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Extremely low noise InAs and AlGaAsSb avalanche photodiodes for low photon detection in infrared wavelengths

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ABSTRACT

There is an increased demand for low noise avalanche photodiodes (APDs) for infrared wavelengths at 1550 nm for long range Light Detection and Ranging applications. Here we present two classes of APD that produce high avalanche gain but with extremely low excess noise factors, $F \sim 2$. InAs APDs show $F < 2$ and offer detection wavelength up to 3500 nm, although this drops to ~3000 nm when cooled. For reducing effects of scattering in atmosphere, InAs could be an attractive option. In addition InAs APDs are based on a simple homojunction design, which is relatively easy to grow epitaxially. AlGaAsSb when combined with InGaAs, provides a direct replacement for the traditional InGaAs/InP APDs. It is therefore capable of room temperature performance with excess noise performance similar to Si APDs but operates at 1550 nm. We will present results that show noise equivalent power as low as 69 fW/Hz$^{0.5}$.

Keywords: Avalanche photodiodes, infrared APD, excess noise, InAs APDs, AlGaAsSb APDs

1. INTRODUCTION

Low photon sensing is vital for a wide range of applications from free space optical communication to Light Detection and Ranging (LIDAR). The latter is increasingly used for monitoring of greenhouse gases, CO_2 and CH_4, and for navigation systems. These applications commonly used infrared wavelengths, such as 1570 nm and 2000 nm for CO_2 sensing, 1650 nm and 3240 nm for CH_4, while the 1550 nm wavelength is used in navigation LIDAR to permit higher transmitter optical power (defined by eye safety requirement). Therefore avalanche photodiodes (APDs) that are capable of providing high internal gain and low excess noise hold the key to achieving low photon sensing in the infrared wavelengths. In this paper, 2 APD technologies are presented.

First, a simple homojunction design utilizing InAs, which has a bandgap of 0.35 eV, is described. Because of its narrow bandgap InAs can provide efficient detection at infrared wavelengths up to ~3500 nm at room temperature. The longest detection wavelength will however reduce if InAs is cooled. It is well known that longer infrared wavelength has better penetration through atmospheric obscurant such as light fog. To date, the best APDs covering the wavelength between 1500 to 3500 nm is HgCdTe APDs. However, access to HgCdTe is limited due to cost, as well as phasing out of Hg-based product as outlined in the Minamata Convention on Mercury. Therefore, development of APDs capable of matching the performance of HgCdTe is desirable.

Due, to the small bandgap, InAs APDs will require some cooling to reduce the dark current when low photon sensing is required. For mass-market application, room temperature APDs are needed. At 1550 nm, the commercial APDs at present incorporate InGaAs absorption with either InP or InAlAs as the avalanche region. The excess noise factor, F, for both InP and InAlAs, increases rapidly at high gain, limiting the useful gain for these APDs to typically below 20 to maintain low F. We will show that AlGaAsSb, lattice matched to InGaAs, provide the much needed solution for low noise APDs grown on widely available InP substrates.

2. INDIUM ARSENIDE AVALANCHE PHOTODIODES

Avalanche gain in InAs p-n junction, was first reported by Lucovsky and Emmons [1], who reported avalanche gain at bias below 10 V. The avalanche gain properties were only investigated comprehensively, using a series of pin and nip diodes, to demonstrate that the pure electron initiated gain is significantly larger than the pure hole initiated gain by Marshall [2]. This indicated that the electron ionization coefficient, α, is significantly larger than the hole ionization coefficient, β, as shown in Figure 1. The large α/β ratio is expected to yield low F, independent of the magnitude of the avalanche gain [3]. This low excess noise factor with $F < 2$ was obtained in InAs avalanche photodiodes [4], achieving performance that is comparable to CdHgTe APDs, as shown in Figure 1. In addition to the low excess noise factor, the negligible β values in InAs for electric fields below 70 kV/cm, also produce bandwidth that is not constrained by the avalanche gain, leading to an extremely large gain-bandwidth product of 580 GHz [5]. These successful demonstrations of InAs APDs with $F < 2$ and a very large gain-bandwidth product, were achieved by carefully controlling the wet etching of InAs mesa diodes using a combination of phosphoric acid and sulfuric acid, followed by surface passivation using SU8 or BCB dielectrics.

