# InGaAs/InAlAs Avalanche Photodiode With Low Dark Current for High-Speed Operation

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***Abstract*— Waveguide InGaAs/InAlAs avalanche photodiodes (APDs) with high bandwidths (>40 GHz) and low dark current (<50 nA at 90% of breakdown voltage) were demonstrated. The excess noise is low, corresponding to $k \sim 0.2$ line in the local excess noise model. Using these values bit error rate (BER) was calculated to assess the potential of our APDs. Calculated sensitivities of −21.5 dBm at 25 Gb/s and −14.2 dBm at 40 Gb/s are predicted for a BER of $10^{-10}$. Analysis showed that with lower amplifier noise, the low dark current and low excess noise from our APDs are necessary to optimize the sensitivity.**

***Index Terms*— Avalanche photodiodes bandwidth, bit-error-rate, receiver sensitivity at 25 Gb/s.**

## I. Introduction

HIGH speed photodiodes are in demand to respond to the ever increasing internet traffic within Ethernet and long haul backbone optical networks. For instance Ethernet systems with bit rates of n × 100 Gb/s, such as 100GE-ER4 and the proposed 400GE-LR16, require components operating at 25 Gb/s. In order to satisfy the sensitivity requirement of the receiver, one of the proposed solutions for 100GE-ER4 standard is to utilize semiconductor optical amplifier (SOA) and conventional multi-channel, 4 × 25 Gb/s PIN photodiodes (PDs). However, an SOA has a rather small extinction ratio, high power consumption [1], and requires a relatively large packaging module. An attractive and effective alternative is to replace the 25 Gb/s PIN photodiode and SOA combination with an APD.

APDs can provide higher sensitivity than PDs due to their internal gain, making them more attractive in the high data rate systems as the electronic noise increases with frequency. APDs need to exhibit low dark current, high responsivity both at 1310 and 1550 nm, and low excess avalanche noise factor $F$. $F$ is usually measured as function of avalanche gain, $M$, and compared to the excess noise corresponding to a given ratio of ionization coefficients, $k$, in the local avalanche noise model [2]. The interest in using APDs is evident from various reported results. Liow *et al.* [3] reported a waveguide Ge/Si APD which has a −3 dB bandwidth, $f_{3dB}$, of 20.6 GHz at $M = 2.2$. This produces a modest gain-bandwidth product (GBP) of 45 GHz that leads to a calculated sensitivity of −30 dBm at BER = $10^{-10}$ for a single 25 Gb/s Ethernet channel. Assefa *et al.* [4] introduced a Ge/Si APD on nanophotonic chip and reported a $f_{3dB} = 30$ GHz at $M = 10$, producing a GBP of 300 GHz for a 40 Gb/s direct detection optical system. However, both devices operate at the wavelength of 1310 nm, and due to the low absorption for Ge at 1550 nm, they are not suitable for long haul optical transmission systems. $In_{.53}Ga_{.47}As/In_{.52}Al_{.48}As$ (hereafter referred to as InGaAs/InAlAs) APD grown on InP substrate has been considered for high speed system due to the wide bandgap and low excess noise factor in InAlAs [5]. Nada *et al.* [6] reported a vertically illuminated InGaAs/InAlAs APD, with an avalanche region thickness, $w$, of 100 nm, that produces $f_{3dB} = 18.5$ GHz at $M = 10$ and a responsivity-bandwidth product of 168 A/W·GHz. Yoshimatsu *et al.* [7] also utilized this type of APD together with a 1× 4 demultiplexer and built a 4 × 25 Gb/s APD-ROSA with a sensitivity of −20 dBm at BER = $10^{-10}$ for a 50 km optical transmission. Higher bandwidths were reported by Makita *et al.* [8] and Lahrichi *et al.* [9], using waveguide InGaAs/InAlAs APDs exhibiting $f_{3dB} = 35$ GHz at a $M = 2 \sim 3$ and $f_{3dB} = 50$ GHz at a $M = 3.7$ respectively. The bandwidth at low gain was sufficient for operation at 40 Gb/s. Unfortunately, these APDs showed a rapid increase in dark current, $I_d$, under the reverse bias between 10 V ($I_d = 0.1$ μA) to 14.5 V ($I_d = 1$ μA) and 10 V ($I_d = 2.5$ μA) to 18.5 V ($I_d = 70$ μA) respectively, owing to the high tunneling current originating from the thin 100 nm avalanche region [10]. In this work, we employed an optimized avalanche region thickness to achieve an InGaAs/InAlAs APD with low dark current of < 50 nA at 90% breakdown voltage, a responsivity of 0.65 A/W with a 60% coupling efficiency, low excess noise factor equivalent to $k \sim 0.2$ in the local model, a wide bandwidth $f_{3dB} > 40$ GHz at $M = 2$ and a GBP = 115 GHz. These characteristics were used to show that a receiver, incorporating our APD, can achieve good sensitivities. For a BER of $10^{-10}$ we calculated sensitivities of −21.5 dBm at 25 Gb/s (with $f_{3dB} = 18$ GHz and $M = 6.3$) and −14.2 dBm at 40 Gb/s (with $f_{3dB} = 30$ GHz and $M = 3.6$).

