Overview of photon counting detectors based on CMOS processed Single Photon Avalanche Diodes (SPAD), InGaAs APD’s, and novel Hybrid (Tube + APD) detectors

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ABSTRACT

An overview of photon counting detection using CMOS compatible Single Photon Avalanche Diodes (SPAD) will be presented. These SPADs have a planar structure, and are processed using CMOS technology. The most promising aspect of this technology is the potential for building large area arrays that can be operated in photon counting mode – without the read-out noise and bulkiness associated with low noise CCD cameras. Using the iAQC (integrated Active Quenching Circuit) produced by Micro-Photonics Devices, a low noise InGaAs/InAlAs APD will be characterized for photon counting. Finally, Characterization data from a photon counting module using Intevac’s IPD’s (Tube+APD hybrid) will be presented for photon counting at 1064nm.

Introduction:

The simplest method of detecting light is by converting light energy into a voltage output using a detector-amplifier configuration as shown in Fig.1. In such a configuration, the voltage output is directly proportional to the light intensity, and the lowest light levels detectable is when the SNR = 1, or when $V_{out}$ equals the sqrt of the detector + amplifier noise. At this light intensity, the output from the amplifier equals the noise of the detector/amplifier combination, this value is referred to as the Noise Equivalent Power or NEP. At high bandwidths, the amplifier noise is the dominant source of noise, whereas at low bandwidths, the detector noise is the dominant source. In the configuration as shown in figure 1, a NEP of 30fW/√Hz is achievable for a 30MHz bandwidth input power signal. This means the lowest light intensity detectable will be about 0.2nW. To detect lower levels, photon counting will be required.

![Figure 1. Detector + Amplifier SNR](image-url)
What is Photon Counting:

In linear mode operation as shown in figure 1, the input power produces an output that is directly proportional to the input light intensity. In photon counting mode, or geiger mode as it is often referred to – one photon which is detected, generates a output pulse that is counted. It is very important to note that in this mode of operation, photons are counted, and there is a “dead-time” before the next photon can be detected and counted. For example, if $10^6$ photons arrive at the detector at the exact same time – only one pulse will be generated indicating that only 1 photon has been detected. However, if $10^6$ photons were available for detection, photon counting would not be required – linear mode detectors would do just fine. If on the other hand, only 25 photons per second were available for detection – which corresponds to an intensity of 0.01fW, then photon counting would be required.

The detector that is used in this mode of operation is a Single Photon Avalanche Diode (SPAD). A SPAD is a semiconductor junction diode where a self-sustaining avalanche multiplication process can be triggered. A SPAD is biased above the breakdown voltage – referred to overvoltage (see Fig.2, left). SPADs are therefore remarkably different from ordinary Avalanche Photodiodes (APD), which work in linear amplifying mode biased slightly below the breakdown voltage.

At a defined overvoltage, the electric field within the depleted region of the device is very high, so that a single photon triggers a multiplication process, where an avalanche current of tens of milliams flows through the junction. This current is then used to initiate a TTL output pulse to indicate a photon has been detected, and the current rising edge signals the photon arrival time.

In order to detect the subsequent photon, the avalanche current must be quenched. Lowering the SPAD bias voltage below breakdown, and then resetting it back to its overload voltage accomplish this. The time it takes to reset the SPAD to its overvoltage is known as the “dead-time”, since in this period, the SPAD cannot detect any incoming photon. It is therefore desirable to have the dead-time as short as possible. The simplest approach is the passive quenching shown in Figure 2, however, this quenching method leads to very long dead times (200ns or more). Active quenching which is commonly used, provides dead times of less than 50ns.

Integrated Active Quenching Circuit:

The simplest quenching method is the passive quenching as shown in figure 2 (right), but such a configuration suffers from: Long dead times, low counting rates and photon timing spread. A much more effective approach is to actively quench the SPAD, this approach provides: Short well-defined dead times, high counting rates, and excellent photon timing resolution.
S.Cova, M.Ghioni, and F.Zappa of Politecnico di Milano, have done a tremendous amount of research in this area. Figure 3 shows the evolution of the quenching circuits developed by this group.

