Near Infrared Single Photon Avalanche Detector with Negative Feedback and Self Quenching

Krishna Linga, Yuriy Yevtukhov, Bing Liang

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

ABSTRACT

We present the design and development of negative feedback design with internal discrete amplifier approach used for the development of a single photon avalanche photodetector in the near infrared wavelength region. These new family of photodetectors with negative feedback and requiring no quenching mechanism using Internal Discrete Amplification (IDA) mechanism for the realization of very high gain and low excess noise factor in the visible and near infrared spectral regions operate in the non-gated mode under a constant bias voltage. The demonstrated device performance far exceeds any available solid state Photodetectors in the near infrared wavelength range. The measured devices have Gain > 2X105, Excess noise factor < 1.05, Rise time < 350ps, Fall time < 500ps, Dark current < 2X10^6 cps at room temperature, Operating Voltage < 60V. These devices are ideal for researchers in the field of Ladar/Lidar, free space optical communication, 3D imaging, industrial and scientific instrumentation, night vision and quantum cryptography, and other military, defence and aerospace applications.

Keywords: single photon detector, photon counting, near infrared, avalanche photodetector, discrete amplification, excess noise factor, self quenching and negative feed back.

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] existing devices require significant effort in achieving continuous non-gated operation, with out external quenching circuit and ability to resolve multiphoton events and further device performance improvements in photon detection efficiency, after pulsing, cross-talk, timing resolution and dynamic range[5-6].

We propose to use negative avalanche feedback combined with discrete amplification as a new method to develop single photon avalanche photon detector with very high 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 a semiconductor detector through photo absorption and conversion processes are distributed among amplification channels of the built-in discrete amplifiers, 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 enables a low-noise output signal from the discrete amplifier photodetector that is proportional to the number of primary signal electrons generated in the detector.

This paper describes the negative feedback avalanche photon detector using discrete amplification mechanism, the measured performance characteristics and analyzes the discrete amplification photon detector operating in the 1000-1700 nm wavelength range.

2. NEGATIVE FEEDBACK AVALANCHE 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 the discrete amplification mechanism in InP devices are shown in Figure 1[7].

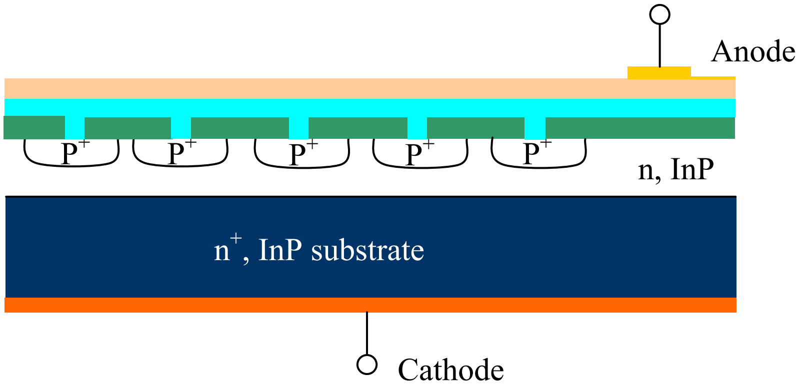

Figure 1: InP based device concept demonstrating internal discrete amplification with negative feedback.

Due to discretization of the input signal into equal charge components and subsequent definition of a charge package in each channel of the threshold amplifier, it is possible to attain an extremely low noise factor of the amplification. The measured results on the InGaAs/InP detectors show that the excess noise factor is less than 1.1 that is identical to the Si devices confirming that the discrete amplification mechanism enables a low excess noise factor independently of the material system chosen for the device design to extend the wavelengths from visible to near infrared wavelengths..

The multichannel threshold amplifiers were made as an integral multi-element solid-state structure, in which the amplification mechanism is based on the process of avalanche multiplication of charge carriers in the InP avalanche layers. Over breakdown mode of avalanche is used for threshold amplification. Delay-layers with limited mobility of charge carriers are used to achieve the negative feed back that enables switching the channel amplifier off and on, as well as to reset a channel with the accumulated charge packet. Photodetectors based on this principle have separate absorption, amplification and feed back regions. While the absorption region could be relatively conventional, the amplification and negative feed back regions would function as described above. The negative feedback element of internal discrete amplification in a multichannel amplifier significantly reduces the requirement of semiconductor material uniformity and allows fabrication of large area photodetectors and multi-element arrays, if one can limit the amount of leakage current.