## II. Structure and Experimental Details

A separate absorption and multiplication (SAM) APD structure was grown by molecular beam epitaxy on InP semi-insulating (SI) substrate. It comprises a 1200 nm InGaAs absorption layer, 50 nm InGaAlAs (with a bandgap of 1.1 eV)

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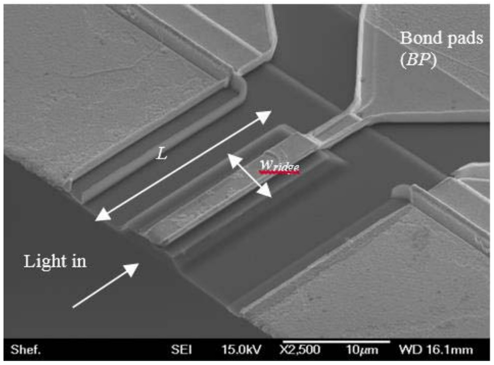


Fig. 1. Top view of the side illuminated waveguide APD, obtained using a scanning electron microscope.

grading layer, 200 nm InAlAs bandgap grading/field control layer and 200 nm InAlAs multiplication layer. The 200 nm multiplication layer was chosen as it is predicted to produce an optimum sensitivity for a 10 Gb/s system [11]. Waveguide APDs (W-APDs) and vertically illuminated circular mesa test diodes with diameters of 200 $\mu$m were fabricated using the following steps. Ti/Pt/Au (10/20/200 nm) was thermally evaporated, followed by rapid thermal annealing at 420 °C for 60 s to form the p-type top ohmic contact. Next we performed a selective wet-chemical etching using 1:8:80 mixture of $H_2SO_4$:$H_2O_2$:$H_2O$ to define the device size. The n-contact, using In/Ge/Au (20/20/200 nm), was then evaporated. We then etched down to the SI InP substrate, deposited a 200 nm $SiN_x$ passivation layer using a plasma-enhanced chemical vapor deposition at 300 °C and finally evaporated the Ti/Au (10/500 nm) bond pads (BPs) on the SI substrate. The waveguide ridge width $w_{ridge}$ is 4 $\mu$m and the length $L$ are 15, 30 and 50 $\mu$m. An example of the fabricated W-APD is shown in figure 1.

To measure the excess noise we used a customized circuit [12]. As the light was coupled vertically in our excess noise set-up, measurements were carried out on circular mesa APDs with top optical windows. Mesa APDs with diameters of 200 $\mu$m were used to ensure that light was confined to the center of the device to prevent mixed injection profile at the mesa sidewall. Phase sensitive detection was used so that gain and excess noise can be measured independent of the dark current and system noise. A 1.52 $\mu$m He-Ne laser was used to provide pure electron injection profile for the measurements.

The on-wafer frequency response measurements between 10 MHz and 40 GHz were performed using the laser with a 40 GHz optical modulator. The modulator was driven by a 50 GHz Agilent network analyzer with a modulating RF power of $-2$ dBm. The modulated laser was coupled to the absorption area of the W-APDs using a lens fiber. The system frequency response was calibrated using a high speed photodiode with a $-3$ dB bandwidth of 50 GHz (U2t photonics photodetector with product number XPDV2120R).

## III. Experimental Results and Discussion

Room temperature dark current-voltage characteristics of W-APDs, together with those from the bond pads only, are shown in figure 2. Breakdown voltage, defined at a dark current of 100 $\mu$A, was found to be 34 V. Low dark current was achieved in all our devices. Our largest W-APD with an area of $4 \times 50$ $\mu m^2$ still exhibits a reasonably low value of 50 nA at 90% of the breakdown voltage. The dark current prior to the breakdown voltage is similar and is independent of the device geometry suggesting that it is not related to a bulk mechanism. A comparison with the leakage current measured on a reference bond pad-only structure yields good agreement, particularly at low voltages, indicating that the dark current originates from non-optimized bond pad deposition. Further improvement of bond pad via effective etchant and appropriate etching depth to the SI substrate, effective passivation, and improving the resistivity of the substrate may help reduce the leakage dark current. Despite the un-optimized bond pads, the dark current remains below 50 nA in our diodes at a bias of 90% of the breakdown voltage. This is approximately 20 times lower than the $6 \times 20$ $\mu m^2$ waveguide APD operating at 40 Gb/s, reported by Makita *et al.* [8] and the 20 $\mu$m diameter vertically illuminated APD operating at 25 Gb/s, reported by Yoshimatsu *et al.* [7]. The comparison is shown in figure 2. The lower dark current in our devices is attributed to the negligible tunneling current arising from InAlAs multiplication layer. To achieve an avalanche gain of 10, the required the electric field will be 1 MV/cm for a 100 nm thick InAlAs avalanche region but reduces to 730 kV/cm for a 200 nm thick avalanche region [10]. The corresponding band to band tunneling current density reduces from 0.5 A/cm$^2$ to $1.79 \times 10^{-4}$ A/cm$^2$. Therefore, the dark current in our APD utilizing a 200 nm InAlAs avalanche region can have substantially lower dark than that employing a 100 nm avalanche region.

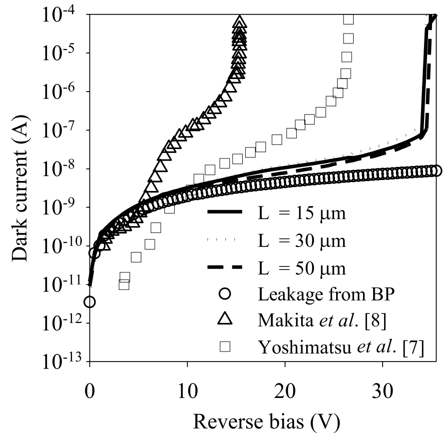


Fig. 2. Dark current measurements for the W-APDs with waveguide lengths of 15, 30 and 50 $\mu$m. The leakage current originating from the bond pad, BP, with length of 125 $\mu$m, deposited on the semi-insulating substrate (◯) and that from a 40 Gb/s InGaAs/InAlAs W-APD with an area of $6 \times 20$ $\mu m^2$ reported by Makita *et al.* [8] and a 25 Gb/s InGaAs/InAlAs vertically illuminated APD with a diameter of 20 $\mu$m reported by Yoshimatsu *et al.* [7], are included for comparison.

In order to deduce the avalanche gain in our InGaAs/InAlAs APD, it is necessary to measure the responsivity value at the punch-through voltage to provide a reference for photocurrent value at unity gain. A responsivity value of $\sim 1.1$ A/W at reverse bias of 17 V was measured for test mesa diodes with diameter of 200 $\mu$m, under optical powers ranging from 50-250 $\mu$W, assuming a semiconductor reflectivity of 0.3.

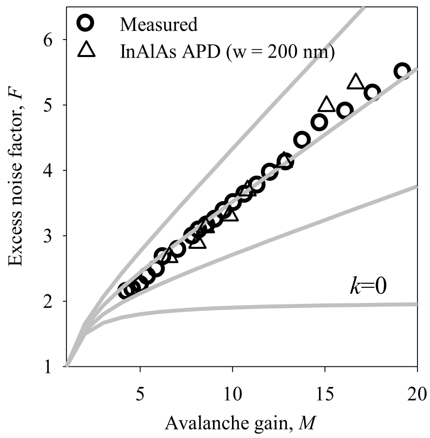


Fig. 3. Measured avalanche excess noise factor. The lines corresponding to $k = 0$ to 0.2 (with an increment of 0.1), in the local noise theory [2].

The absorption coefficient of InGaAs was extracted from the responsivity measurement of a p-i-n diode consisting of InP p and n cladding layers and a 1 $\mu$m InGaAs i-layer. From the measured responsivity of 0.48 A/W, we deduced an absorption coefficient of 7954/cm. Using this value the theoretical responsivity from the 1.2 $\mu$m InGaAs absorption region in the InGaAs/InAlAs APD should be 0.54 A/W. This suggests an avalanche gain of $M = 1.1/0.54 = 2.04$ at the punch-through voltage. Measurements on W-APDs, using a lens fiber, produced a lower responsivity of 0.65 A/W at the punch-through voltage, indicating approximately 60% of coupling efficiency since the avalanche gain is independent of device geometry. This low optical coupling efficiency is due to the mismatch between the optical field profiles of the lens fiber and our W-APDs as well as lack of anti-reflection (AR) coating, and un-optimized cleaved facet of our W-APD. Typical excess noise factor as a function of gain has been measured using a 1.52 $\mu$m laser, and is shown in figure 3. Low excess noise factors falling on the line $k \sim 0.2$ in the local noise theory were measured at $M > 5$. This low excess noise verifies the appropriateness of using a thin 200 nm InAlAs avalanche region.

The frequency responses of W-APDs with different waveguide lengths were measured and their relative frequency responses normalized to their values at 1.09 GHz were calculated for bandwidth comparison. The normalization point was selected due to the high noise level in the setup before 1 GHz. The devices with different waveguide lengths are similar, with wide bandwidths up to 40 GHz at $M = 2$ as shown in figure 4 (a). This indicates their frequency responses are not limited by device capacitance. The upper measured frequency is currently limited by the optical modulation in our system. Figure 4 (b) shows a typical $f_{3dB}$ as a function of gain characteristic for the device with $L = 15$ $\mu$m. The devices show a decrease of $f_{3dB}$ as avalanche gain increases, corresponding to a modest GBP $\sim$ 115 GHz.

To assess the potential of our W-APDs, we calculated the optical receiver sensitivity. BER is assumed to be the performance criterion for digital receivers and the receiver sensitivity is defined as the minimum average optical power to obtain a given BER value. Using the method described in [13],

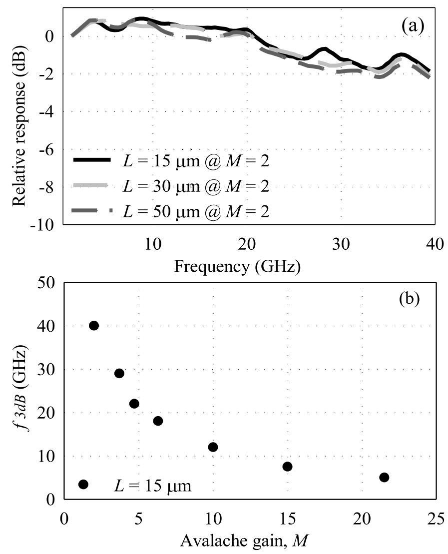


Fig. 4. (a) Normalized frequency responses of the devices with different W-APD lengths at $M = 2$; (b) a typical $f_{3dB}$ as a function of gain for a W-APD with $L = 15$ $\mu$m.

TABLE I

VALUES USED FOR SENSITIVITY CALCULATION AT 25 Gb/s

| | Yoshimatsu *et al.* [7] | This work |
|---|---|---|
| $f_{3dB}$ (GHz) | 18.5 | 18 |
| $M$ | 10 | 6.3 |
| $R$ (A/W) | 0.91 | 0.65 |
| $I_d$ (nA) | 500 | 20 |
| Sensitivity (dBm) | -24 | -21.5 |

TABLE II

VALUES USED FOR SENSITIVITY CALCULATION AT 40 Gb/s

| | Makita *et al.* [8] | This work |
|---|---|---|
| $f_{3dB}$ (GHz) | 35 | 30 |
| $M$ | 3 | 3.6 |
| $R$ (A/W) | 0.95 | 0.65 |
| $I_d$ (nA) | 1000 | 14 |
| Sensitivity (dBm) | -15 | -14.2 |

the sensitivities at 25 and 40 Gb/s were calculated. The signal was determined by the input average optical power, $P$, and the diode responsivity, $R$. The system total noise was determined by the sum of noise power from the APD and trans-impedance amplifier (TIA). The noise power from APDs, $N_{apd}$, accounting for the multiplication process is approximated by $N_{APD} = 2q(R \times P + I_d)M^2F \times f_{3dB}$ and the input referred equivalent noise current for the TIA is assumed to be 15 pA/$\sqrt{\text{Hz}}$ at 25 Gb/s [14] and 35 pA/$\sqrt{\text{Hz}}$ [15] at 40 Gb/s. Values for $R$, $I_d$, $M$, $F$ and $f_{3dB}$ from our W-APD as well as those from Yoshimatsu *et al.* [7] and Makita *et al.* [8], listed in Tables I and II, were used to calculate the sensitivity required to achieve BER of $10^{-10}$ at 25 and 40 Gb/s.

At 25 Gb/s, the calculated sensitivity of our W-APD is 2.5 dBm poorer than that calculated using parameters from Yoshimatsu *et al.* [7]. Similarly at 40 Gb/s the sensitivity is 0.8 dBm poorer than that calculated using parameters from Makita *et al.* [8]. Both APDs reported by Yoshimatsu *et al.* [7] and Makita *et al.* [8] have higher responsivity than our APD,

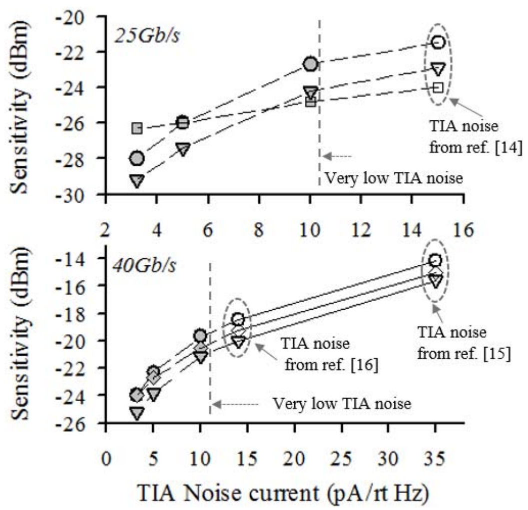


Fig. 5. Calculated sensitivity (◯) for bit error rate (BER) of $10^{-10}$ at 25 and 40 Gb/s as a function of TIA noise current. The calculated sensitivities for the 25 Gb/s InGaAs/InAlAs APD by Yoshimatsu *et al.* [7] (□) and 40 Gb/s InGaAs/InAlAs waveguide APD by Makita *et al.* [8] (◇) and our W-APD with improved responsivity of 0.91 A/W (▽) are included for comparison. Solid symbols filled in grey are the calculated sensitivities for very low TIA noise.

which improves their sensitivity. However their higher dark currents also suggest that for these high speed TIAs, the dominant noise source is the amplifier noise rather than the dark currents from the APDs. To verify this, we have calculated the sensitivities using lower TIA noise current values of 3.2 and 5 pA/$\sqrt{}$Hz. These are typical values for TIAs used in 10 Gb/s channels. If the high speed TIA can achieve a low noise current of 3.2 pA/$\sqrt{}$Hz, the benefit of the lower dark current in our W-APD will be apparent. At 25 Gb/s, our W-APD provide a 1.7 dBm improvement over that of Yoshimatsu *et al.* [7] while matching that of Makita *et al.* [8] at 40 Gb/s, as shown in figure 5. Reducing the TIA noise is an active area of research [16]–[18], with highly encouraging low noise of 14 pA/$\sqrt{}$Hz achieved at 40 Gb/s [16]. With the expected improvement in the TIA noise, it is imperative that the APDs should also be designed to exhibit low dark current and low excess noise to optimize the sensitivity.

In addition to assessing the performance with low TIA noise, it is also useful to analyze potential improvement achieved by optimizing the optical coupling, for instance by matching the optical mode. Using the responsivity value of 0.91 A/W reported by Yoshimatsu *et al.* [7], the sensitivity of our W-APD, at 25 Gb/s and a TIA noise current of 15 pA/$\sqrt{}$Hz, is still 1.1 dBm higher. However with the responsivity of 0.91 A/W, our APD is predicted to yield 2.9 dBm improvement if the TIA noise is reduced to 3.2 pA/$\sqrt{}$Hz. At 40 Gb/s, the higher responsivity will enable our APD to produce better sensitivity than that calculated for Makita *et al*. [8]. The improvement in the predicted sensitivity increases from 0.6 dBm to 1.2 dBm as the TIA noise reduces from 35 to 3.2 pA/$\sqrt{}$Hz.

## IV. Conclusion

InGaAs/InAlAs APD have been grown and characterized. The APDs show low dark currents 50 nA at 90% of the breakdown voltage and low excess noise factor equivalent to $k \sim 0.2$ in the local model. A wide bandwidth up to 40 GHz at low gains ($M = 2$) independent of waveguide length and a GBP of 115 GHz was achieved. Calculations using noise current values from commercial TIA suggest that our APDs can achieve sensitivities of $-21.5$ dBm at 25 Gb/s and $-14.2$ dBm at 40 Gb/s to maintain a BER of $10^{-10}$. If the noise current can be reduced below 5 pA/$\sqrt{}$Hz, the lower dark current from our APD, provide a clear improvement in sensitivity over that reported by Yoshimatsu *et al.* [7] at 25 Gb/s. Due to the larger bandwidth required for 40 Gb/s operation, the amplifier noise is the dominant noise source. As a result, the benefit of low dark current from our APD was not observed.

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