# High gain and low excess noise near infrared single photon avalanche detector

Krishna Linga, Yuriy Yevtukhov and Bing Liang

Amplification Technologies Inc
1400 Coney Island Ave, New York NY 11230
linga@amplificationtechnologies.com

## ABSTRACT

We present the discrete amplification approach used for the development of a very high gain and low excess noise factor in the near infrared wavelength region. The measured devices have the following performance characteristics: gain > $2X10^5$, excess noise factor < 1.05, rise time < 350ps, fall time < 500ps and operating voltage < 60V. In the photon counting mode, the devices can be operated in the non-gated mode under a constant dc bias and do not require any external quenching circuit. These devices are ideal for researchers in the field of deep space optical communication, spectroscopy, industrial and scientific instrumentation, Ladar/Lidar, quantum cryptography, night vision and other military, defence and aerospace applications.

**Keywords**: single photon detector, photon counting, near infrared, avalanche photodetector, discrete amplification

## 1. INTRODUCTION

Several applications such as deep space optical communication, time-resolved spectroscopy, 3D imaging and quantum cryptography have generated significant interest in the single photon avalanche Photodetectors. Although significant effort has been put in to the development of single photon avalanche Photodetectors in the near infrared wavelengths[1-4] the current devices require improvement in the photon detection efficiency, after pulsing, timing resolution, dynamic range and the ability to resolve multiphoton events[5-6].

We propose to use Discrete Amplification (DA) mechanism as a new method to develop single photon avalanche photon detector with improved performance characteristics in the near infrared wavelengths[7]. The discrete amplification mechanism is a new approach to internal amplification of ultra low level electrical signals. In this approach, free charge carriers generated in semiconductor detector through photo absorption and conversion process are distributed among amplification channels of the built-in discrete amplifier, with one electron per channel. Each amplification channel operates independently as a binary amplifier that transforms a signal charge carrier into a charge packet. Combining these charge packets from the active channels produces a low-noise output signal from the DA-detector proportional to the number of primary signal electrons generated in the detector.

This paper describes the discrete amplification photon detector, more detailed performance characteristics and analysis of discrete amplification photon detector operating in the 1000-1700 nm wavelength range.

## 2. DISCRETE AMPLIFICATION PHOTON DETECTOR

The discrete amplification photon detectors contain spatially dispersed discrete amplifiers to efficiently detect ultra low level optical signals in linear and photon counting modes in the near infrared spectral range. The key elements of discrete amplification mechanism in InP devices are shown in Figure 1[7].

