Development of low excess noise SWIR APDs

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ABSTRACT

There is a strong interest in developing sensitive Short Wavelength Infrared (SWIR) avalanche photodiodes (APDs) for applications like eye safe laser ranging and robotic vision. The excess noise associated with the avalanche process is critical in dictating the sensitivity of APDs. InGaAs APDs that are commonly used in the SWIR region have either InP or InAlAs as an avalanche layer and these materials have excess noise factor of 0.5 and 0.22, respectively. Earlier, Spectrolab had developed APDs with impact ionization engineering (I^2E) structures based on InAlAs and InGaAlAs heterostructures as avalanche layers. These I^2E APDs showed an excess noise factor of 0.15. A photoreceiver based on the I^2E APD exhibited an noise equivalent power (NEP) of 150 fW/rt(Hz) over 1 GHz bandwidth at 1.06 µm. In this paper, a new multiplier structure based on multiple stages of I^2E is studied. The APDs show optical gains over 100 before device breakdown. The increased gain and low excess noise will improve the sensitivity of InGaAs APDs based photoreceivers.

Keywords: avalanche photodiode, low excess noise, photoreceiver, lidar, multiple impact ionization engineering, short wavelength infrared detector, laser ranging, Indium Phosphide (InP), Indium Aluminum Arsenide (InAlAs)

1. INTRODUCTION

There is always interest for high sensitivity SWIR photoreceivers [1, 2]. A wide range of technologies have been developed and some of them reach single photon sensitivity. Most of the time, there are other application constraints, like cost, power consumption, reliability, operating environment, and robustness. APDs are preferred in many applications because of low cost and robustness. For example, Silicon APD based photoreceivers are widely used in NASA missions. These photoreceivers have state-of-the-art NEP, 40 fW/rt(Hz) with a bandwidth of 140 MHz, and proven performance in space, with life time over 10 years in space. However, at wavelengths beyond 1.1 µm, silicon becomes transparent to infrared light. Spectrolab has been working on low noise III-V compound semiconductor APDs for wavelengths beyond 1.1 µm with a goal of achieving Si-like performance in SWIR spectrum. At 1.55 µm, InGaAs APDs have high quantum efficiency, low dark current, and high bandwidth. Commercial InGaAs APDs that have an InP or InAlAs multiplier have much higher excess noise than APDs that use a silicon multiplier. The typical commercial available III-V APD photoreceivers have NEPs in the range of several pW/rt(Hz).

2. LOW NOISE PHOTORECEIVER

A photoreceiver has a front end photodetector to convert incident light into current and an electronic amplifier to amplify the current to match the rest of the electronic circuits. Transimpedance amplifiers (TIAs) provide high bandwidth and low noise and are widely used in photoreceivers. PIN photodiodes and APDs are common photodetectors. The NEP of an APD based photoreceiver is modeled in Eq. 1, which also applies to a PIN photodetector by placing the gain to unity.

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The APDs have shot noise, thermal noise, 1/f noise, and excess noise. The thermal noise and 1/f noise are not dominant noise sources in high speed photoreceivers. The NEP of an APD based photoreceiver is expressed as:

$$NEP = \frac{1}{Rsp}\left[2qI_d F + \frac{\alpha^2}{M^2}\right]^{1/2} \qquad \text{Eq. 1}$$

$$F = kM + (2 - \frac{1}{M})(1 - k) \qquad \text{Eq. 2}$$

where, R_{sp} is the APD responsivity at unity gain, q is the electron charge, I_d is the APD dark current, F is the APD excess noise factor, α is the TIA input noise current, M is the APD optical gain, and $k=\alpha/\beta$ or β/α ($k<1$ always), where α and β are electron and hole ionization coefficients.

