in optical communications. Several authors have performed reliability assessments of InGaAs/InP APDs [11–13]. The inferior reliability of planar and mesa InGaAs PIN photodiodes was investigated by C.P. Skrimshire et al. in [11], and in [12], Itzler et al. presented manufacturable InGaAs/InP APDs with multiple Zn dopant diffusions that endowed high reliability. In addition, the long-term reliability of planar InGaAs/InP APDs with recess etching using closed-ampoule diffusion was investigated by J. Jung et al. in [13]. However, the reliability of highly reliable InGaAs/InP APDs fabricated with open-tube diffusion has rarely been investigated.

In this paper, the long-term reliability evaluation of open-tube diffused planar InGaAs/InP APDs, especially 10-Gbps InGaAs/InP APDs, was investigated. Since tested APDs are highly reliable, the accelerated life tests (ALTs) in this study were designed to apply hybrid stresses (both thermal and electrical stresses) to estimate device reliability in a reasonably short testing period. The acceleration factors applied were the temperature and injected current to observe the failure of the tested APDs. The reliability characteristics were examined with the ALTs by monitoring the dark current and breakdown voltage. Furthermore, the failure mechanism was examined by using an infrared (IR) imaging system. Based on the test results, the minimum activation energy was computed using the Eyring model with two stress conditions, thermal and electrical stress. In terms of the time to market, the presented approach is an unprecedented methodology for short-period reliability testing. Therefore, this paper could act as a reference for subsequent studies when performing reliability assessments of APDs.

2. APD Test Structure Description

Design of APD Test Structure

The design and fabrication processes of the tested APDs were established by Wooriro Co. It is well known that the capacitance ($C_{APD}$) of an APD greatly augments the noise of the transimpedance amplifier (TIA) and that the capacitance should be designed to be as small as possible, because it is a limiting factor of the bandwidth by the RC time constant. For the use of 10 Gbps optical communication, the capacitance should be less than 0.2 pF and the gain-bandwidth product (GBP) should be larger than 60 GHz. For a GBP of 60 GHz, the multiplication layer width (MLW) should be less than 0.3 µm. In this study, a floating guard ring (FGR) structure, as shown in Figure 1, was used to suppress edge breakdown at the MLW. The thickness of the absorption layer, including the grading layer, was also limited to be within 1.0 µm. In addition, a structure attached to the carrier with the flip-chip bonding technique was used for back illumination to enhance the quantum efficiency and minimize the parasitic capacitance caused by the bonding pad. Since the capacitance of the quartz carrier was less than that of the ceramic carrier, quartz was used as the submount
material. Furthermore, even for a planar structure, the chip–on–carrier (CoC) has a lower capacitance than commercially available APDs because the chip is floated approximately 3–4 μm from the carrier’s surface [5]. To float an APD chip from the carrier’s surface, we formed an Au post pattern on the carrier with a 3 μm-thickness by electro-plating, followed by a 3 μm-thick Au/Sn solder bumper deposition using E-beam evaporation.

![Cross-section of the open-tube diffused 10 Gbps planar InGaAs/InP APD test structure.](image)

**Figure 1.** Cross-section of the open-tube diffused 10 Gbps planar InGaAs/InP APD test structure.

The cross-sectional view of the tested APD is shown in Figure 1. The thickness of the target light absorption and amplification layers were set to be 0.9 μm and 0.3 μm, respectively. The targeted charge density and thickness of the electric field control layer were set to be approximately \(3.2 \times 10^{12}\) cm\(^{-2}\) and 0.1 μm, respectively. The grading layer was composed of multiple layers of InGaAsP having an intermediate bandgap between that of the InP and InGaAs layers, and the thickness was 0.1 μm. The active diameter of the tested APD where amplification occurred was designed to be approximately 30 μm, and the diameter of the tested APD including the guard ring was designed to be approximately 60 μm.

The experiments for the APD reliability assessment were conducted using a TO-46-can-type module. The TO module assembly process was as follows: (1) The APD CoC and resistor were attached to the TO-46, header as shown in Figure 2; (2) the window cap sealing was produced by the resistance-welding technique to maintain hermetic conditions. A specially designed aspherical lens cap was resistance-welded in a nitrogen atmosphere to obtain a hermetic sealing. Here, the tested APDs were electrically connected with two 1-kΩ resistors in series, as shown in Figure 2, to avoid unexpected sudden APD chip damage from bias voltage fluctuation or shock.
Table 1. The failure criteria of the tested APDs.

| Parameter Measured | Condition | Criterion of Failure |
|-------------------|-----------|----------------------|
| VBR @ 10 μA       | ΔVBR      | > ± 10%               |
| ID @ 0.95 V BR    | I D       | > 1 μA               |

The tested APDs were interconnected to the dry oven and the Keithley SMU 236 by Teflon wires to apply the thermal and electrical stresses simultaneously and the Keithley SMU 236 was connected to a PC to monitor the dark current. For the LM APD, the monitored dark current was extracted at 0.95 V_{BR}.

The dark current (I_D) and breakdown voltage (V_{BR}) are critical factors in determining the failure or degradation of the APD characteristics, the failure criteria of which are shown in Table 1.
Table 1. The failure criteria of the tested APDs.

| Parameter | Measured Condition | Criterion of Failure |
|-----------|--------------------|----------------------|
| $V_{BR}$  | @ 10 $\mu$A        | $\Delta V_{BR} > \pm 10\%$ |
| $I_D$     | @ 0.95 $V_{BR}$    | $I_D > 1 \mu$A        |

The reliability testing procedure was designed as follows: first, a high-temperature storage test was performed at 498 K to evaluate any degradation in the tested APD due to thermal effects. The pre-accelerated life tests were then performed to determine the proper testing conditions for the thermal and electrical stresses. After the optimal conditions for the accelerated life tests applying the thermal and electrical stresses were determined under the constraint of the time to market, the main accelerated life tests were finally performed to extrapolate the activation energy and estimate the APD lifetime.

3.2. Modeling Scheme

In previous studies, the activation energy ($E_a$) was extrapolated using the Arrhenius model, which is utilized for only one thermal variation [15–18]. However, in this paper, because the devices used to observe failure using the ALT experiments were highly stable, the activation energy ($E_a$) was estimated with the Eyring model because two different factors, temperature and current, were considered simultaneously.

The Eyring Model equation is expressed as

$$MTTF = R_0I^{-n} \exp\left(\frac{E_a}{k_B T}\right)$$

where $MTTF$ is the mean-time-to-failure, $R_0$ is a fitting parameter, and $I$ and $T$ are the injected current and temperature, respectively. $K_B$ is the Boltzmann’s constant and $E_a$ is the activation energy. From the testing scheme using a hybrid of stress factors $I$ and $T$, the activation energy and the APD lifetime under practical use conditions can be estimated.

4. Results and Discussion

4.1. Initial Temperature-Dependent Electrical Characteristics

The current–voltage (I–V) characteristics of the tested APDs were initially measured. The measurements of the electrical characteristics were performed using a Keithley source-measure unit (SMU) 236. Since the tested APDs were operated in the linear mode (LM) at the 1550 nm wavelength, the dark current ($I_D$) was defined as the reverse current when the voltage was at 95% of the breakdown voltage ($V_{BR}$). Here, the breakdown voltage was defined as the voltage when the reverse current of the tested APD was 10 $\mu$A, as summarized in Table 1.

To investigate the temperature dependence of the tested APDs, a thermal experiment was performed between 298–498 K. Figure 4 shows the temperature-dependent electrical characteristics. In Figure 4, the breakdown voltage linearly increased as the temperature increased, indicating that the impact ionization process was the dominant effect. The dark current also linearly increased in the range of a few tens of $nA$ as the temperature increased.

The results indicate that temperatures below 498 K, in particular, temperatures between 473 K and 498 K, produce severe stress compared with the rest of the temperatures when evaluating dark current. Moreover, the gradual increase in both the breakdown voltage and dark current due to thermal stress indicated that they were affected by thermal stress. For this reason, we conducted reliability experiments under severe temperature conditions of over 448 K.
The results indicate that temperatures below 498 K, in particular, temperatures between 473 K and 498 K, produce severe stress compared with the rest of the temperatures when evaluating dark current. Moreover, the gradual increase in both the breakdown voltage and dark current due to thermal stress indicated that they were affected by thermal stress. For this reason, we conducted reliability experiments under severe temperature conditions of over 448 K.