The integrated active quenching circuit (iAQC) has low power consumption making it ideal for portable systems, is rugged and reliable and provides improvements in performance: better timing resolution, reduced capacitance, reduced avalanche charge, reduced afterpulsing, reduced cross-talk in arrays.

The Active Quenching module (AQM) based on the iAQC, which is used to examine both, the Silicon SPAD and the InGaAs SPAD is shown in Fig.4.

This AQM module has an internal maximum detector bias voltage supply of 36V, if more voltage is required, an external supply can be added. The bias voltage, dead-time, and avalanche quench amplitude are user controlled through a RS485 interface. The hold-off time can be defined from 40ns to 200ns, and can be easily extended indefinitely by using the module gating option.
Single Photon Avalanche Diodes (SPAD) – Silicon Devices:

Photon counting with specialized avalanche photodiodes has been commercially available for many years using SPAD devices with the reach-through structure as shown in Figure 5, left. The advantages of this structure are the high photon detection efficiency in the visible and near IR region, and the large active diameter. The disadvantages are the high bias voltage (250-500V), and the dedicated fabrication process. In addition this process is not ideally suitable for the production of monolithic arrays.

Recent progress has also allowed for the development of commercial modules based on SPAD’s fabricated in CMOS technology. The planar structure, which can be processed using CMOS technology, is shown in figure 5, right. These SPAD’s provide many advantages such as: ultrafast timing resolution, high fabrication yield and thus low cost, low power consumption for portable systems, and make possible the production of monolithic arrays for producing large area photon counting arrays. The main disadvantage of the CMOS SPAD is the lower photon detection efficiencies at longer wavelengths. The planar SPAD using CMOS technology has a thinner depletion layer than the reach-through APD, and at longer wavelengths (near infrared), this thin layer greatly reduces the detection efficiencies. For shorter wavelengths (in the visible range) a reduced thickness of the depletion layer can suffice; at wavelengths below 550nm the efficiency of the planar SPAD is even greater than that of the reach-through devices because a the neutral layer at the top surface is thinner and absorbs a lower percentage of the incident light.

Figure 5: SPAD Reach-Through structure with thick depleted region (left), planar structure with thin depletion for ultrafast timing response (right).

Figure 6: Photon detection efficiencies vs. wavelength (left) and timing resolution using planar SPAD + iAQC (right)
These SPAD’s are currently available with active diameters of 20, 50 and 100um, have photon detection efficiencies of better than 55% at 532nm, and dark counts of less than 15 dark counts per second. Figure 6 (left), illustrates the photon detection efficiencies at various overvoltages; detection efficiencies of better than 55% can be achieved by applying an AR coating on the detector. Figure 6 (right), illustrates the fast timing resolution which has been demonstrated using these SPAD’s. Recently 35ps timing resolution with a 100um detector at room temperature, has been demonstrated. Modules developed using the planar SPAD and the iAQC can achieve 50ps timing resolution, in comparison, modules using the reach-through SPAD are achieving timing resolutions in the order of 300ps.

Combining these SPAD’s with integrated Active-Quench circuits (iAQC) has led to the development of easy to use photon counting modules as shown in Fig.7. These modules have low power consumption and low acquisition cost. The low power consumption makes them ideal for portable systems, which can be used in the detection of biological threats. They can be supplied with a specific option for ultrafast timing. It was the ultrafast timing resolution that allowed biomedical researchers to measure with a new technique conformational changes on the angstrom scale as opposed to the nanometer scale.

A very promising aspect of this technology is the potential for building large area arrays that can be operated in photon counting mode – without the read-out noise and bulkiness associated with low noise CCD cameras. Discussion and illustration of these arrays are not covered in this paper, but will be presented in the near future.
Single Photon Detection for 1064 and 1550nm:

Figure 8 shows the detection efficiency provided by silicon photodetectors and photomultiplier tubes (PMT) for the 300 to 1100nm range. It is seen that at wavelengths > 950nm, the roll-off in sensitivity is dramatic for all Silicon based detectors. The next two sections will explore detector technology capable of photon counting at 1064nm and 1550nm. In particular, we will examine novel InGaAs APDs, and hybrid photomultiplier tube technology - PMT + APD.