High sensitive photoreceivers require the photodetector responsivity/quantum efficiency as high as possible. The contribution of the TIA noise, α^2/M^2, is reduced as the APD gain is increased. The excess noise and dark current product increases with APD gain increase. In the low gain regime, the TIA noise is dominant; in the high gain regime, excess noise is dominant. There is an optimum gain point where the NEP reaches a minimum. This minimum NEP is a function of the electronic noise (α) and the APD excess noise factor. The minimum NEP is reduced as the contribution from both noise sources (the APD and amplifier) are reduced. Thus a low excess noise APD is necessary to reduce the photoreceiver minimum NEP.

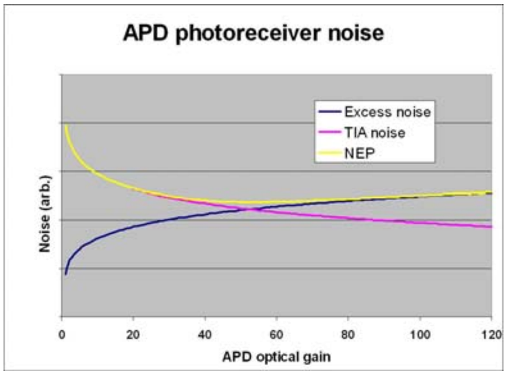

Figure 1 APD photoreceiver NEP vs. APD optical gain.

In Figure 1, an APD photoreceiver NEP versus APD gain is shown. The graph illustrates the contribution of excess noise and TIA noise components as a function of optical gain. The NEP reaches a minimum around APD optical gain of 55, when the excess noise surpasses the TIA noise.

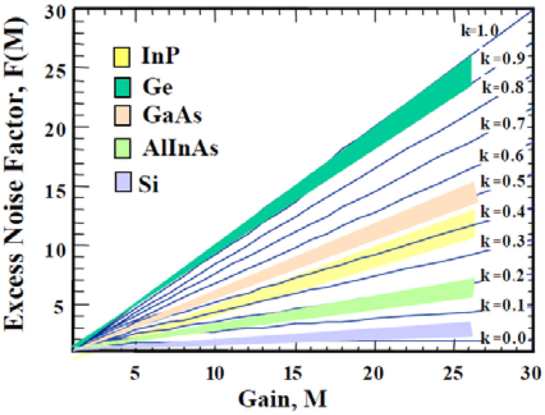

Figure 2 Excess noise factors for commonly used semiconductor materials.

McIntyre local field theory describes the excess noise in the thick multiplier well [3]. Figure 2 summarizes the common semiconductor materials excess noise factor as a function of APD optical gain. Silicon is the material of choice for low excess noise APDs because it has a very small k factor and hence very low excess noise at all gains. Researchers have pursued different approaches to get low excess noise APDs in silicon and other material systems [4, 5, 6].

Spectrolab has been developing low excess noise APDs with I^2E structures [2]. In this approach, the multiplier layers of the APD consist of InAlAs and a 100 nm thick lattice matched InGaAlAs, which have different ionization threshold energies. It turns out that the probability of avalanche events is higher in InGaAlAs than InAlAs. Compared to InAlAs, the avalanche events are enhanced in the InGaAlAs layer. The localization of the avalanche events results a lower effective k value than both InAlAs and InGaAlAs. The APD structure and current voltage characteristics from a 75 µm APD are shown in Figure 3.