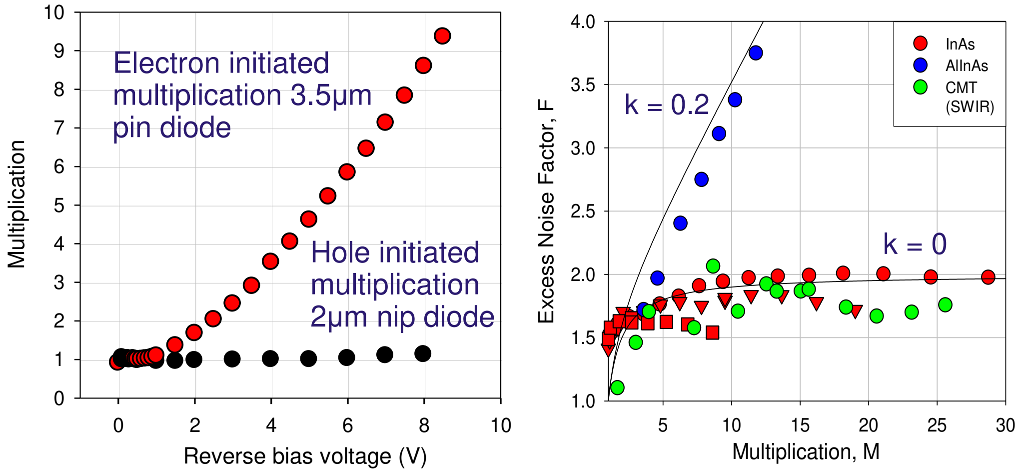

Figure 1. Left: Measured avalanche gain (multiplication factor) under pure electron injection in a pin diode and pure hole injection in a nip diode. Right: Measured room temperature excess noise factor in InAs and comparison to HgCdTe (CMT).

To assess the potential applications that could benefit from our low noise InAs APDs, we measured the absorption spectra of InAs as a function of temperature, as shown in Figure 2. Of particular interest is the absorption spectra at 200 K as this can be achieved using a multi-stage peltier cooler. The peak response was observed to be at the wavelength of 3.2 µm. The response drops to 94% of the peak value at the wavelength of 3240 nm which is the methane absorption line. Therefore InAs can be potentially used for low photon sensing for methane detection. The temperature dependence of an InAs APD cooled using a 4 stage peltier cooler is shown in Figure 2. It can be seen that the dark current drops by more than 2 orders of magnitude relative to the value at room temperature. This demonstrate the potential to have a compact cooled InAs APD.

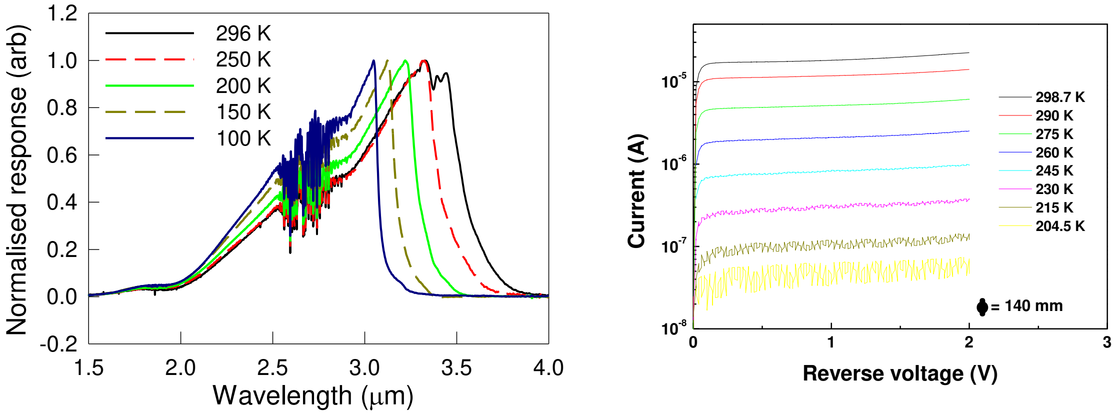

Figure 2. Left: Measured spectral responses of InAs diodes, as a function of temperature. Right: Temperature dependence of dark current of an InAs APDs cooled using a 4 stage peltier cooler.

