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Low-noise AlGaAsSb avalanche photodiodes for 1550 nm light detection

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ABSTRACT

Avalanche photodiodes (APD) can improve the signal to noise ratio in applications such as LIDAR, range finding and optical time domain reflectometry. However, APDs operating at eye-safe wavelengths around 1550 nm currently limit the sensitivity because the APDs' impact ionization coefficients in the avalanche layers are too similar, leading to poor excess noise performance. The material AlGaAsSb has highly dissimilar impact ionization coefficients (with electrons dominating the avalanche gain) so is an excellent avalanche material for 1550 nm wavelength APDs.

We previously reported a 1550 nm wavelength AlGaAsSb SAM APD with extremely low excess noise factors, 1.93 at a gain of 10 and 2.94 at a gain of 20. Using a more optimized design, we have now realized an AlGaAsSb SAM APD with a lower dark current (7 nA at a gain of 10 from a 230 µm diameter APD), a higher responsivity (0.97 A/W) and a lower excess noise (1.9 at a gain of 40), compared to our previous SAM APD. Noise-equivalent-power (NEP) measurements of our APD with a simple transimpedance amplifier circuit produced an NEP 12 times lower than a state-of-the-art APD under identical test conditions, confirming the advantage of low-noise AlGaAsSb SAM APDs.

1. INTRODUCTION

Avalanche photodiodes (APD) are widely used to provide high detection sensitivity due to their internal gain mechanisms. Current APDs operating at eye-safe wavelengths at around 1550 nm typically consist of InGaAs/InAlAs and InGaAs/InP in a separate absorption and multiplication (SAM) APD structure. The avalanche materials of these SAM APDs, InAlAs[1] and InP[2], have very similar electron (α) and hole (β) impact ionization coefficients, and thus an impact ionization coefficient ratio ($k = \beta/\alpha$) close to unity. This is well known to produce an excess noise factor (F) which tends towards gain (M), as described by the $F(M)$ expression (assuming negligible carrier dead space effects) as shown in equation 1. When k approaches unity, the APD's useful gains often do not exceed 10 to 20.

$$F = kM + (1-k)\left(2 - \frac{1}{M}\right). \tag{1}$$

In recent years extremely low $F(M)$ characteristics were measured from materials $Al_{0.85}Ga_{0.15}As_{0.56}Sb_{0.44}$ (hereafter referred to as AlGaAsSb)[3] and AlAsSb[4], which are lattice-matched to InP substrates. These materials promise to bring new levels of sensitivity to APDs operating in the eye-safe infrared region. AlGaAsSb SAM APDs can make use of high-quality InGaAs absorbers, and such structures are compatible with established InP manufacturing processes.

Phlux Technology have previously reported an InGaAs/AlGaAsSb SAM APD, with excellent low excess noise properties of F = 1.93 and 2.94 at gains of 10 and 20 respectively[5]. In this study, we report further improvements made to the design, fabrication and reliability which have improved the APD's excess noise, gain and dark current characteristics.

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2. EXPERIMENTAL DETAILS

The SAM APD wafer was grown by molecular beam epitaxy on a semi-insulating InP substrate. It consisted of an InGaAs absorption layer and an AlGaAsSb multiplication layer, which were separated by a field control layer to create different electric fields and a grading layer to aid carrier transport. Circular mesa diodes of radii between 30 and 280 μm were fabricated using a wet etching process. Ti/Au metal contacts were evaporated onto contact layers to form Ohmic contacts. The devices were passivated to facilitate remote bond pads and wire ball bonding.

All measurements were taken at room temperature. Gain and responsivity measurements were performed using phase-sensitive techniques, implemented using a lock-in amplifier and modulated light from a 1550 nm laser and a 940 nm LED. The gain data from 940 nm and 1550 nm wavelength measurements were indistinguishable. This is expected as photons of both wavelengths are solely absorbed in the absorber, providing pure carrier injection into the AlGaAsSb multiplication region. A reference photodiode with identical InGaAs absorber thickness provided experimental value of responsivity at the unity gain for the SAM APD. This value was later used to obtain gain values for the SAM APD, because its avalanche gain at punchthrough voltage was designed to be greater than unity.