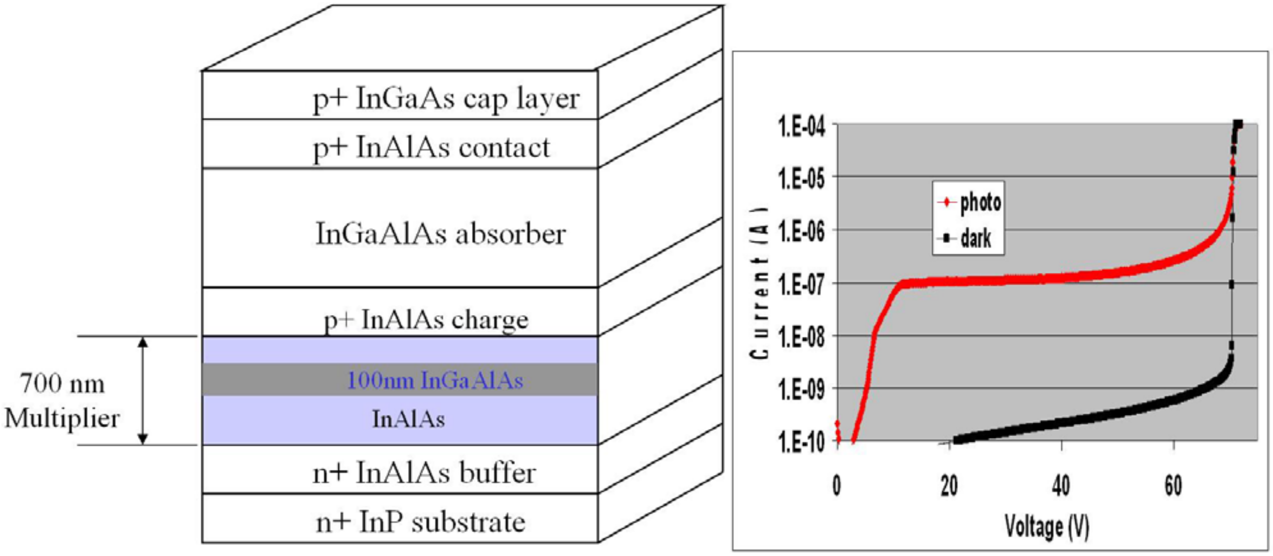

Figure 3 Left: Spectrolab I^2E APD structure;

Right: 75 µm APD current voltage characteristics at room temperature.

Figure 3 shows Spectrolab I^2E APD design and the I^2E multiplier consists of InGaAlAs and InAlAs layers. A 100 nm InGaAlAs with a bandgap around 1.2 eV was inserted into an InAlAs multiplier. The total thickness of the I^2E multiplier is 700 nm. The current-voltage characteristics of a 75 µm diameter APD is shown on the right. The I^2E APDs show excellent uniformity across the 3” wafer, which enables devices like focal plane arrays to be fabricated.

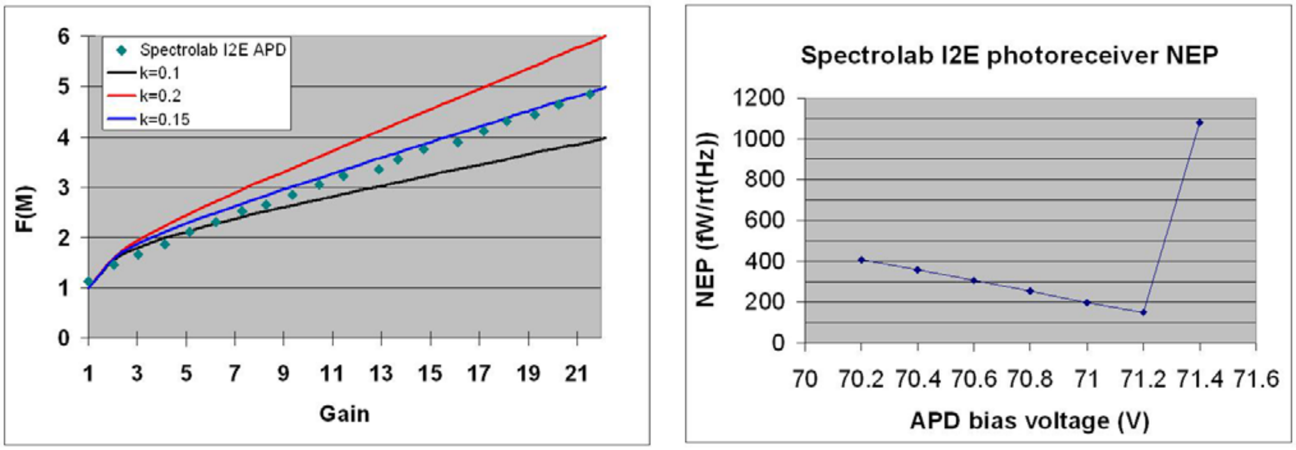

Figure 4 Left: Excess noise of Spectrolab I^2E APD; Right: NEP of the I^2E APD photoreceiver.