The mesa InAs APDs with low dark current and low excess noise were evaluated for low photon detection capability. We used a 50 µs laser pulse with a wavelength of 1550 nm and a calibrated attenuator to control the laser power. The laser was focused onto mesa InAs APDs cooled to 77 K to minimize the dark current such that it does not dominate the overall noise in the measurements. Figure 3 shows the detected signal for estimated photon numbers of 35 to 87. The noise floor was dominated by the amplifier used as the noise floor remained constant independent of the detector bias voltage. The signal can be differentiated from the noise floor at optical power level as low as 35 photons. Increasing the bias to increase the avalanche gain led to detection of as few as 15 photons [6].

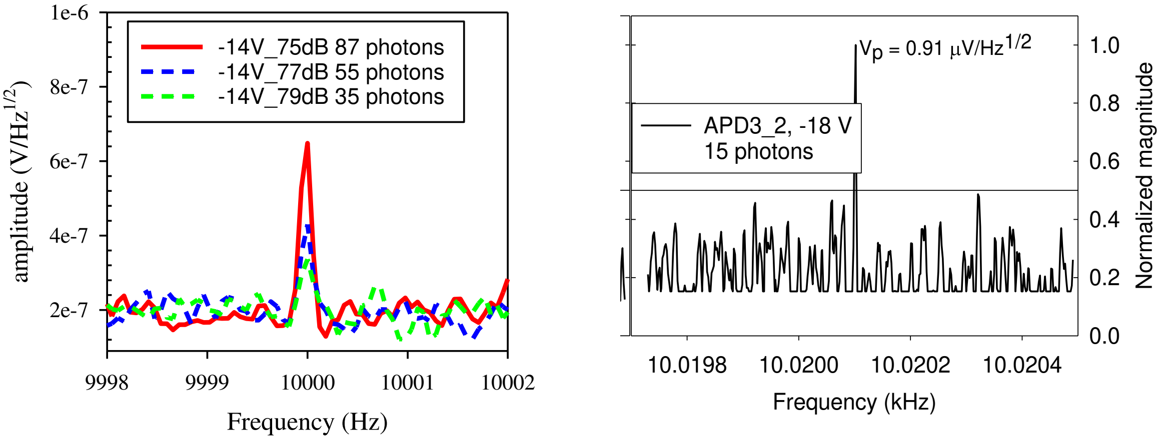

Figure 3. Measured responses from 77 K cooled mesa InAs APDs when the optical power was attenuated to achieve photon numbers between 15 – 87 photons per 50 µs pulse [6].

Having proven that mesa InAs APDs are capable of detecting low photon number, we developed planar InAs APDs. The InAs wafer with a thick 10 µm undoped region, was implanted with Be at room temperature, 7° off axis using implant conditions of 1×10^{14} cm^{-3} at 200 keV and 3.8×10^{13} cm^{-3} at 70 keV to produce a 1 µm deep P^+ region. After implantation the photoresist was removed and the sample was annealed at 550 °C for 30 s in a nitrogen rich atmosphere to recover the crystal. Figure 4 shows that the dark current at close to 0 V drops by more than 6 orders of magnitude when the temperature was reduced from room 296 to 77 K [7]. These planar InAs APDs exhibit high gain of over 300 at 200 K, confirming that low dark current and high gain planar devices have been successfully fabricated.