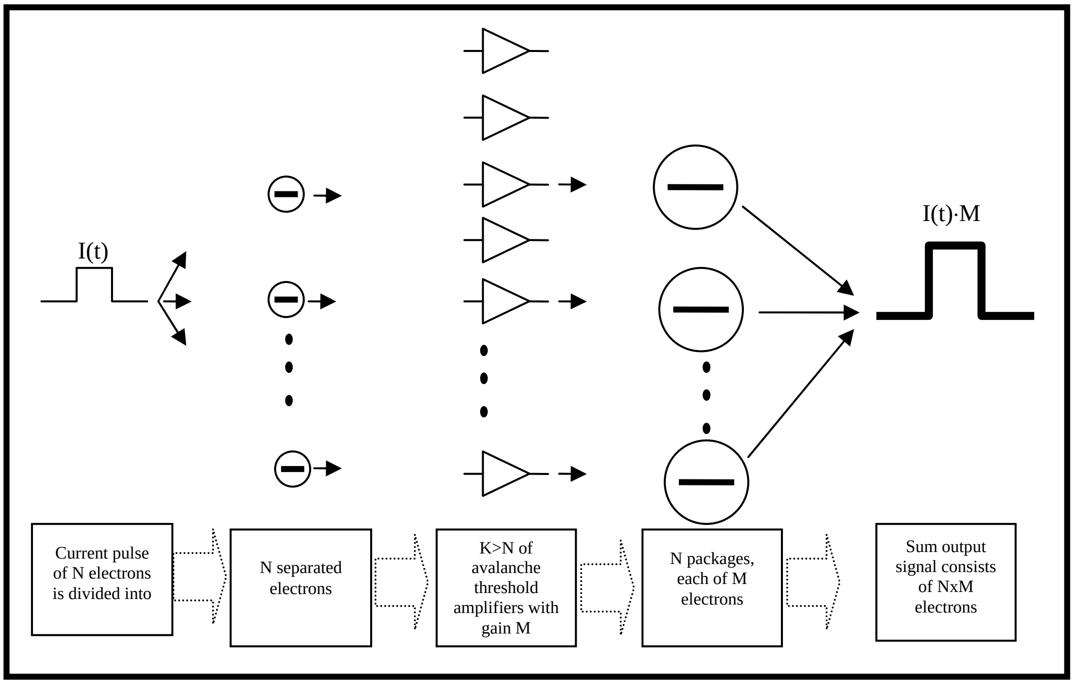


**Figure 1:** Principle of operation of DA photodetector

The photoelectrons generated in the absorption layer due to photo conversion process are spatially divided into N equal charge components. Each individual elementary charge is directed into an individual channel of a multichannel threshold amplifier with the number of channels K > N. In each channel of the threshold amplifier the elementary charge is then amplified by a factor of M (gain) so that at the output of each individual amplification channel we have a charge packet of M elementary charges.

Gain M is made the same for all channels by introducing a threshold element that switches off the amplification process after a required number of elementary charges M has been accumulated in the charge packet. The charge packets at the multichannel amplifier have fixed charge. Finally, all charge packets are added into a single amplified output signal containing MN elementary charges. This output signal is large enough in the order of several mV to be detected by standard electronic signal measuring equipment.

The discrete amplification photodetector device designed in InGaAs/InP is shown in Figure 2. The epitaxial layers was grown using the proven method of Metal Organic Chemical Vapor Deposition (MOCVD). The starting material is bulk InP crystal sulphur doped ($n^+$) with very low resistivity. On top of the substrate, the first layer of n+ InP buffer layer was grown to prevent the migration of substrate defects on to the absorption layer or to the surface. The second layer is ternary Indium Gallium Arsenide (InGaAs) layer with 53% Indium and 47% Gallium that is lattice matched to the InP buffer layer. The lattice matched $In_{0.53}Ga_{0.47}As$ absorption layer has a band gap of 0.73 eV at room temperature. This low bandgap energy enables the absorption (collection) of photocarriers in the 1.06 to 1.55 µm spectral region. A quaternary InGaAsP layer was grown on InGaAs to reduce the band discontinuity between the InP avalanche region and InGaAs absorption layer. The band discontinuity between the InP avalanche region and InGaAs absorption layer increases the hole pile up at the interface and create the low carrier transition and causes increased rise and fall time. The final layer is an InP avalanche region.

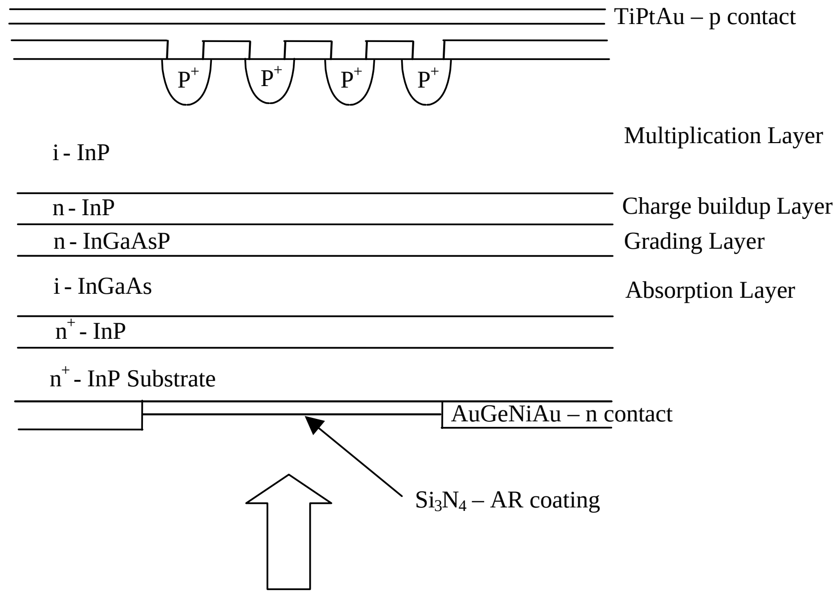


**Figure 2:** InGaAs/InP based discrete amplification device cross section

## 3. DEVICE PERFORMANCE CHARACTERISTICS

The performance characteristics of InGaAs/InP discrete amplification photodetectors were measured after the device fabrication was completed. The devices were mounted on a TO5 & TO8 packages for the characterization and the measured results are as follows:

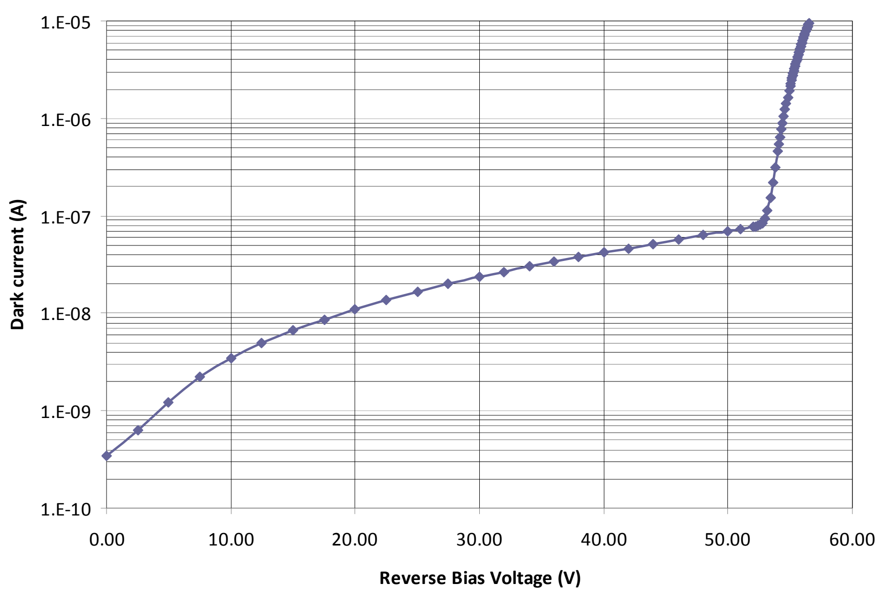


**Figure 3:** Dark current Vs. Reverse bias voltage of InGaAs/InP discrete amplification detector measured at room temperature. The active diameter of the detector is 210µm.

Figure 3 shows the measured dark current variation as a function of reverse bias voltage at room temperature. The 210um diameter device exhibited low dark current of 65nA at 95% of the break down voltage at 300K. For separate absorption, charge and multiplication avalanche devices, the dark current usually dominated by the generation current in the absorption layer. The measured dark current density at an operating bias voltage is approximately 2E-4A/cm$^2$ at room temperature.

Figure 4 shows the Photon Detection Efficiency (PDE) variation as a function of reverse bias voltage. The measured Photon Detection Efficiency is in the range of 20% at room temperature. The photon detection efficiency of a Discrete Amplification Photon Detector (DAPD) is the product of probability that an incident photon will create an electron-hole pair and the probability that the carrier injected will trigger an avalanche event.

