High-speed photon counting with linear-mode APD receivers

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ABSTRACT

HgCdTe and InGaAs linear mode avalanche photodiodes (APDs) were fabricated and tested for properties suitable for high speed photon counting when integrated with commercially available 2-GHz resistive transimpedance amplifiers (RTIA). The 2.71-µm, 100-µm diameter-HgCdTe APDs were fabricated in using a n+/p vertical carrier transport architecture designed to reduce carrier drift time and facilitate high speed operation. At 215K, a gain of 100 was measured with an excess noise of 2.5. The InGaAs/InAlAs APDs were fabricated using two absorber alloy compositions, one optimized for 950nm – 1300nm operation and the other 950nm-1550nm operation. Both were fabricated using multiple, cascaded gain regions that allowed for high gain and low avalanche-induced shot noise. Gain exceeding 6,000 was the excess noise factor was measured to be below 20 at a gain of M=1,200 (effective k~0.03). The InGaAs/InAlAs APDs were integrated into receivers consist of a multi-gain-stage APD coupled to a commercial 2-GHz resistive transimpedance amplifier (RTIA) and are operated as thresholded photon-counters. At a linear gain of M=1800, a single photon detection efficiency greater than 85% was measured at a maximum count rate of 70 MHz; at a linear gain of M=1200, single photon detection efficiencies greater than 20% were measured at maximum count rates of 80 MHz. At the temperature tested, 185 K, the receiver’s dark count rate (DCR) is dominated by electronic amplifier noise from the TIA for low threshold settings, and by dark counts from the APD at high threshold settings.

Keywords: single photon counting, avalanche photodiode, HgCdTe, InGaAs, APD, avalanche photodiode, SWIR

1. INTRODUCTION

Low-noise short-wavelength infrared (SWIR) avalanche photodiodes (APDs) can be operated as thresholded photon counters without being biased above their breakdown voltage. Such thresholded, or “sub-Geiger”, receivers are typically realized by integrating a low-noise/high-gain APD with a resistive transimpedance amplifier (RTIA). These sub-Geiger receivers are sensitive to single photons because the high-gain tail of an APD’s gain distribution extends far beyond its mean gain, and a fraction of the pulses emitted by a linear-mode APD in response to single photon input exceed the threshold necessary to reject noise from the RTIA. The photon detection efficiency (PDE) depends upon the gain distribution, and for a given mean gain, higher PDE is obtained from APDs characterized by lower excess multiplication noise.1 We report new results from two low-noise APD technologies – electron-avalanche HgCdTe, and multi-stage InGaAs – including p photon counting m easurements made with the InGaAs APD.

The chief merit of thresholded linear APD photon counters over Geiger APD photon counters is speed. Afterpulsing

![Figure 1: Gain versus operating voltage obtained for a SWIR APD.](image-url)
and the need to quench the APD below its breakdown voltage between detection events limits the maximum count rate (MCR) that can be achieved by a Geiger APD; typical quench times are well over 1 µs. Sub-Geiger APDs are thought to be less susceptible to afterpulsing than Geiger APDs because less current flows through the junction during detection events, and consequently there is a smaller change in trap occupancy; it is the release of trapped carriers following a detection event that causes afterpulsing. The bias of a sub-Geiger APD photon-counter is not gated during operation, and in free-run, the MCR is limited only by the APD’s impulse response duration – typically on the order of nanoseconds rather than microseconds. This speed advantage translates into much faster bit rates for single photon quantum information applications, and insensitivity to blinding by obscurants in single photon laser radar applications.

Zhao et al. recently reported an InGaAs sub-Geiger single photon detector based upon a self-quenching gain saturation mechanism, which operates at a gain of roughly $10^6$ with a 30-ns single photon response. However, the self-quenching device’s 300-ns recovery time limits its MCR to rates similar to Geiger APD technology. The sub-Geiger InGaAs single photon detectors reported here are more directly comparable to those of Clark et al., which were assembled from an InGaAs APD with a thin bulk InAlAs multiplier and a 580-MHz RTIA. A maximum single photon detection rate of 14%, an associated dark count rate (DCR) of 850 kHz, and MCR of about 50 MHz were reported for those receivers. At 70%, the single photon detection rate of the multi-stage receiver reported here is significantly higher, but the 55-MHz DCR is also higher, owing to the elevated amplifier noise level of the 2-GHz RTIA used in our receiver (250 nA RMS versus 45 nA RMS for the 580-MHz TIA).