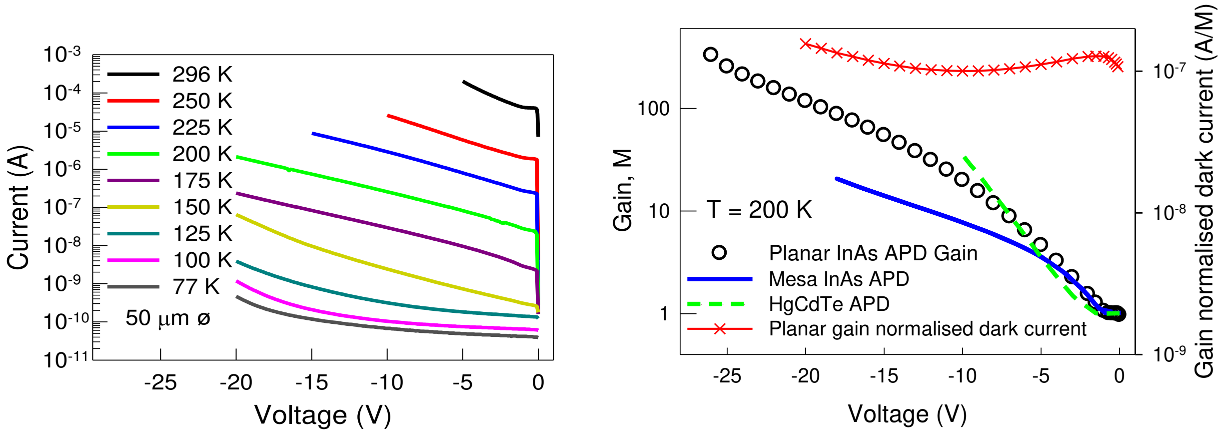

Figure 4. Left: Temperature dependence of dark current from planar InAs APDs. Right: Comparison of avalanche gain from planar InAs APDs with other InAs and HgCdTe APDs.

3. ALUMINIMUM GALIUM ARSENIDE ANTIMONY AVALANACHE PHOTODIODES

The band structure from InAs provided the features to achieve low excess noise, in particular by suppressing hole impact ionization coefficient. Analyzing the valence band features, pointed to the fact that InAs has a very large spin-orbit split off band that is almost equal to its bandgap. This helps to confine holes in the light and heavy hole bands, which have relatively high scattering rates leading to a lack of energetic holes that can initiate impact ionization. Besides InAs, we noted that changing the group V element in In-V compound semiconductors, from P to As, and to Sb leads to a significantly reduced hole ionization coefficient, β, observed from InP to InAs, and to InSb. We therefore investigated Sb based alloys lattice matched to InP substrate. We found that AlAsSb diodes with nominal avalanche width of 200 nm exhibited excess noise matching those of Si APDs [8]. When the avalanche region thickness was increased to 1500 nm in a pin diode (P1), a clear trend of low excess noise factor was observed when pure electron injection, under illumination of 420 nm light, was used. The excess noise factor follows the lines of k = 0.005 [9] in the McIntyre's noise model [3]. The results are shown in Figure 5. It was clear that the excess noise increases dramatically when the avalanche process was initiated using a mixed injection profiles due to the use of 542 and 633 nm lasers and when pure hole injection was used in a nip diode with a 1500 nm avalanche width (N1). Figure 5 also shows that very low excess noise can be obtained using a thick 1000nm wide $Al_{0.85}Ga_{0.15}As_{0.56}Sb_{0.44}$ (AlGaAsSb) avalanche region [10]. When the avalanche region is reduced to 600 nm [11], F < 2 was obtained when gain is less than 25. As before the excess noise increased when mixed injection was used.