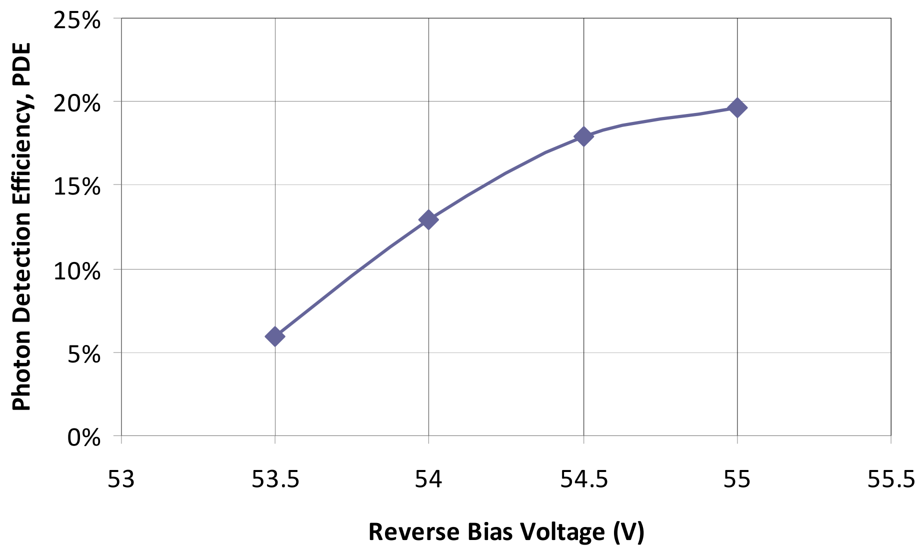


**Figure 4:** Photon Detection Efficiency (PDE) variation with reverse bias voltage measured using the current and counting methods

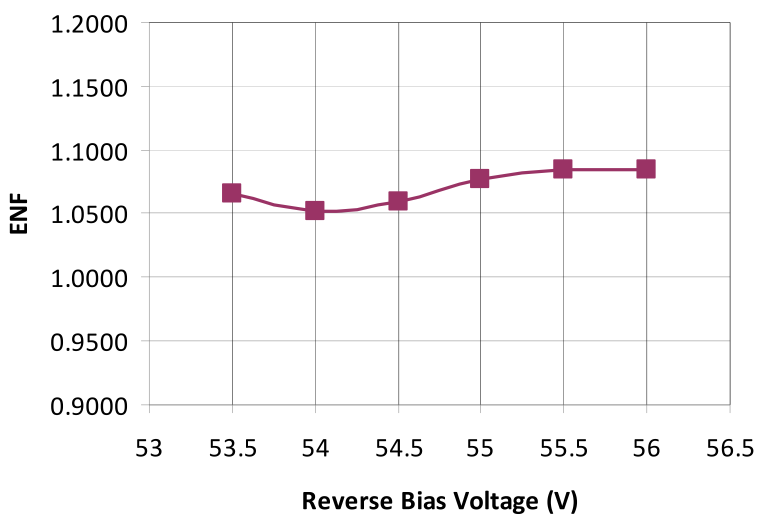


**Figure 5:** Excess Noise Factor (ENF) variation with reverse bias voltage

The excess noise characterizes the noise introduced in the process of amplification by the statistical fluctuations of gain (M). The excess noise factor measured on the near infrared discrete amplification photon detector is shown in Figure 5. The measured results show that the excess noise factor is less than 1.08 for wide operating bias voltage range.

One of the important benefits of Discrete Amplification Photon Detector (DAPD) is its ability to operate above the breakdown voltage. DAPD has a fixed gain at a given operating bias voltage above the breakdown voltage without requiring an additional quenching or resetting electronics to remove the bias on the device. Gain can be varied by an order of magnitude by varying the operating bias voltage. Gain as a function of operating voltage is shown in Figure 6. The wide overvoltage range of DAPD provides better voltage stability. Figure 7 shows the gain variation as a function of number of photoelectrons per sec. The gain is uniform until 3E6 photoelectrons per sec and is non linear as the number of photoelectrons increases.

Figure 8 shows the Single Electron Response (SER) amplitude of 200um diameter discrete amplification photondetector. The measured rise time is less than 350psec and the fall time less than 500ps. The pulse width is less than 1nsec.

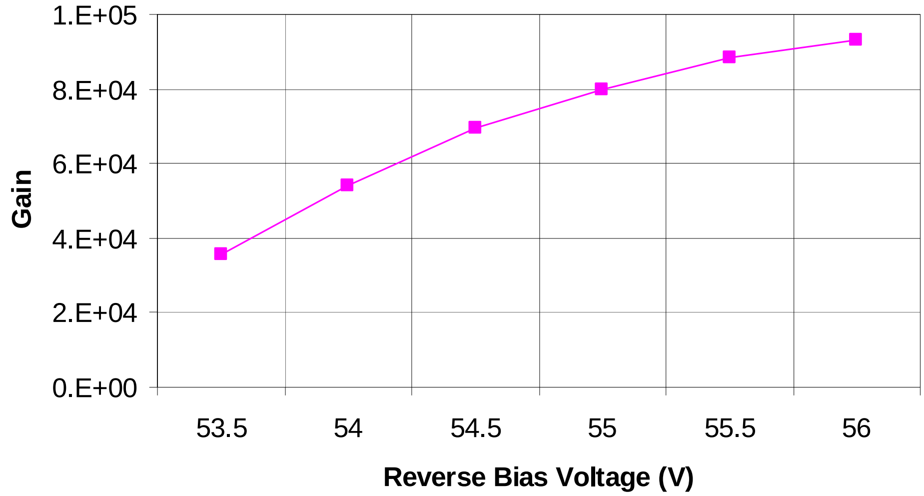


**Figure 6:** Measured gain as a function of reverse bias voltage

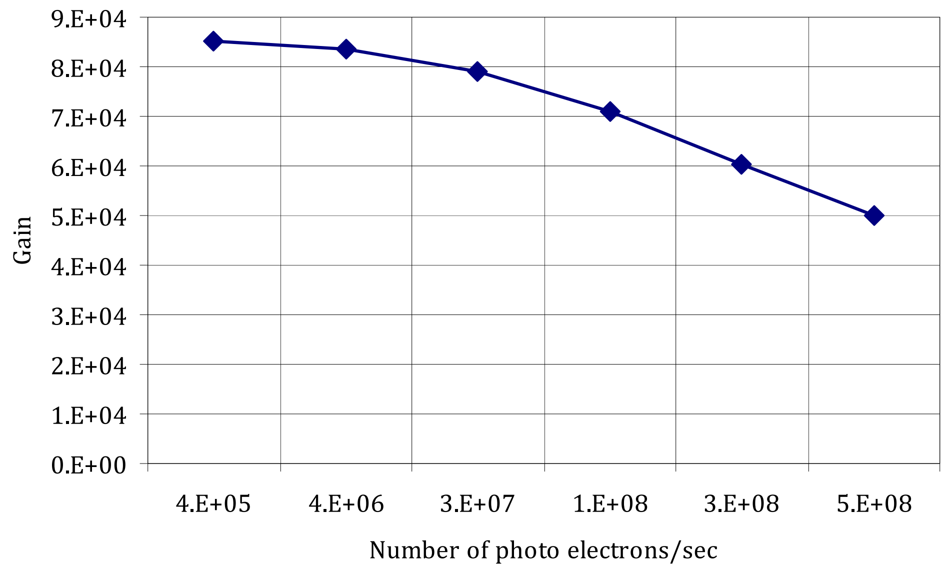


**Figure 7:** Measured gain as a function of number of photoelectrons/sec.

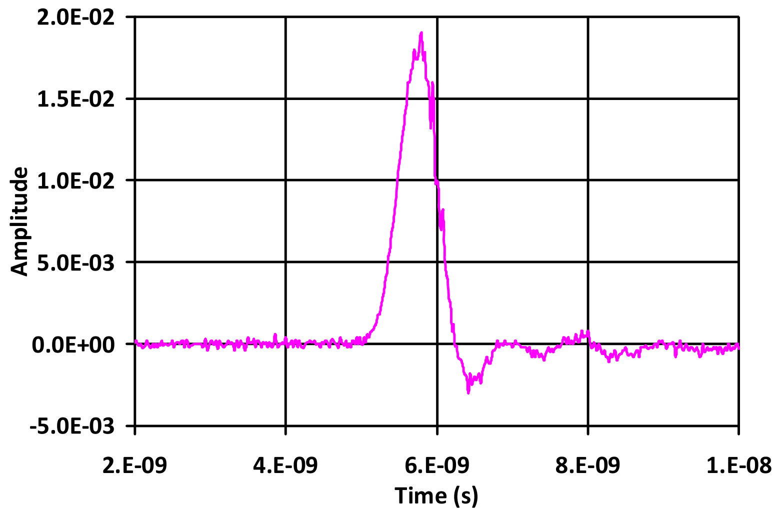


**Figure 8:** Measured Single Electron Response (SER) of 200um diameter near infrared DAPD device.

## 4. CONCLUSIONS

We have described the performance characteristics of new generation of discrete amplification photon detectors (DAPD) working in near infrared wavelengths and operating at above break down voltage. The DAPD devices has a combination of low noise, high gain and self reset makes it possible to measure single photons at high speed. These DAPD devices exhibit high photon detection efficiency, fast single electron response and high gain. The DAPD devices are promising devices for deep space optical communications, target detection and tracking, secured communication, spectroscopy and for other applications where a single photon detection capability is needed.

## 5. REFERENCES


1. V. Paul, G. Kahraman, C. Sang, D. Sarah and P. Kumar, “14 MHz rate counting with room temperature InGaAs/InP avalanche photodiodes”, Journal of Modern Optics, Vol. 51, pp. 1369-1379, June 2004.
2. H. Becker, W. Farr and D. Zhu, “Radiation response of emerging high gain, low noise detectors”, IEEE Trans. On Nuclear Science, Vol. 54, pp. 1129-1135, Aug 2007.
3. K. Zhao, A. Zhang, Y. Lo and W. Farr, “InGaAs single photon avalanche detector with ultra low excess noise”, Applied Phys. Letters, Vol. 91, pp. 081107, 2007.
4. M. Liu, C. Hu, X. Bai, X. Guo, J. Campbell, Z. Pan and M. Tashima, “High-performance InGaAs/InP single-photon avalanche photodiode”, IEEE Journal of Sel. Topics in Quantum Electronics, Vol. 13, pp. 887-894, Aug 2007.
5. K. A. McIntosh, J. P. Donnelly, D. C. Oakley, A. Napoleone, S. D. Calawa, L. J. Mahoney, K. M. Molvar, E. K. Duerr, S. H. Groves, and D. C. Shaver, “InGaAsP/InP avalanche photodiodes for photon counting at 1.06 µm”, Appl. Phys. Lett., Vol. 81, pp. 2505, 2002.
6. T. Alexei, S. Darius and Z. Anton, “Single photon counting at telecom wavelength and quantum key distribution “, Journal of Modern Optics, Vol. 51, pp. 1399-1415, June 2004
7. K. Linga, E. Godik, J. Krutov, D. Shushakov, V.E. Shubin, S.L. Vinogradov and E.V. Levin “Solid state photomultiplier: Noise parameters of photodetectors with internal discrete amplification”, Proc. SPIE, Vol. 6119, pp. 61190K, 2006
8. Karve, G.; Xiaoguang Zheng; Xiaofeng Zhang; Xiaowei Li; Ning Li; Shuling Wang; Feng Ma; Holmes, A., Jr.; Campbell, J.C.; Kinsey, G.S.; Boisvert, J.C.; Isshiki, T.D.; Sudharsanan, R.; Bethune, D.S.; Risk, W.P, “Geiger

mode operation of an In0.53Ga0.47As-In0.52Al0.48As avalanche photodiode”, IEEE J. Quantum Electron, Vol. 39, pp. 1281-1286, 2003

9. Y. Kang, Y.-H. Lo, M. Bitter, S. Kristjansson, Z. Pan, and A. Pauchard, “InGaAs-on-Si single photon avalanche Photodetectors”, Appl. Phys. Lett., Vol. 85, pp. 1668-1670, 2004
10. W. Farr, “Negative avalanche feedback detectors for photon-counting optical communications”, Proc. SPIE, Vol. , pp. , 2009
11. K. A. McIntosh, J.P. Donnelly, D.C. Oakley, A. Napoleone, S.D. Calawa, L.J. Mahoney, K.M. Molvar, E.K. Duerr, S.H. Groves and D.C. Shaver, “InGaAsP/InP avalanche photodiodes for photon counting at 1.06 μm”, Applied Physics Letters, vol. 81, No. 14, pp. 2505, 2002
12. K. Tsujino, M. Makoto and M. Sasaki, “Experimental determination of the gain distribution of an avalanche photodiode at low gains”, IEEE Electron Device Lett., Vol. 30, pp. 24-26, 2009