This unique combination of absorption, amplification and feed back mechanisms designed in to a single device achieves combination of very high performance characteristics that enables reliable registration of single photoelectrons. These photodetectors could operate in both photon-counting and analog (linear) mode depending on the signal intensity.

The back-illuminated single photon counting photodetector device with negative avalanche feed back, discrete amplifier and absorption regions designed using InGaAs/InP material system 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 950 to 1700 nm wavelength region. A quaternary InGaAsP layer was grown on InGaAs absorption layer 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. The fabrication of the device was done using the standard InGaAs/InP processing methods in a III-V compound semiconductor foundry and will be described in detail in future publications.

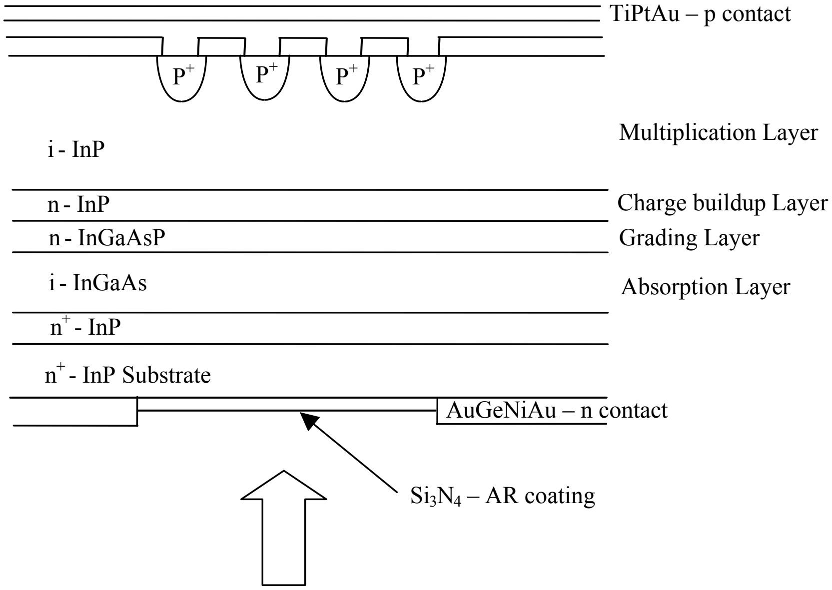

Figure 2: Back-illuminated InGaAs/InP single photon counting device cross section with absorption, negative feedback and discrete amplifier regions

3. DEVICE PERFORMANCE CHARACTERISTICS

The device performance characteristics of InGaAs/InP single photon avalanche photodetector with integrated negative feed back, discrete amplifier and absorption regions were measured on the wafer level as well as after the devices were packaged in a TO5 and TO8 packages. The performance characteristics of the devices were identical and there was no change in performance after the mounting, wire bonding and sealing of TO5 packages.

Figure 3 shows the measured dark current performance of 210 um diameter active area device as a function of reverse bias voltage at temperatures of 291, 273 and 243K. As shown in Fig. 3, the device exhibited low dark current of less than 65nA at 95% of the break down voltage at 291 K. Figure 4 shows the variation of break down voltage as a function of temperature. In Figure 4, the break down voltage is defined as the voltage at which the single electron response pulse emerges. The measured results indicate that the dark current increases with the increase in the active area of the device. For separate absorption, charge and multiplication avalanche devices, the dark current usually dominated by the generation current in the absorption layer.