4.2. Results of the High-Temperature Storage Tests

Prior to the accelerated life testing, a high-temperature storage test (HTST) was performed at 498 K for 100 h. Although the thermal stress of 498 K was considered to be a high level of thermal stress for the tested APDs, the breakdown voltage and dark current remained fairly constant, as shown in Figure 5. From these results, it was concluded that the degradation of the APD could not be observed via an HTST within a short period of the testing time.

4.3. Pre-ALT Experiments

The accelerated life test conditions were preliminary designed to observe the degradation within a reasonable time period considering the time to market. Since there was nearly no degradation detected in the tested APDs during the HTST, it was confirmed that thermal stress did not impact the degradation of the tested APDs.

To determine the optimum life testing conditions, the pre-accelerated life tests were first performed at 498 K with a constant current stress of 100 µA for 180 h, as shown in Figure 5. However, no degradation in the APD characteristics, $V_{BR}$ and $I_D$, was observed...
under the combination of thermal and electrical stresses, indicating that the tested APDs showed greater reliability than the conventional APD. Thus, the conditions for the second accelerated life test included the application of a constant current stress of 500 μA at 448 K.

However, the pre-ALT experiment with four tested APDs under a current stress of 500 μA at 448 K also showed nearly no degradation for 2000 h, indicating that the mean time-to-failure (MTTF) could not be estimated under these conditions, as shown in Figure 6. Based on these two test results, the third accelerated life test under a current stress of 1000 μA at 448 K was conducted on the four tested APDs. Unlike the preceding experiments, device failures were observed under this test condition, as depicted in Figure 7. Therefore, the appropriate test conditions considered for the ALT experiments included current stress levels of 500 μA and 1000 μA at the elevated temperatures of 473 K and 498 K.

There were eight tested APDs used for each test condition; however, the results of the APDs tested under the current stress of 1000 μA at 498 K were not considered because the device failures were observed in a short period of time; thus, the statistical significance could not be confirmed. Therefore, an additional five tested APDs were used for the test conditions of 1000 μA at 498 K.

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**Figure 6.** Monitored electrical characteristics of the (a) breakdown voltage ($V_{BR}$) and (b) dark current ($I_D$) at 448 K with 500 μA.

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**Figure 7.** Monitored electrical characteristics of the (a) breakdown voltage ($V_{BR}$) and (b) dark current ($I_D$) at 448 K with 1000 μA.
4.4. Accelerated Life Test Experiment Scheme

Based on the preliminary life testing results, the two accelerated temperatures (448 K and 498 K) and the two accelerated current levels (500 µA and 1000 µA) were used in the tests to extrapolate the activation energy of the device failure within an acceptable testing time period. The preliminary and main accelerated life test conditions are summarized in Table 2.

Table 2. Accelerated life test conditions.

| Temperature (K) | Current (µA) | Number of Samples | Note                |
|-----------------|--------------|-------------------|---------------------|
| 498             | -            | 4                 | HTST                |
| 498             | 100          | 4                 | Preliminary ALT experiments |
| 448             | 500          | 4                 |                     |
| 448             | 1000         | 4                 |                     |
| 473             | 500          | 8                 | Main ALT experiments |
| 473             | 1000         | 8                 |                     |
| 498             | 500          | 8                 |                     |
| 498             | 1000         | 13                |                     |

The main ALT experiments were composed of four groups of hybrid stresses: two distinct thermal stresses (473 K and 498 K) and electrical stresses (500 µA and 1000 µA). The current–voltage (I–V) characteristic variation during the main ALT experiments and the monitoring characteristics of the breakdown voltage ($V_{BR}$) and dark current ($I_D$) under the conditions of 473 K with a constant current stress of 500 µA are presented in Figures 8 and 9, respectively. Similar results were observed under all test conditions of the main ALT experiments. In the figures, it can be observed that the dark current increased and the breakdown voltage decreased when the tested APD was degraded.

![Figure 8](image_url)  
**Figure 8.** The typical current–voltage (I–V) characteristic degradation of the APDs at 473 K and 500 µA.

