Geiger Mode Avalanche Photodiodes for Microarray Systems.

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ABSTRACT

New Geiger Mode Avalanche Photodiodes (GM-APD) have been designed and characterized specifically for use in microarray systems. Critical parameters such as excess reverse bias voltage, hold-off time and optimum operating temperature have been experimentally determined for these photon-counting devices. The photon detection probability, dark count rate and afterpulsing probability have been measured under different operating conditions. An active-quench circuit (AQC) is presented for operating these GM-APDs. This circuit is relatively simple, robust and has such benefits as reducing average power dissipation and afterpulsing. Arrays of these GM-APDs have already been designed and together with AQCs open up the possibility of having a solid-state microarray detector that enables parallel analysis on a single chip. Another advantage of these GM-APDs over current technology is their low voltage CMOS compatibility which could allow for the fabrication of an AQC on the same device. Small area detectors have already been employed in the time-resolved detection of fluorescence from labeled proteins. It is envisaged that operating these new GM-APDs with this active-quench circuit will have numerous applications for the detection of fluorescence in microarray systems.

Keywords: Avalanche Photodiode, microarray, Active Quench Circuit, AQC, GM-APD

1. INTRODUCTION

Photon counting detectors have found numerous applications in such fields as astronomy[1], time-correlated single photon counting (TCSPC)[2], light detection and ranging (LIDAR)[3], and single-molecule detection[4,5]. In the detection of fluorescence from DNA microarrays, photomultiplier tubes (PMTs) and charge coupled detectors (CCDs) have been used extensively[6,7]. Geiger mode avalanche photodiodes (GM-APD) provide an alternative to these detectors in the detection of weak optical signals from DNA microarray systems.

The application of GM-APDs for the detection of both steady-state and time resolved fluorescence from DNA microarrays has been demonstrated[8]. In a multiplex application, there is the possibility of using time-resolved information to distinguish between multiple fluorescent labels as an alternative to a steady-state detection method that depends on the Stokes shift between absorption and emission wavelengths. The time resolved multiplex advantage that is possible with GM-APDs, makes arrays of these single photon counting devices attractive for the quantitative analysis of DNA microarray information.

It is important in the detection of weak optical signals, to have an internal gain in the detector itself, such as a PMT or APD, rather than to contribute noise externally by electronic amplification. As these detectors can count single photons of light, they theoretically can operate at the ultimate limits of sensitivity. APDs have such advantages as high quantum efficiencies and time resolution, small size, reliability and ruggedness[9]. Their low operating voltage make them ideally suited to fabrication with an active quench circuit (AQC) on the same device. However, there are disadvantages such as dark counts, afterpulsing and light emission from the detector during an avalanche.

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2. THEORY OF GEIGER MODE-AVALANCHE PHOTODIODES

When an incident photon is absorbed in the active area of an avalanche photodiode, an electron hole pair is generated due to the high voltage between the *pn* junction by the process of impact ionization[10]. This electron hole pair can cause further ionizations and result in an avalanche of electrons and holes. The current from this avalanche can be detected by external electronic circuitry.

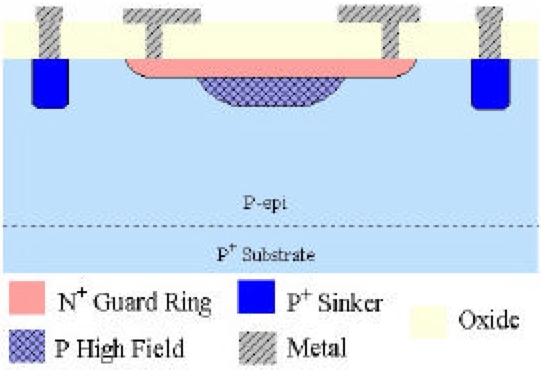

Figure 1. Shallow Junction-APD

There are two modes in which avalanche photodiodes can be operated; a) linear mode and b) geiger mode. In linear mode, the device is biased below breakdown voltage which results in the avalanche current being proportional to the photon flux. However, if the device is biased above breakdown, the avalanche will be self sustaining and requires external control circuitry to quench the avalanche current before subsequent photons can be detected. It is this external quench circuit that allows single photons to be detected. Not only is it the design of the APD, but also that of the external control circuitry that is critical for the optimum performance of these photon counting devices. GM-APDs have been designed with numerous detector diameters ranging from 10µm to 500µm. Figure 2, illustrates a design of a 100µm GM-APD that has been fabricated. These devices have experimentally been characterized for optimum operating conditions, such as excess reverse bias voltage, hold-off time and operating temperature.