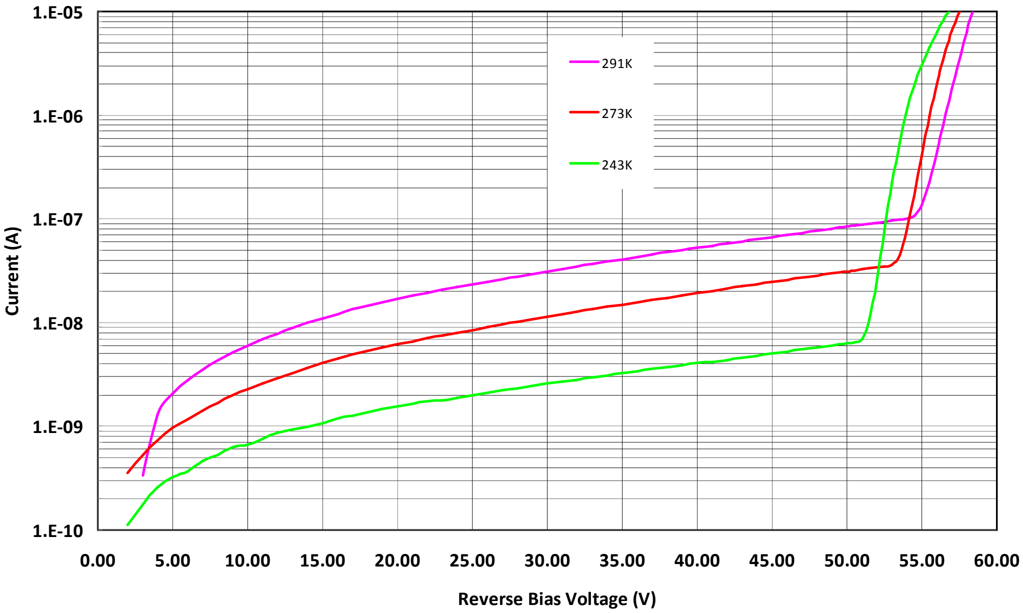

Figure 3: Dark current characteristics of a 210um diameter InGaAs/InP single photon discrete avalanche amplification detector measured at three different temperatures and at various bias voltages.

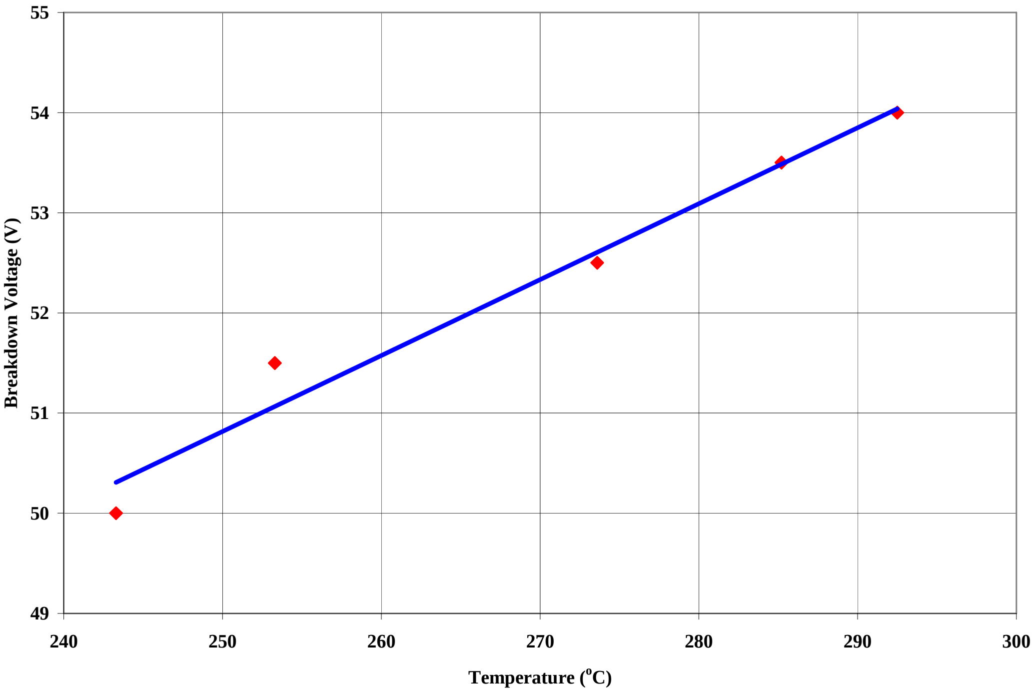

Figure 4: Breakdown voltage variation of single photon discrete avalanche amplification detector at various operating temperatures.

Figure 5 shows the Photon Detection Efficiency ("PDE") variation as a function of reverse bias voltage. The measured Photon Detection Efficiency was 20% at room temperature and an operating bias of 2V above breakdown voltage. The photon detection efficiency of single photon avalanche amplification photon detector is determined by three parameters:

i. Geometrical Efficiency or Fill Factor
ii. Quantum Efficiency, and
iii. Geiger Breakdown or Avalanche Initiation Probability (AIP)