In Figure 4, the excess noise factor of the Spectrolab I^2E APDs is shown on the left [2]. The I^2E APD data show k value less than 0.1 at low gain, which is due to dead space effect. At high gain, the I^2E APD data show a consistent k=0.15. The low effective k value of I^2E APD is the benefit of impact ionization engineering. With further optimization, the I^2E could further reduce APD excess noise factor. On the right of Fig. 4, the NEP of an I^2E APD photoreceiver is shown. The photoreceiver has a 1 GHz bandwidth TIA. The NEP shows a minimum of 150 fW/rt(Hz) at 71.2 V, which corresponds to an APD optical gain of 45. The I^2E photoreceiver NEP does not show smooth transition from TIA noise dominant to excess noise dominant behavior, like in Figure 1. The sharp rise at 71.4 V is the result of a much higher dark current contribution to the APD noise near breakdown.

3. HIGH GAIN APDS

In Eq. 1, the APD excess noise is actually part of a product of excess noise factor and the dark current. For a typical III-V APD, the optical gain should be as high as possible before the dark current sharply increases at breakdown. Because of the limited gain of the device characterized in Figure 3, the APD cannot reach the NEP minimum predicted by the excess noise factor, shown in Fig. 1. At the same time, the optimum optical gain becomes higher with a low excess noise APD. In other words, an APD should have high optical gain and low dark currents to take full advantage of low excess noise.

Spectrolab designed a multiple stage I^2E multiplier to reach high optical gain with low dark current. The new multiple I^2E stages are designed to boost gain with each additional stage. In Spectrolab design, there is no intentional doping in each stage, which differentiates our design from other research groups. The new multi-stage I^2EAPD structures with InGaAs absorber were grown in a production scale MOVPE reactor on 4″ n+ InP substrate. All the epitaxial layers are lattice matched with InP substrate.

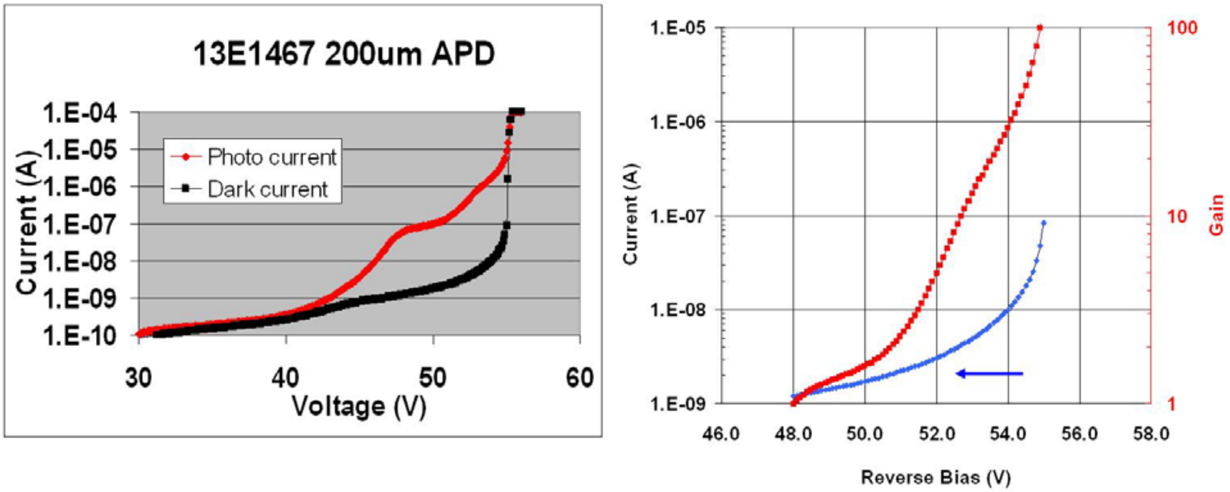

Figure 5 Left: Current voltage characteristic of a Spectrolab 5 stages I^{2}E APD with diameter of 200 µm;

Right: optical gain vs. APD bias voltage.

In Figure 5, the voltage current characteristics of a 5 stage I^{2}E APD is shown on the left. On the right, the optical gain versus APD bias voltage is shown. The unity gain is defined at bias voltage of 48 V. The APD reaches a gain of over 100 before breakdown. The corresponding dark current is less than 100 nA at room temperature. It must be noted that the gain about 100 is a conservative estimation. The fast rising of photocurrent at 48 V indicates that there may be already some gain when the APD punchthrough is reached at around 48 V.

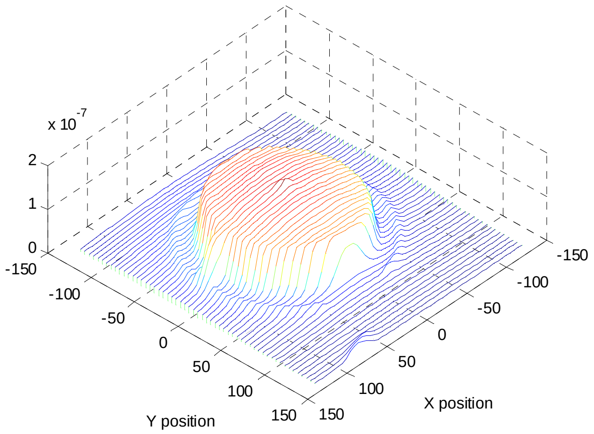

Figure 6 Raster scan profile on a 200 µm diameter 5 stages I^{2}E APD at gain of 140.

In Figure 6, a raster scan spot profile is shown. A UV laser beam was focused into a spot less than 5 µm in diameter. The laser beam was scanned across the APD and the photocurrents are recorded. In the scanning profile, the APD mesa and the ring metal contact near the mesa edge are clearly defined. The photo responses are uniform across the APD. The profile proves that the high gain is not the result of single point breakdown.

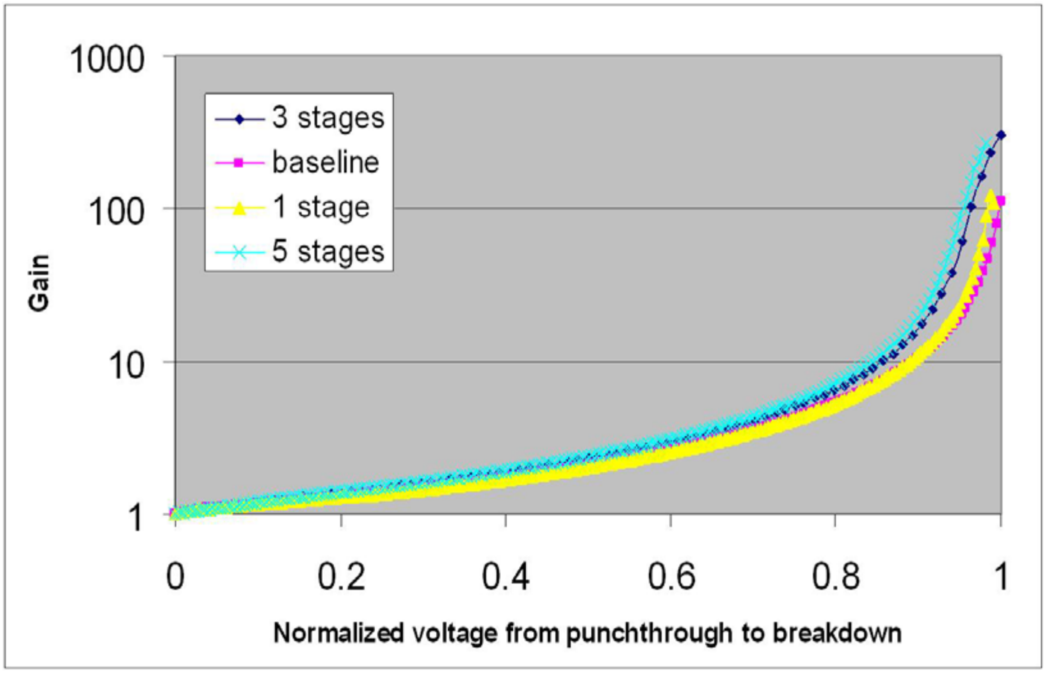

Figure 7 optical gain for various I^{2}E stages APDs.