Single Photon Avalanche Diodes (SPAD) - III-V Devices for 1550nm:

A tremendous amount of effort was focused on developing InGaAs APDs for telecommunication applications, but until recently, little work was done on larger area APD’s that would be useful for Military systems, or Geiger mode operation, i.e. to work as SPAD detectors. In the last couple of years, developments on low noise InGaAs APDs have been presented for both linear mode and Geiger mode operation. For this paper we examine an InGaAs/InAlAs, which was tested in SPAD photon counting mode. The AQM module illustrated in figure 4 was used to test this device. It is seen that although these devices show promise for continuous Geiger Mode operation, the afterpulsing due to trapping needs to be reduced before this will be possible. InGaAs devices for this operation still have not been developed – but we are optimistic that such a SPAD is possible and will be introduced. It is our hope that such a SPAD will be able to work with the AQM module so that a complete module, which can operate in continuous mode, will be introduced.

With currently available InGaAs devices, even the newly available InGaAs /InAlAs APD with low excess noise, it is seen that free running photon counting operation is practically not possible – it can be only obtained by enforcing a very long hold-off time of several hundred microseconds after each output pulse. Gated operation is possible, and a remarkable decrease in dark-counting rate is observed by increasing the gate-off time – which confirms and underlines a very strong afterpulsing effect due to trapping and delayed release of avalanche carriers. However, we are very optimistic that these barriers will be overcome and a free-running photon counting module can be made available in the near future.

![Graph of Dark current vs. Overvoltage @ various temperatures in gated detector operation with 100us gate-off time, 50ns gate-on time.](image)

Figure 9: Dark current vs. Overvoltage @ various temperatures in gated detector operation with 100us gate-off time, 50ns gate-on time.
Figure 10: The afterpulsing effect (due to trapping and delayed release of carriers) increases the probability of dark counts as the gate-off time is reduced, as shown by data measured at various temperatures with 50ns gate-on time and 1V overvoltage.

Figure 11: Dark counts vs temperature with two different gate-off times, Overvoltage = 1.5V, gate-on = 50ns.

Figure 12: Photon-timing resolution measured with the InAlAs/InGaAs device operating in cryogenic conditions at 30k. NB: The measurement is carried out with the time sorter in the inverted stop-time configuration, hence the delay scale is inverted, the true photon-timing delay increases from right to left.
1064nm Photon Counting with Hybrid Photomultiplier detectors:

The module described in this section uses a hybrid photomultiplier tube manufactured by Intevac, Santa-Clara, CA. The tube which is referred to as a intensified photodiode (IPD), is sensitive from 900 to 1300nm and has an active diameter of 1mm. The IPD uses an active transferred electron photocathode, and a GaAs schottky avalanche photodiode as an anode. Figure 13, illustrates the outline of the package – first stage amplification consists of a very low noise electron-hole multiplication due to energetic impact of photoelectrons on the top surface of the APD. This is then followed by traditional APD multiplication. These two processes are sufficient to overcome preamplifier noise and is therefore capable of photon counting.

OEC has developed a module incorporating the Intevac IPD as shown in Fig.14. The module uses an un-cooled IPD, but units with a TE-cooled IPD are available. This module provides both a TTL output pulse for photon counting, and a linear output for analog mode operation. The characterization of the OEC 1064nm photon counting module are summarized in below.

Figure 14: Photon counting module using IPD – optimized for 1064nm detection, courtesy of OEC, Kirkland, QC.
Summary:

New silicon detectors using CMOS processing techniques have been demonstrated for photon counting. One of the many advantages using this technology is, the ability to produce monolithic arrays. Using state of the art IAQC circuits; low power consumption and fast timing resolution modules have been developed and are currently available.

III-V detectors have been examined for photon counting using AQM modules, but it is seen that continuous mode photon counting is still not possible with the available devices. However, having a robust AQM module will ensure a quick introduction of a complete photon counting module for 1550nm applications once a suitable III-V SPAD detector becomes available.

For high-end applications requiring high photon detection efficiencies at 1064nm, it is illustrated that the a hybrid tube + APD provides the highest detection efficiency at 1064nm – with a photon detection efficiency of 30% at 1064nm.

References:


