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High sensitivity InAs photodiodes for mid-infrared detection

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ABSTRACT

Sensitive detection of mid-infrared light (2 to 5 μm wavelengths) is crucial to a wide range of applications. Many of the applications require high-sensitivity photodiodes, or even avalanche photodiodes (APDs), with the latter generally accepted as more desirable to provide higher sensitivity when the optical signal is very weak. Using the semiconductor InAs, whose bandgap is 0.35 eV at room temperature (corresponding to a cut-off wavelength of 3.5 μm), Sheffield has developed high-sensitivity APDs for mid-infrared detection for one such application, satellite-based greenhouse gases monitoring at 2.0 μm wavelength. With responsivity of 1.36 A/W at unity gain at 2.0 μm wavelength (84 % quantum efficiency), increasing to 13.6 A/W (avalanche gain of 10) at -10V, our InAs APDs meet most of the key requirements from the greenhouse gas monitoring application, when cooled to 180 K. In the past few years, efforts were also made to develop planar InAs APDs, which are expected to offer greater robustness and manufacturability than mesa APDs previously employed. Planar InAs photodiodes are reported with reasonable responsivity (0.45 A/W for 1550 nm wavelength) and planar InAs APDs exhibited avalanche gain as high as 330 at 200 K. These developments indicate that InAs photodiodes and APDs are maturing, gradually realising their potential indicated by early demonstrations which were first reported nearly a decade ago.

Keywords: avalanche photodiodes, gas sensing, InAs, LIDAR, mesa, photodiodes, planar.

1. INTRODUCTION

Mid-infrared light is used in a wide range of electro-optical active sensing applications, due to the atmospheric transmission window from 2 to 5 μm. With these applications relying on photodiodes to detect the incoming optical signals, performance of the photodiodes are therefore of great significance. Amongst the many performance parameters associated with a photodiode, the greatest consideration must be given to the responsivity across the wavelength region of interest, dark current and operation temperature, which are discussed in this work.

Photodiodes do not offer internal gain so their responsivity is limited by the conversion efficiency of photons to electrons. In contrast, APDs provide internal gain, often termed the multiplication factor, M, so they can have a much higher overall responsivity, which are the products of M and the base responsivity. Although APDs tend to have higher dark currents and a higher cost compared to photodiodes, their internal gain usually brings an overall improvement to performance and hence they are preferred for applications that have weak optical signal (photon-starved), particularly when a high bandwidth is required (e.g. optical fibre-based communication systems).

The APD's multiplication factor is derived from the impact ionization process, in which an energetic carrier (electron or hole) gives up part or all of its energy to create a new electron-hole pair. The impact ionization process is however subjected to statistical fluctuations so the multiplication factor is always accompanied by avalanche noise, which is characterized by excess noise factors, F. An ideal APD therefore provides the characteristics of high M with low F.

The early work by McIntyre[1] established that near ideal excess noise characteristics could be achieved when impact ionization is dominated by only one carrier type. One example of such behaviors is when the ionization coefficient for electrons, α, is large but the ionization coefficient for holes, β, is zero, so that the ratio of ionization coefficients, k, is zero. In such a case, only electrons impact ionize and APDs exhibiting this unique behavior are referred to as electron APDs (e-APDs). E-APDs made with CdHgTe (composition with cutoff wavelength of ~ 4.5 μm at 77 K)[2, 3] are well established, with InAs electron APDs being a comparatively recent development. $F(M)$ characteristics from electron APDs are characterized by $M(V)$ characteristics with M increasing exponentially with V, where V is the reverse bias.

In this work, we review the progress made in InAs APDs, including demonstrations of their impact ionization characteristics, as well as the development of planar InAs APDs, before describing our InAs APDs and the associated amplifier circuit designed for greenhouse gases monitoring applications based on LIDAR.

2. REVIEW OF PROGRESS IN INAS APDS

2.1 Avalanche properties and dark currents of InAs

The first positive indication that InAs APDs have an electron-dominated impact ionization process was the exponential $M(V)$ characteristics[4], as shown in Figure 1 (left). This was soon followed by $F(M)$ characteristics with $k = 0$[5], as shown in Figure 1 (right), which includes data of AlInAs[6] and CdHgTe[2] for comparisons. Confirmation of electron-dominated impact ionization in InAs was eventually provided by disparate electric field dependences of α and β obtained experimentally[7].

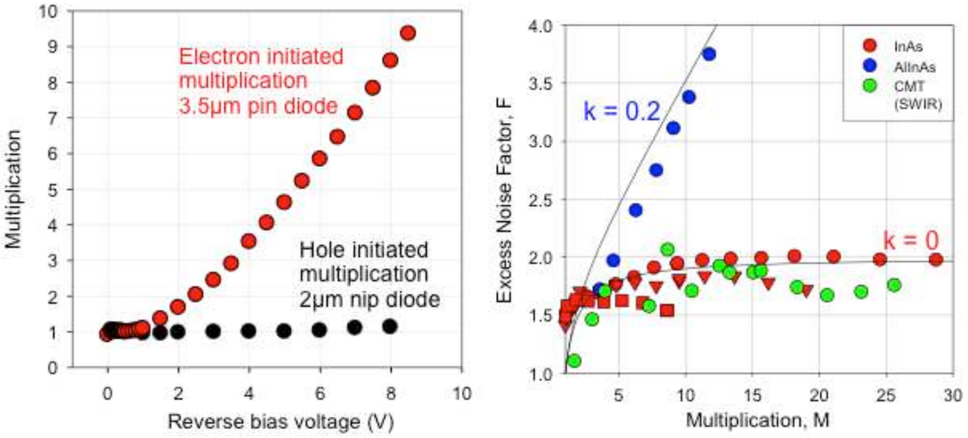

Figure 1. Experimental results of multiplication versus reverse bias voltage (left) and excess noise versus multiplication (right) from InAs diodes[4,5]. Excess noise results of AlInAs [6] and CdHgTe [2] are included in the right plot for comparisons.

Although excellent $F(M)$ characteristics are crucial to good APDs, the dark currents are critical too and often the determining factor for the APDs' operation temperature. The temperature dependence of dark current density from mesa InAs APDs, as shown in Figure 2, was reported by Ker et al[8]. The dark current density decreases with decreasing temperature, showing that bulk leakage current is dominant over surface leakage current. The work also found that the bulk dark current is dominated by diffusion current while the surface dark current is caused by mid-gap recombination current. At 77 K, when the APD exhibited $M = 20$, the dark current density was ~ 80 µA/cm^2.

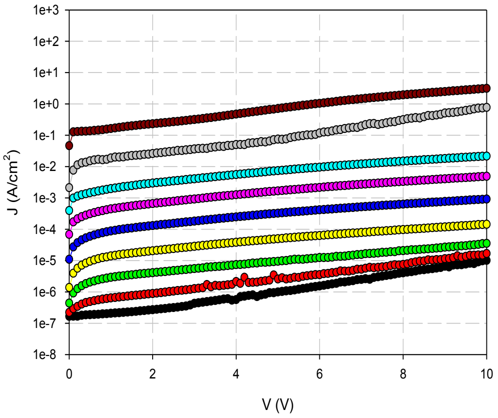

Figure 2. Experimental results of dark current density versus reverse bias voltage, at temperatures of 77, 100, 125, 150, 175, 200, 220, 250 and 290 K (bottom to top)[8]. The devices used were mesa InAs APDs.

2.2 Planar APDs

The experimental demonstrations mentioned above were achieved only after significant progress in wet chemical etching (to create the mesas) and the surface passivation (to protect the mesa sidewalls) had been made. While the mesa topology offers a fast turn-around cycle from wafer growth through fabricating APDs with low dark currents, it can be difficult to completely remove the surface leakage in mesa InAs APDs with a small diameter, as required by some high sensitivity applications. An optimized planar topology (such as those for commercial APDs for 1.55 μm wavelength) can help control the APD surface conditions so that the surface dark currents are reduced. The planar topology is also likely to provide better device fabrication yield and device reliability as well as a more economical fabrication process, as evidenced by the development of more mature APD technologies (Si, InGaAs and CdHgTe).

The development of planar InAs APDs began to show potential when competitive photodiodes[9] and then APDs[10] were obtained through utilising Beryllium (Be) ion implantation and post-implant annealing. In Ref [10], the planar APDs exhibit high multiplication factors while having dark currents that are bulk-dominated, as shown in Figure 3. With no isolation trenches, there was electrical isolation between adjacent planar InAs photodiodes if the separation is at least 7.5 μm[9].

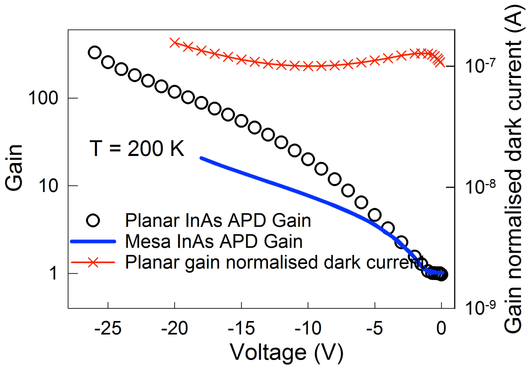

Figure 3. $M(V)$ data (with 1550 nm laser illumination) of a planar InAs APD cooled to 200 K[10]. The data are compared to reference mesa InAs APD[8].

3. APDS FOR GREENHOUSE GASES SENSING

Beyond demonstration of desirable impact ionization characteristics and compatibility with the planar manufacturing process, efforts were focused on developing single-element InAs APDs specifically for a satellite-based greenhouse gases monitoring application, funded by European Space Agency. The application relies on Differential LIDAR operating at ~ 2.0 μm wavelength to measure the concentrations of greenhouse gases (e.g. CO_2, CO and CH_4) as functions of distance from the Earth's surface. The main performance targets are summarized in Table 1. In particular, the combination of the the operation wavelength range and the weak incoming optical signal means that InAs APDs are one of the few possible detector technologies for the application.

The developed InAs APDs have diameters of 200 μm. They exhibit photoresponce within the specified wavelength range and room temperature down to 250 K, as shown in Figure 4. At 200K (the desired minimum operating temperature), the cut-off wavelength is 3.3 μm. Mean values of quantum efficiency obtained from the APDs (with anti-reflection coatings) cooled to 200 K are 66 and 84 % at 1.55 and 2.0 μm wavelengths, respectively. These values exceed the minimum 60 % required by the application.

Table 1. Summary of key performance targets for the InAs APDs developed for greenhouse gases sensing.

Parameter	**Target value**	**Comments on actual performance**
Operation wavelength	0.5 – 3.5 μm	Met at room temperature. When cooled to 200 K the cutoff (defined as 50% relative to peak response) is 3.3 μm.
Quantum efficiency	> 60 %	Met at room temperature down to 180 K.
Active area diameter	≥ 200 μm	Met. APD diameters were 200 μm.
Operating temperature	≥ 200 K	Not met. 180 K is required to reach the required NEP.
Noise equivalent power	≤ 100 fW Hz$^{-1/2}$	Predicted NEP (based on measured TIA noise and APD characteristics) indicates compliance if APD is cooled to 180 K.
Excess noise factor	< 2.0	Met. Excess noise factor extracted from noise spectrum of APD cooled to 180 K and 200 K.

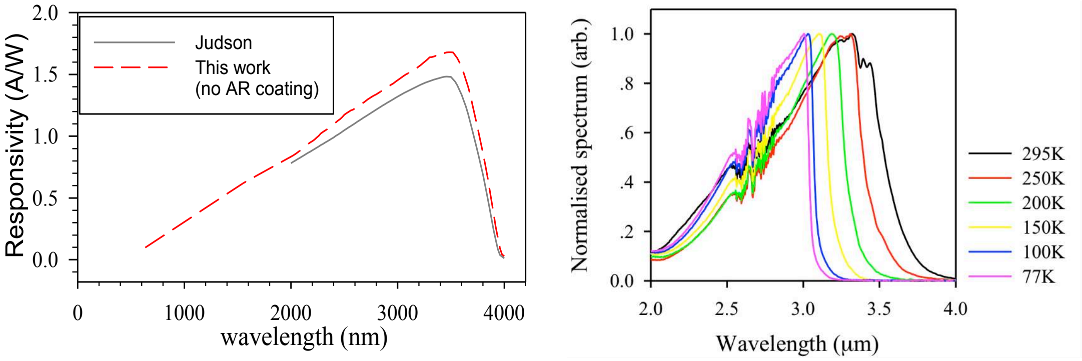

Figure 4. Photoresponse data of the InAs APD at room temperature (left) and lower temperatures (right). The cut-off wavelength is 3.3 μm at 200 K.

The target value of the noise equivalent power (NEP) required us to custom-design and construct trans-impedance amplifiers (TIAs) with low noise. When having a Si photodiode in place of the InAs APDs, the TIA achieved a noise voltage of 8 nV Hz$^{-½}$, consistent with the ~ 8 nV Hz$^{-½}$ indicated by circuit simulations, as shown in Figure 5(left). With knowledge of performance of the TIAs and InAs APDs, the NEP can be predicted using the expression

$$NEP = \frac{2eFR_o + \sqrt{(2eFR_o)^2 + 4R_o^2[2eFI_{db} + (i_{on}/M)^2]}}{2R_o^2} \text{ in W Hz}^{-½}, \qquad (1)$$

where e is the electron charge, R_o is the un-multiplied responsivity, I_{db} is the bulk component of the APD's dark current, and i_{on} is the noise current of the TIA, given by the ratio of noise voltage to the feedback resistor (5100 Ω). Combining the InAs APD performance values at a temperature of 180 K and wavelength of 2.0 μm, which are R_o = 1.36 A/W and I_{db} = 10 nA, and F = 1.5, and i_{on} = 1.6 pA Hz$^{-½}$, the predicted NEP values as a function of avalanche gain are plotted in Figure 5(right). The application's NEP requirement of < 100 pW/√Hz (Table 1) is satisfied with the APD operating at 180 K with $M > 11$.

The $M(V)$ data, plotted for temperatures from 175 to 200 K in Figure 6(left), show that obtaining $M > 11$ is well within the performance of the APD. The requirement on excess noise factor is also satisfied, with extracted values of F at 180 K well below 2.0, as shown in Figure 6(right).

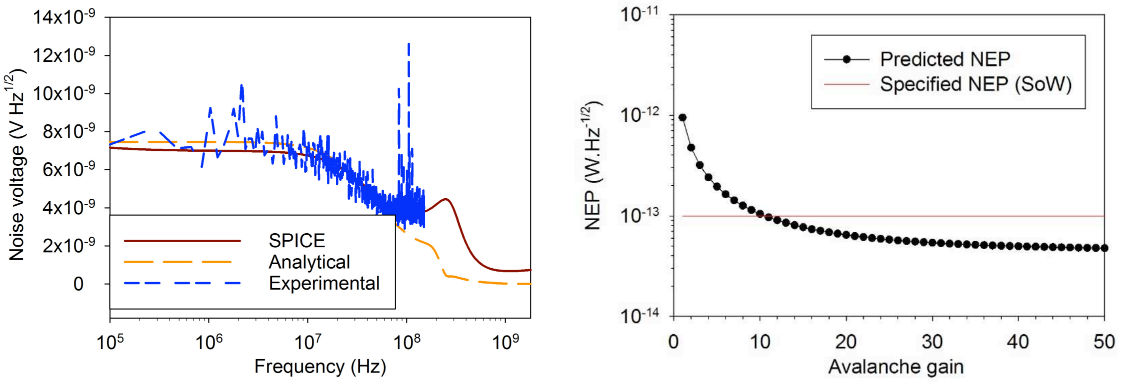

Figure 5. Noise voltage of the trans-impedance amplifier (left) and predicted NEP (right), as part of the detector development for the greenhouse gases sensing application. The experimental and simulated TIA noise voltage (~ 8 nV Hz$^{-½}$) was obtained with a Si photodiode in place of the InAs APD. The predicted NEP satisfies the application's requirement (≤ 100 pW Hz$^{-½}$) when the avalanche gain exceeds 11.

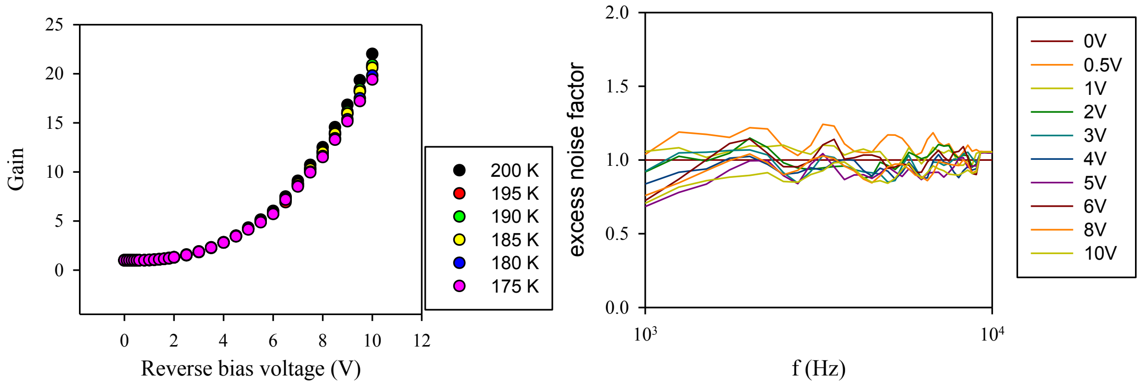

Figure 5. Multiplication factors at various temperatures (left) and excess noise factors at 180 K (right) of the InAs APD.

4. CONCLUSIONS

Over the past few years, progress in InAs APD research has built on experimental evidence of desirable APD characteristics. The recent progress includes realization of planar InAs photodiodes and APDs as well as development of mesa InAs APDs for demanding applications, including satellite-based greenhouse gases sensing with a main operating wavelength of 2.0 μm. We have presented characteristics of the InAs APDs and the associated amplifier circuit designed and implemented for this particular application. The application's requirement of Noise Equivalent Power ≤ 100 pW Hz$^{-1/2}$ has been met with our InAs APDs cooled to 180 K (slightly higher than the desired minimum operation temperature of 200 K) and our TIAs with noise voltage ~ 8 nV Hz$^{-1/2}$. When operating without avalanche multiplication and cooled to 200 K, the InAs APDs exhibit quantum efficiency of 84 % at 2.0 μm wavelength (66 % for 1.55 μm), corresponding to responsivity of 1.36 A/W.

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