In Figure 7, optical gains are compared between an InAlAs APD without I^{2}E, an InAlAs APD with 1 stage I^{2}E, an InAlAs APD with 3 stage I^{2}E, and a InAlAs APD with 5 stage I^{2}E (from right to left). The bias voltages are normalized from punchthrough to breakdown voltage, where 0 is at punchthrough and 1 is breakdown voltages. It is clear that the APDs show higher gain with more I^{2}E stages in the multiplier. Spectrolab's high gain APDs can be further optimized to reach higher gains with low excess noise and that work is continuing.

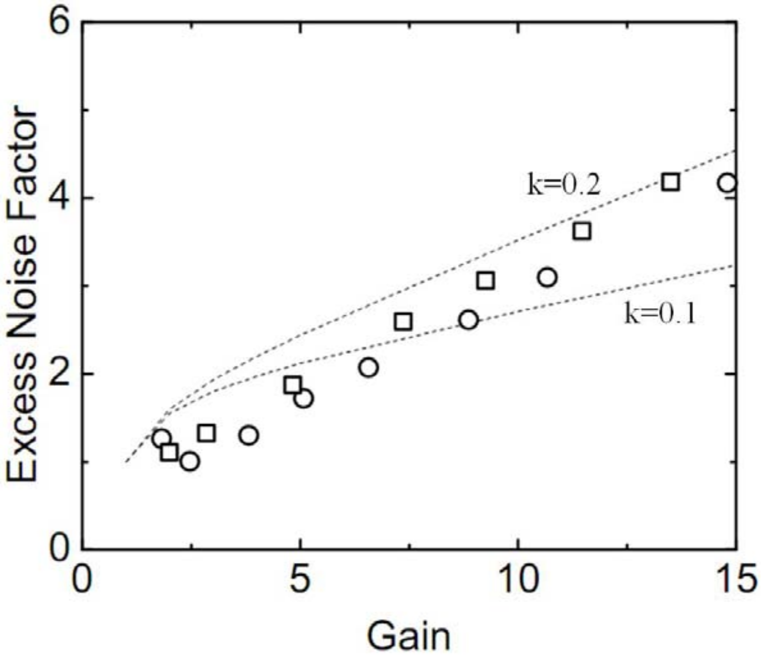

Figure 8 Excess noise factors of a 5 I^{2}E stages APD.

In Figure 8, the excess noise factors of a 5 stage I^{2}E APD are shown. The dashed lines are corresponding to McIntyre local field model of k=0.1 and k=0.2 respectively. Two measurements are shown in the graph. Both of them show effective k values between 0.1 and 0.2. Further optimization of multiple stage APDs could show effective k values less than 0.1.

Spectrolab are still optimizing the multi-stages I^{2}E APD design. More stages APDs are going to be grown and fabricated. We expect the overall optical gain will increase even higher. At the same time, we are optimizing the charge layer and absorber to achieve low dark current and high quantum efficiency at room temperature.

4. SUMMARY

Spectrolab has developed low noise I^{2}E APDs. The effective k value achieved was about 0.15 in a single stage I^{2}E multiplier. A photoreceiver was built by integrating the single stage I^{2}E APD and a GHz TIA. The photoreceiver showed a NEP of 150 fW/rt(Hz) over a 1 GHz at room temperature. APDs with multiple I^{2}E stage show gain over 100 before breakdown. High gain APDs using several I^{2}E stages have been fabricated and characterized. These APDs achieve gains of greater than 100 prior to breakdown with low excess noise. These high gain and low excess noise APDs show great potential for high sensitivity photoreceiver applications.

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