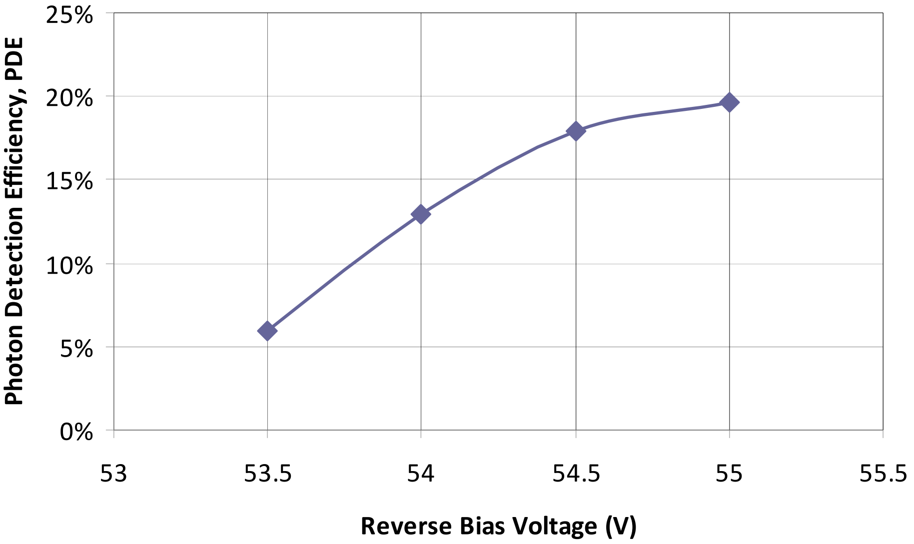

Figure 5: Photon Detection Efficiency (PDE) characteristics of single photon discrete avalanche amplification detector at room temperature and various reverse bias voltages. The measured PDE includes after pulsing and cross-talk

In discrete amplification devices the fill factor is the ratio of the active photosensitive area of the device to the total device area. The fill factor is determined by the design and size of the pixels. The quantum efficiency of DAPD photodetector is a function of wavelength and is typically in the range of 80-90%. The Geiger breakdown or avalanche initiation probability ("AIP") is the probability that a single carrier, generated in or near the Geiger-mode APD depletion region, triggers a Geiger avalanche event. The AIP depends on the applied bias and the type of carrier initiating breakdown.

The PDE is given by the product of these three parameters,

$$\mathrm{PDE}\ (\lambda) = F_f\ \eta\ (\lambda)\ \varepsilon\ (V)$$

Where F_f is the fill factor, $\eta(\lambda)$ is the quantum efficiency and $\varepsilon(V)$ is the avalanche initiation probability, which is a function of bias voltage.

Excess noise factor in an avalanche Photodetectors is defined[8] as

$$F = \{M^2\}/\{M\}^2 = 1+\sigma 2/\{M\}^2$$

The excess noise calculated using the above formula characterizes the noise introduced in the process of amplification by the statistical fluctuations of gain (M). For the ideal, no-noise amplification, F=1. The higher the noise-factor, the lower the amplitude resolution and threshold sensitivity of the detector in the analog mode. The excess noise factor measured on single photon avalanche photodetector is shown in Figure 6. The measured results show that the excess noise factor is less than 1.08 for broad operating bias voltage range.

Figure 7 shows the measured gain characteristics of single photon avalanche photodetector with integrated absorption, amplification and negative feed back regions. The single photon avalanche amplifier has a fixed gain at a given operating bias voltage above the breakdown voltage. As seen from Figure 6, the gain can be varied by an order of magnitude by varying the voltage. The gain variation is more linear for discrete avalanche amplifier photodetector, i.e., the operating range of overvoltage is higher than that of the Geiger Mode APD devices. The wide overvoltage range of discrete avalanche amplifier provides better voltage stability.

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

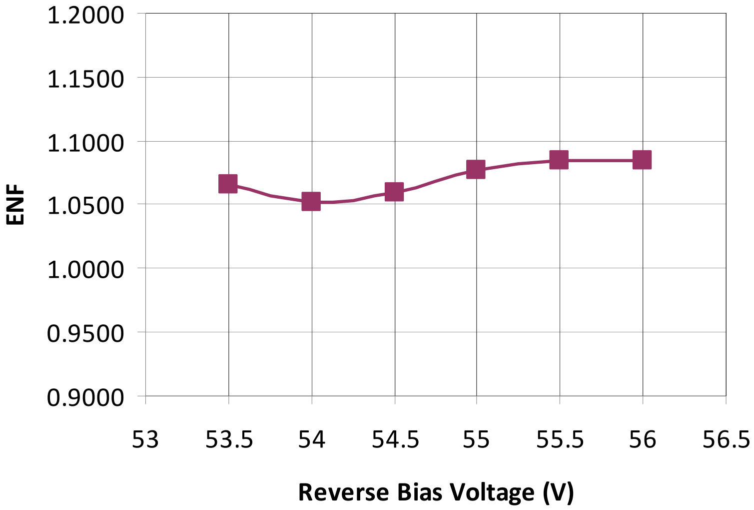

Figure 6: Measured Excess Noise Factor (ENF) of single photon discrete avalanche amplification detector