Back-illuminated, SWIR-cutoff HgCdTe APDs were designed for high speed operation using a vertical charge...
transport architecture. The vertical charge transport APD architecture reduces the drift time for photocarriers created by absorbed photons, as compared to lateral-collection ‘loop hole’ HgCdTe, which have comparably larger photocarrier drift times. As predicted, the SWIR APDs performance was characterized low excess noise and with maximum gains of 100. At these gain levels, photon counting with commercially-available RTIAs is not possible.

2. COMPARISON OF SWIR HGCDE TE APDs TO MULTI-STAGE INGAAS APDS

Electron-avalanche HgCdTe APDs are good candidates for thresholded linear photon counting because of their low multiplication noise and high gain. The impact ionization process in bulk HgCdTe is inherently low noise\(^4\), with an excess noise factor close to unity at gains as high as \(M=1000\) for mid-wave infrared (MWIR)-cutoff alloy compositions\(^1,5,6,7\). However, MWIR-cutoff HgCdTe requires cryogenic cooling to suppress thermal dark current, and is therefore not suitable for all applications. SWIR-cutoff HgCdTe APDs have also been reported in the literature, but with lower maximum gain and higher noise than the MWIR-cutoff devices. Beck et al. reported an excess noise factor of \(F=2\) at a gain of \(M=25\) for 2.2-\(\mu\)m-cutoff HgCdTe APDs measured at 297 K\(^8\); the same group reported maximum avalanche gains just over \(M=100\) for 2.6-\(\mu\)m-cutoff devices at 198 K in a paper by Mitra et al.\(^9\) Other recent results in the literature are similar for SWIR-cutoff HgCdTe APDs\(^10\).

The lower gain observed for SWIR-cutoff HgCdTe APDs is qualitatively consistent with Beck’s empirical model, although the fit parameter \((a)\) relating bandgap \((E_G)\) to threshold voltage \((V_{th})\) is quantitatively different for SWIR-cutoff material than for MWIR-cutoff alloys:\(^{11}\)

\[
M(V) = 1 + 2^{(V_{th}/V_{th})}, \quad V_{th} = a \times E_G \quad (1)
\]

Gain rises more slowly with applied reverse bias \((V)\) for HgCdTe alloys with wider bandgap \((E_G)\), so a lower gain is achieved at the maximum reverse bias that the APD structure can tolerate.

We report excess noise data on a new electron-avalanche HgCdTe APD fabricated from 2.7-\(\mu\)m-cutoff, liquid-phase-epitaxy (LPE)-grown material. Excess noise data from a 150-\(\mu\)m-square device and a 100-\(\mu\)m-diameter circular device are plotted in Figure 2. The APDs were tested at 77 K and 215 K under 1550-nm illumination. Our 215 K data closely matches that published previously by Beck et al. for their 2.2-\(\mu\)m-cutoff device, which was measured at room temperature up to a gain of \(M=25\).\(^5\) It can be seen that at higher gains, the excess noise factor measured at 215 K lies slightly above the \(F=2\) asymptote corresponding to purely single-carrier multiplication \((k=0)\), and fits an effective impact-ionization coefficient ratio of somewhat less than \(k=0.01\), according to McIntyre’s formula:\(^{12}\)

\[
F(M,k) = M \left[ 1 - (1-k) \left( \frac{M-1}{M} \right)^2 \right]. \quad (2)
\]

At 77 K, the measured excess noise falls below the \(F=2\) asymptote, and the SWIR APDs behave more like the \(F=1\) MWIR electron-avalanche devices, with the likely added excess noise effects of phonon scattering increasing the measured excess noise to \(F=1.5\).

Highly impact-ionization-engineered \((I^2E)\) InGaAs APDs are another candidate for thresholded linear photon counting.
counting. We previously reported 10-stage InAlAs/InGaAs APDs with an excess noise factor of approximately $F \approx 25$ at a gain of $M=1000$ (Figure 4). The 10-stage devices were optimized for 1064-nm operation by using a 15% InAlAs / 85% InGaAs quaternary alloy for the absorber material. However, the low-noise character of the multi-stage multiplier is independent of the alloy composition of the absorber, as new data for a 7-stage InGaAs APD demonstrates (Figure 3).

The SWIR HgCdTe APDs reported thus far have lower excess multiplication noise and lower gain-normalized dark current density at 200 K than the multi-stage InGaAs APDs reported here. Figure 5 compares estimates of noise-equivalent power (NEP) at 1550 nm, across a 500-MHz bandwidth, for three different low-noise SWIR APD technologies. The curve labeled “InGaAs APD with thin InAlAs multiplier” is of the variety reported by Lenox et al.\textsuperscript{14}, which reduces avalanche noise by using the dead space effect to truncate the gain distribution of a thin multiplier. The dependencies of gain-normalized dark current and excess noise factor on gain for this type of device were parameterized based upon measurements taken on Voxtel’s 75-µm VFI-1JA low-noise InGaAs APD die. Excess noise measurements for this device fit Eq. (2) for $k=0.2$, and its gain-normalized dark current at 200 K fits a power law of the form:

$$\frac{I_{dark}}{M} = AM^B,$$

where $A=14.2$ pA and $B=-0.6391$. Stable operation of single-stage InGaAs APDs with thin InAlAs multipliers typically

![Figure 5: Estimated NEP at 1550 nm, across a 500-MHz bandwidth, for three different SWIR APD technologies. The calculation is based upon published values of gain-normalized dark current density and excess noise factor at 200 K, applied to a 75-µm-diameter device.](image)

![Figure 6: Estimated NEP at 1550 nm, across a 500-MHz bandwidth, for three different SWIR APD technologies. A TIA with 45 nA RMS input-referred noise is assumed.](image)
is not possible much above a gain of \( M = 30 \), and the curve in Figure 5 is dashed to reflect that fact. Gain-normalized dark current data measured for a 50-\( \mu \)m 10-stage APD fits the same power law with \( A = 5.4 \) nA and \( B = -0.6778 \) when scaled by area for comparison with a 75-\( \mu \)m device; the excess noise data fit Eq. (2) for \( k = 0.02 \). The 10-stage InGaAs APD’s dark current is proportional to the trap density in its InAlAs multiplier, and a drop of at least two orders of magnitude is anticipated from ongoing manufacturing development work, so a hypothetical dashed curve that is calculated with \( A \) set to 54 pA is also plotted for the multi-stage InGaAs technology. Gain-normalized dark current density data published by Mitra et al.\(^9\) for their 2.6-\( \mu \)m-cutoff HgCdTe APD was used to generate the NEP curve for the HgCdTe APD in Figure 5. Purely single-carrier (\( k = 0 \)) multiplication was assumed, and the gain-normalized dark current of a hypothetical 75-\( \mu \)m device was found to fit the power law with \( A = 169.8 \) pA and \( B = -0.7717 \).

NEP was calculated by equating the mean-square signal photocurrent to the variance of the total diode current due to amplified shot noise, solving for the photocurrent, and dividing by the multiplied responsivity to find the incident optical power for which the power signal-to-noise ratio is unity:

\[
1 = \frac{S}{N_{power}} = \frac{0.5 I_{photo}^2}{BW \times 2q M^2 F(M) \left( \frac{I_{dark}}{M} + \frac{I_{photo}}{M} \right)}
\]

\[
NEP = \frac{2}{R \times M} \left\{ G(M) + \sqrt{G(M)\left[ I_{dark} + G(M) \right]} \right\}
\]

\[
G(M) = BW \times q M F(M)
\]

In Eq. (4-6) \( I_{photo} \) and \( I_{dark} \) are respectively the multiplied photocurrent and dark current, the optical signal is taken to be harmonic with a modulation index of unity, \( BW \) is an effective noise bandwidth in Hz, \( q \) is the elementary charge in C, \( F(M) \) is given by Eq. (2), and \( R \) is the APD’s responsivity in A/W. Eq. (4-6) only treats shot noise, and neglects other potential noise sources such as Johnson noise. The NEP curves plotted in Figure 5 assume an effective noise bandwidth of 500 MHz, and a unity-gain responsivity of 1 A/W, which corresponds to a quantum efficiency of 80% at 1550 nm.

![Figure 7: Plot of PDE and DCR measured for a thresholded linear photon counter assembled from a 50-\( \mu \)m-diameter, 10-stage InGaAs APD and a 2-GHz RTIA, at 185K originally reported in (13).](image-url)
Although SWIR HgCdTe APDs have lower shot noise than multi-stage InGaAs APDs, the maximum gain demonstrated exceeds, and scaling by an effective attempt rate of 100 MHz. The DCR profile, plotted on a semi-log scale, is both the PDE and DCR drop. The McIntyre distribution models dark current in a M=1200, k=0.02 APD.