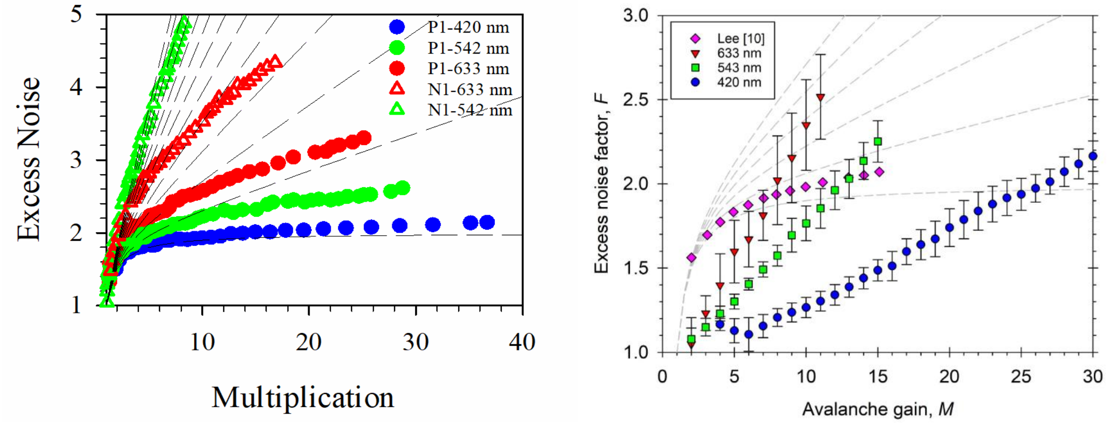

Figure 5. Left: Measured excess noise factor in AlAsSb from a pin (P1) and a nip (N1) with avalanche regions of 1500 nm. Right: Measured excess noise in AlGaAsSb from a pin diode with a nominal avalanche width of 600 nm.

The proven low excess noise in AlGaAsSb shows that it can be a direct replacement of InP to realize low noise APDs operating at the important wavelength of 1550 nm which are key for applications such as infrared LIDAR. A very low noise APD with InGaAs absorption region and AlGaAsSb was achieved by Phlux Technology, a spinout from the University of Sheffield [12]. Figure 6 shows the noise equivalent power (NEP) was at least 12 times lower than a commercial APD from Laser Components, as the AlGaAsSb APD was operated at gain > 100 without suffering from increased excess noise. We have also successfully demonstrated that although not fully optimized for single photon detection, we were able to achieve single photon detection efficiency (SPDE) of 16 %, with a dark count rate (DCR) of 20 Mc/s at an operating temperature of 200 K. Further optimizations will be needed to reduce the DCR.

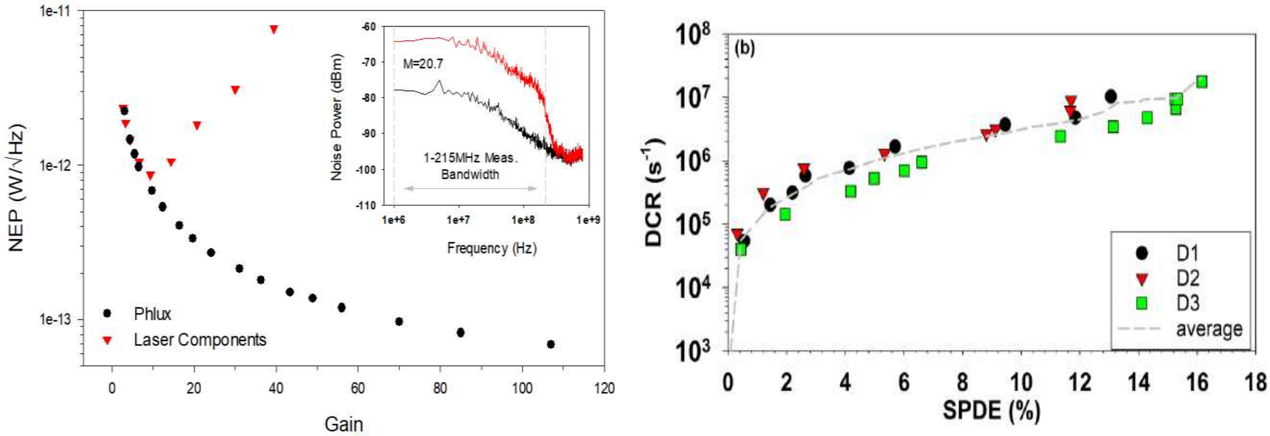

Figure 6. Left: Measured NEP from an InGaAs/AlGaAsSb APD from Phlux Technoloy. Right: Demonstration of single photon detection efficiency of 16 % at 200 K.

4. CONCLUSIONS

We have reported successful development of InAs and AlGaAsSb APDs that exhibit extremely low excess noise factors. The InAs APDs will require cooling in order to suppress dark current, but would be the prime candidate for detection of low photon at infrared wavelengths from 1500 to 3240 nm, suitable for gas sensing applications. The AlGaAsSb on the other hand, is a direct replacement for InP, so that extremely low noise InGaAs/AlGaAsSb APDs can be used for mass-market applications such as room temperature LIDAR systems at 1550 nm.

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