$F(M)$ measurements of the SAM APD were also carried out using phase-sensitive detection and the modulated 940 nm wavelength LED. Further details of the $F(M)$ experimental setup can be found in ref 3[3]. Noise-equivalent-power (NEP) measurements were carried out using the method described in ref 6[6]. The SAM APD was connected to the input of a transimpedance amplifier (TIA) circuit implemented using the LTC6563 [7]. With the SAM APD in the dark and reverse-biased, a spectrum analyser was used to measure the non-illuminated output noise spectral density into a 50Ω load as a function of reverse voltage. The input-referred current noise was given by the measured output voltage noise divided by the TIA's transimpedance gain and normalised over the chosen measurement bandwidth (1 – 215 MHz). For a given reverse voltage, the NEP was given by the ratio of the input-referred current noise to the responsivity.

3. RESULTS

The room temperature dark current-voltage (IV) characteristics of the SAM APD from a range of device diameters are shown in Figure 1(a), indicated by solid lines. The breakdown voltage, defined by the voltage at which the dark current reaches 100 μA, is 67 V and is consistent from all device sizes. When illuminated by 1550 nm wavelength laser light with a 1.1 μW optical power, the punchthrough voltage is observed at 30 V. The responsivity is 1.46 A/W at 30V. The unity gain responsivity estimated from the reference photodiode was 0.97 A/W. Therefore, the gain at punchthrough voltage (30 V) is 1.5.

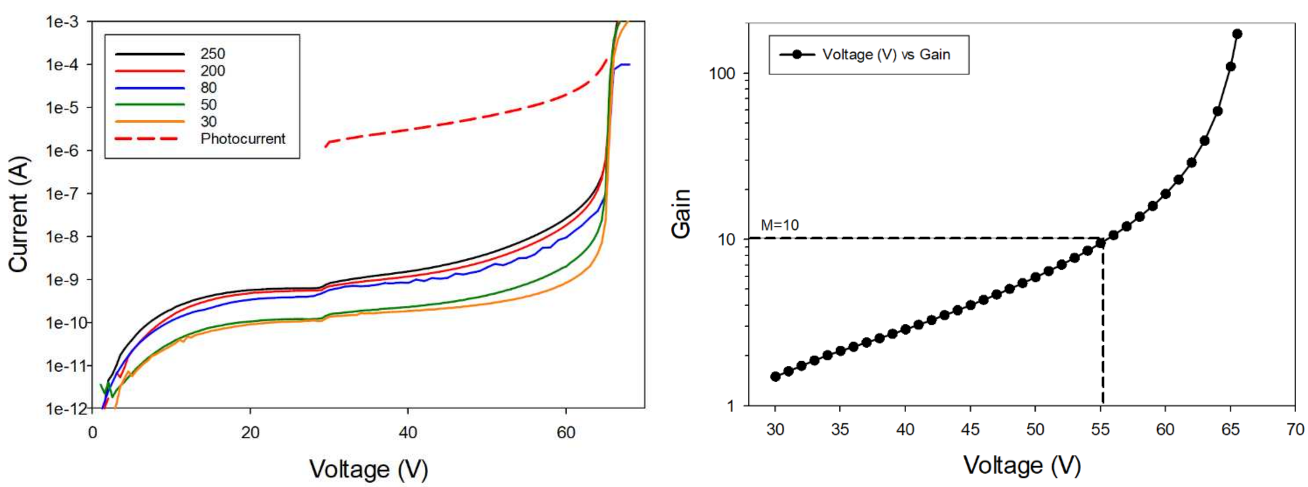

Figure 1 (a) The dark current (solid lines) and photocurrent (dashed line) of the APD when under 1550 nm wavelength illumination. (b) the voltage dependence of the gain.

The voltage dependence of gain is shown in Figure 1(b). A gain of 10 is reached at a reverse voltage of 55.5 V. At this voltage, the dark current of this APD is 7.0 nA which corresponds to a dark current density of 16 μA/cm^2. This is lower than our previous report[5] and commercial 1550 nm wavelength APDs available from Hamamatsu (20 nA)[8], Excelitas (45 nA)[9] and Laser Components (25 nA)[10].

The room temperature $F(M)$ characteristics of the AlGaAsSb APD is presented as the mean value of from 3 devices in Figure 2(a). For comparison, $F(M)$ characteristics for varying k expected from Equation 1 as well as typical APDs with Si[11], InP[12] or InAlAs[13,14] avalanche layers are also included. The excess noise factor of the AlGaAsSb SAM APD was found to be 1.06 at a gain of 10 and 1.9 at 40. These are significantly lower than the excess noise factors of widely available InAlAs and InP APDs as well as Silicon APDs (which cannot detect 1550 nm wavelength light). The excellent $F(M)$ characteristics was achieved using a careful optimization of the electric field profile and avalanche region in our APD structure. The low excess noise of the AlGaAsSb APD enables operation at a much higher gain than InAlAs and InP APDs before the signal to noise ratio begins to deteriorate.