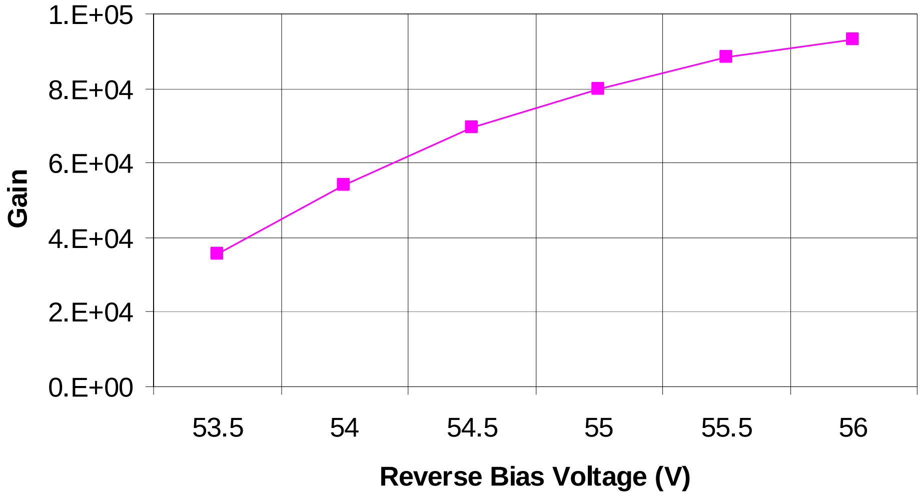

Figure 7: Measured gain characteristics of discrete avalanche amplification photodetector

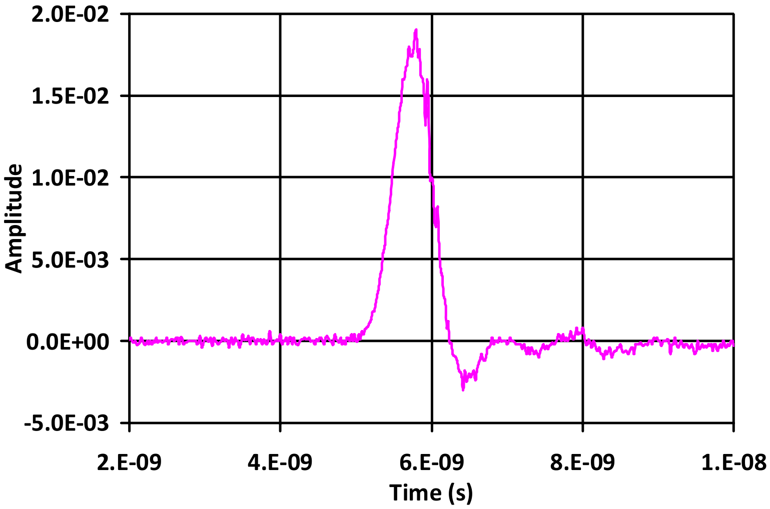

Figure 8: Measured Single Electron Response (SER) pulse of 200um diameter single photon discrete avalanche amplification photodetector.

4. CONCLUSIONS

We have described the design of novel and unique device monolithically integrating negative avalanche feedback, absorption and discrete amplifier regions in to a single device operating in the near infrared wavelengths of 950 to1700nm. The measured performance characteristics of the developed single photon discrete avalanche amplifier photon detectors working in near infrared wavelengths and operating at above break down voltage are presented. The combination of very high gain, low noise and self reset makes it possible to measure single photons at high speed. These devices exhibit high photon detection efficiency, and fast single electron response. These devices are promising devices for deep space optical communications, target detection and tracking, 3D imaging, secured communication, spectroscopy and for other applications where a single photon detection capability is needed in the near infrared wavelengths of 950 to 1700 nm.

Acknowledgments: The authors thankfully acknowledge Bill Farr from JPL for supporting, encouraging and testing the devices. This work was supported by NASA JPL under a Phase II SBIR contract.

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