Based on the main ALT results, device failures were observed and cumulative failure analysis was performed using the log-normal distribution, and the mean time-to-failure (MTTF) of each testing condition was computed. Figures 10 and 11 illustrate the lognormal projection of the MTTF versus the percentage of cumulative failures for the thermal and electrical stresses in the main ALT experiment, respectively. From the figures, it can be observed that the results reasonably followed the normal distribution. In addition, it can also be observed that the electrical stress was more dominant than the thermal stress.
Figure 9. Monitored electrical characteristics of the (a) breakdown voltage ($V_{BR}$) and (b) dark current ($I_D$) at 473 K and 500 $\mu$A.

Figure 10. Lognormal projection of the mean time-to-failure versus the percent of cumulative failures for a 10 Gbps planar InGaAs/InP APD after the ALT experiment at (a) 473 K and (b) 498 K.

Figure 11. Lognormal projection of the mean time-to-failure versus the percent of cumulative failures for a 10 Gbps planar InGaAs/InP APD after the ALT experiment at (a) 500 $\mu$A and (b) 1000 $\mu$A.
4.5. APD Failure Analysis

First, to verify the failure mechanism during device failure, the resistance of the failed APD was computed and is shown in Figure 12. The output data of the median resistance and standard deviation are summarized in Table 3. Although there were some variations between the resistances under different conditions, the results confirm that the series resistance mounted inside the TO-46 did not degrade during the ALT experiment. Because the tested APDs had two 1 kΩ resistors connected in series, the failure of the APD was mainly due to the APD device itself. In addition, the failed APDs showed different resistance values correlated with the initial I–V characteristics and the effect of edge breakdown in the guard-ring region, which was verified using IR thermography.

![Figure 12. Resistance of the failed tested APDs at (a) 473 K and (b) 498 K.](image)

**Table 3. Resistance of the failed tested APDs.**

| Temperature (K) | Current (µA) | Median Resistance (kΩ) | Standard Deviation (Ω) |
|----------------|-------------|------------------------|------------------------|
| 473            | 500         | 2.73                   | 434                    |
| 473            | 1000        | 2.95                   | 547                    |
| 498            | 500         | 4.45                   | 853                    |
| 498            | 1000        | 3.27                   | 614                    |

With IR thermography, the failure mechanism of the tested APDs was further investigated by measuring with FLIR SC5000 in Wooriro [19]. As shown in Figure 13, the red spot indicates premature edge breakdown, which is a conventional failure mechanism of LM APD [17]. Figure 11a,b show the IR results of the failed devices under the conditions of 500 µA and 1000 µA at 498 K, respectively. Based on these results, the failure mechanism was confirmed to be due to the edge breakdown near the guard ring region of the tested APDs.

4.6. Extrapolation of Activation Energy and Estimate the APD Lifetime

Using the test results, the activation energy was obtained from the MTTF using the Eyring model shown in Figure 14. The extracted activation energy was computed to be 1.55 eV, which was larger than the conventional APD activation energy for the wear-out failure mode. Furthermore, the minimum MTTF of the LM APD under practical conditions, which were at room temperature with 100 µA, could be estimated to be approximately 5.44 \times 10^{21} h, indicating its extremely high reliability. Additionally, the minimum survival time (MST), the value of which was located under the surface plot of the MTTF, was
defined as the projection of the MTTF at 448 K and 500 μA, verifying the suitability of the Eyring model.

![Figure 13. IR results of the failed APDs under the conditions of (a) 498 K with 500 μA and (b) 498 K with 1000 μA.](image)

Figure 13. IR results of the failed APDs under the conditions of (a) 498 K with 500 μA and (b) 498 K with 1000 μA.

![Figure 14. The results of the Eyring model for five distinct conditions with the projection of the MST value.](image)

Figure 14. The results of the Eyring model for five distinct conditions with the projection of the MST value.

5. Conclusions

The long-term reliability of open-tube diffused planar InGaAs/InP APDs was investigated through accelerated life testing. For the proposed life testing scheme, both thermal and electrical stresses were applied simultaneously to reduce the testing periods while maintaining statistical significance. Additionally, the Eyring model was used to extrapolate the activation energy. Based on the test results, the activation energy of the tested APD was 1.55 eV, which is far superior to that of any previously developed conventional planar APDs. In addition, this proposed testing scheme, which utilizes a hybrid of accelerated stress factors, can help estimate device reliability within an acceptable testing period, minimizing the time to market.

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