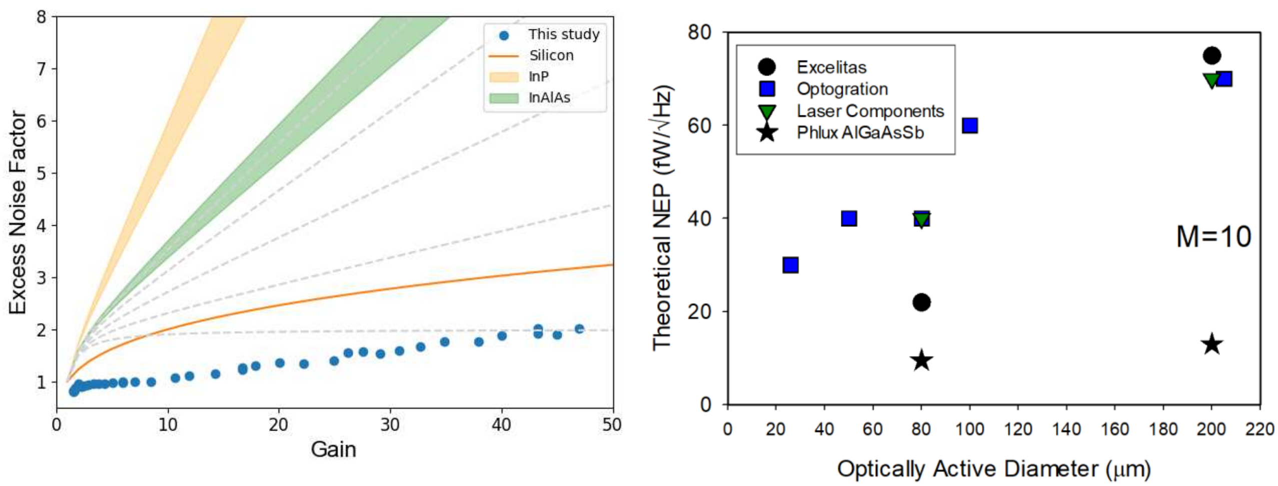

Figure 2 (a) Experimental excess noise characteristics of AlGaAsSb APD (blue circles) compared to Si[11], InP[12] and InAlAs[13,14]. Grey dashed lines indicate the theoretical excess noise for k from 0 to 0.2 in intervals of 0.05. (b) The theoretical NEP of the AlGaAsSb APD compared with commercial InAlAs and InP APDs at $M = 10$.

The effect of the low excess noise factor and low dark current of AlGaAsSb can be demonstrated by calculating the theoretical NEP, given by

$$NEP_{theory} = \frac{1}{R}\left(\sqrt{2qIM^2F + n_{amp}^2}\right), \quad (2)$$

where R is the responsivity, I is the unity gain dark current and n_{amp} is the noise spectral density of an external amplifier. Other sources of noise such as thermal noise and 1/f noise have been ignored because the dominant noise currents are expected to be from the APD and the external amplifier.

If the effect of the amplifier is excluded (i.e. $n_{amp} = 0$), the NEP due to the APD alone can be assessed. Figure 2(b) compares the theoretical NEP values calculated using the responsivity and dark current of the AlGaAsSb APD and NEP values from other commercially available APDs for 1550 nm wavelength detection. The latter group includes NEP values directly from the datasheet (Optogration) or calculated using stated values of R, I, M, and F (Laser Components and Excelitas). All values in Figure 2(b) are for a gain of 10 and at room temperature. Using a 200 μm optically active diameter, the AlGaAsSb APD reaches a low NEP of 13 fW/√Hz, much lower than the average 70 fW/√Hz of other commercially available APDs. The better NEP value is attributed to the low dark current and excess noise factor of the AlGaAsSb APDs.