Figure 5 estimates the NEP of an APD without any noise contribution from a TIA, which is why maximum sensitivity is predicted to coincide with unity gain. In a real receiver, half the mean-square input-referred amplifier noise is added to the term under the radical in Eq. (5), and the optimal operating point of the APD shifts to higher gain (Figure 6). As of this comparison, SWIR HgCdTe APDs are predicted to out-perform low-noise InGaAs APDs at 200 K, but the sensitivity advantage over multi-stage InGaAs APDs is modest when TIA noise is included in the analysis. Moreover, although SWIR HgCdTe APDs have lower shot noise than multi-stage InGaAs APDs, the maximum gain demonstrated for SWIR-cutoff HgCdTe APDs is about an order of magnitude lower than that demonstrated by 10-stage InGaAs APDs, which limits their applicability to SWIR single photon counting.

3. SINGLE PHOTON COUNTING WITH MULTI-STAGE INGAAS APDS

We previously reported a thresholded linear photon counter based upon the 10-stage InGaAs APDs of Figure 4 which achieved a PDE of approximately 70% at 1064 nm, with a DCR of 100 MHz (Figure 7). Both the PDE and DCR drop at higher threshold settings, and the PDE is still greater than 50% when the DCR has dropped to 25 MHz.

The distribution of false counts arising from the RTIA is expected to differ from those originating from the APD itself. The RTIA noise is Gaussian-distributed, whereas the pulse height distribution of the APD is that derived by McIntyre. Figure 8 compares the qualitative DCR vs. threshold profile calculated for Gaussian- and McIntyre-distributed noise as a function of threshold; the simulated DCR is calculated by integrating (or summing, in the case of the McIntyre distribution) the normalized pulse height distribution above the threshold level to find the probability of exceedance, and scaling by an effective attempt rate of 100 MHz. The DCR profile, plotted on a semi-log scale, is

![McIntyre and Gaussian Pulse Height Distributions](image1)

![Simulated DCR](image2)

Figure 8: Pulse height distribution (left) and simulation of DCR profile (right) for Gaussian- and McIntyre-distributed noise (red and blue, respectively). The Gaussian distribution models amplifier noise characterized by 20 electrons RMS and the McIntyre distribution models dark current in a M=1200, k=0.02 APD.

![Comparison of measured DCR profile for 5-, 8-, and 10-stage receivers with 50-μm APDs operated at a 190K and a gain of M=1200.](image3)

Figure 9: Comparison of measured DCR profile for 5-, 8-, and 10-stage receivers with 50-μm APDs operated at a 190K and a gain of M=1200.
notably flatter for McIntyre-distributed APD noise (amplified dark current) than for Gaussian-distributed RTIA noise.

Qualitative comparison of Figure 8 to DCR profiles measured for 5-, 8-, and 10-stage APD receivers operated at a gain of $M=1200$ (Figure 9) demonstrates that the 10-stage receiver’s DCR is dominated by false counts from the amplifier, rather than from the APD itself. To obtain a total gain of $M=1200$, APDs with fewer number of gain stages, require the gain from each multiplication state to be higher, in proportion to the power law. As the operating required from each APD multiplication stage increases, the dark counts the APD come to dominate the DCR. This is because increasing the gain-per-stage requires a higher electric field, and tunnel leakage is an exponential function of electric field strength in the junction.

Figure 10 is a plot of PDE and DCR profiles for four photon-counting sub-Geiger receivers operated at an average gain of $M=1200$. Similar results are obtained for all four devices.

4. CONCLUSIONS

Excess multiplication noise data for two low-noise SWIR APD technologies was compared. Multiplication noise in SWIR-cutoff HgCdTe APDs was found to be somewhat lower than in multi-stage InGaAs APDs, but the SWIR-cutoff HgCdTe devices demonstrated to date cannot operate at gains higher than about $M=100$. In contrast, 10-stage InGaAs APDs can operate at gains over $M>1000$ with low multiplication noise.

The high gain and low noise of the multi-stage InGaAs APD makes it suitable for thresholded linear-mode photon counting. Photon-counting receivers assembled from 10-stage InGaAs APDs have been demonstrated with PDE as high as 70% at an MCR of 25 MHz, but with a high DCR of approximately 100 MHz. The dependence of DCR on threshold indicates that the majority of the false counts under these operating conditions originate in the RTIA rather than the APD itself.

Future work will configure these multi-stage APDs with low noise capacitance transimediance amplifiers (CTIs) with much lower noise, so that the DCR can significantly reduced. Further improvements in performance can be achieved by increasing the number of gain stages used in the multi-stage design, allowing the APD to be operated with lower noise at even higher gain, so that the count threshold may be set higher to reject more of the amplifier noise.

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