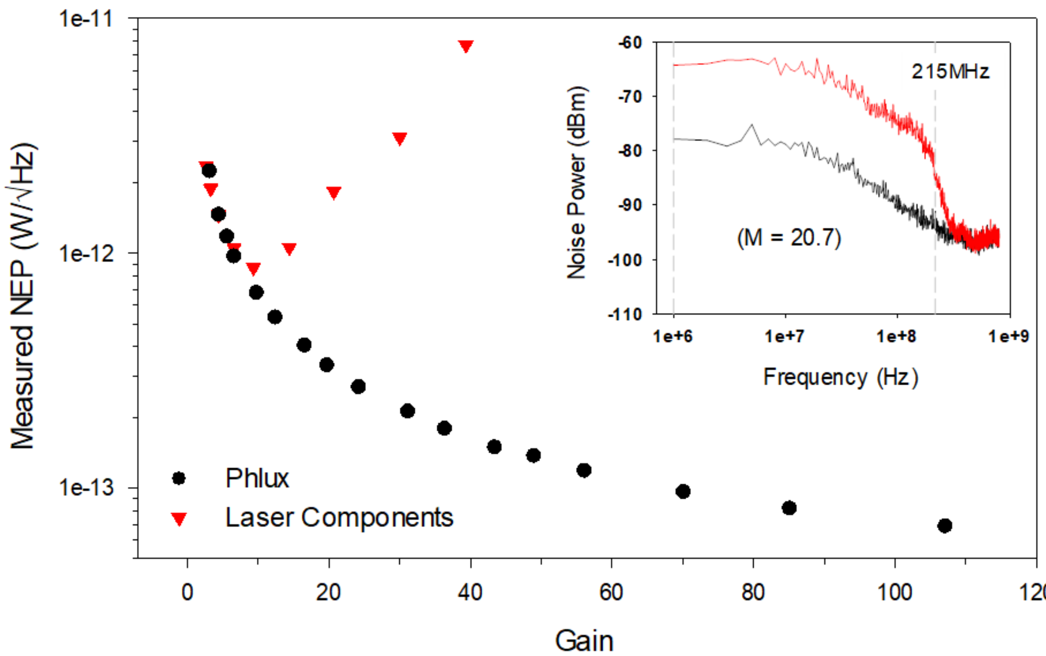

Figure 3 The measured NEP against avalanche gain for a Phlux AlGaAsSb APD (black circles) and Laser Components APD (red triangles), both with an 80µm optically active window, integrated with a TIA. Inset shows the measured TIA output noise spectra for both APDs at $M = 20.7$. Measurement bandwidth is indicated by vertical grey lines.

The NEP measurements which included a TIA provide further evidence of the significant performance improvement offered by our APDs at high gains. The experimental NEP versus avalanche gain data of our AlGaAsSb Phlux APD with a TIA are shown in Figure 3. NEP data taken using an APD with InGaAs absorber, IAG080X[10], is also included. Both APDs have an 80 µm optically active diameter, but their NEP dependences on M are noticeably different for $M > 10$, as expected from their very different $F(M)$ characteristics. At $M = 10$, F values are 1.06 and 3.7 for our APD and the IAG080X. The minimum NEP of IAG080X is 865 fW/√Hz at $M = 10$, before rising rapidly with gain. The NEP of IAG080X deteriorated due to the high excess noise and large multiplied component of the dark current. However, the NEP of AlGaAsSb APD continues to decrease with gain, reaching 69 fW/√Hz at a gain of 106, representing 12 times better sensitivity performance. This is attributed to the device's exceptionally low noise, high responsivity and low multiplied dark current.

The inset of Fig. 3 shows the measured TIA output noise spectra for both APDs at $M = 20.7$. At such gain, the NEP measured using the Phlux APD is still limited by the TIA (n_{amp} in Equation 2). In contrast, the IAG080X has a higher excess noise factor and so the NEP is dominated by noise stemming from the APD. Over the NEP measurement bandwidth (1 – 215 MHz), the amplifier noise floor is 7.5 pA/√Hz. This is presently limited by large low-frequency noise, which is likely to have originated from the measurement setup. Setup improvements are expected to further improve the NEP values.

4. CONCLUSION

At Phlux Technology we have designed and fabricated AlGaAsSb SAM APDs for visible to short-wavelength infrared applications such as LIDAR and range finding. We demonstrated AlGaAsSb APDs with extremely low excess noise factors of 1.06 and 1.9 at gains of 10 and 40 respectively, representing a great improvement over APDs with InAlAs and InP avalanche layers. The dark current of an APD with diameter 230 µm is 7 nA at a gain of 10. Combined with a high unity gain responsivity, an extremely low NEP was predicted, 13 fW/√Hz at a gain of 10 for a device with a 200 µm optically active diameter. This is much lower than other commercially available APDs. Even larger NEP improvements are found at higher gains where the excess noise and dark current remain low. NEP measurements of the AlGaAsSb APD (combined with a TIA) proved that the NEP continues to improve with gain for the entire gain range measured (up to ~100), in contrast to the typical APD's NEP versus gain characteristics. This has resulted in a 12 times improvement in NEP, compared to a state-of-the-art APD.

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