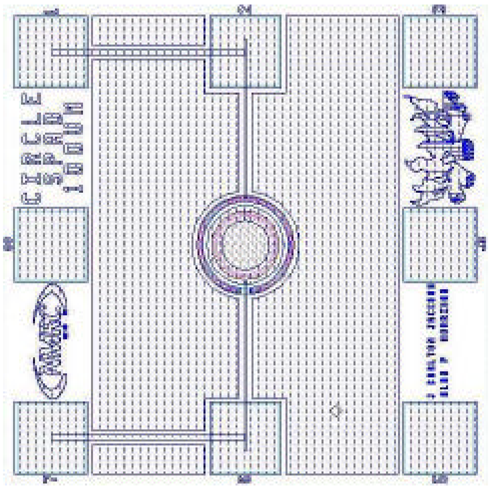

Figure 2. A sample 100mm GM-APD

3. GEIGER MODE QUENCH CIRCUIT

In order to operate an APD in photon counting mode, careful consideration must be given to the design of the external operating circuit. Two methods are currently employed and are referred to as passive quenching and active quenching[11]. Passive quenching, while relatively simple, has a number of drawbacks in its operation. Active quenching, on the other hand, is the preferred method of operation but the design is critical for the efficient operation of an APD in photon counting or geiger mode.

1. Passive Quenching

When an APD is reversed biased above breakdown voltage, V_a, an incident photon can trigger an avalanche in the depletion region and the device will start to breakdown. The large current that subsequently flows can be quenched by passive elements, in this case resistors. A large ballast resistor, R_1 (~200kΩ), can be used to limit the current flowing through the APD. The increase in voltage at node (a) of the APD will drop the voltage across the device to below breakdown. The APD will then start to slowly recharge until the voltage across the device has returned to the original bias voltage. By placing a small sensing resistor R_2 at node (b), a comparator can be triggered to give a TTL/ECL output signal.

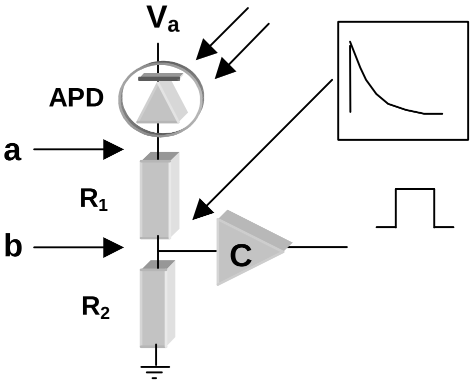

Figure 3. Passive Quench Circuit

During this long recharge period, the APD is less sensitive to photons. The recharge time or dead time can be in the order of 1 or 2μs, which limits the overall maximum counting rate to about 200,000 counts per second. Another drawback of using this passive quench arrangement is the dead time of the detector itself which is not constant nor well defined. This can pose a number of problems in certain applications. The noise of the detector, referred to as the dark count, is also affected by this passive quench arrangement. The initial large current that is allowed to flow before being quenched will dissipate a large amount of energy in the device. The resulting increase in temperature is responsible for an increase in the dark count rate. A further drawback is an affect called afterpulsing, which can have a considerable effect on the dark count rate. During an avalanche, some electrons and holes get trapped in the depletion layer of the device, only to be released later to cause a further avalanche. This again is a major result of the large current flowing by the passive quench arrangement. If the current could be limited quickly, less carriers would fill these traps and result in less afterpulsing and therefore fewer dark counts. It is these limitations that makes a passive quench arrangement unsuitable for numerous applications.

2. Active quenching

To overcome the drawbacks of passive quenching, active quench circuits have been developed[12,13]. When the device breaks down after an incident photon has been absorbed, an active quench circuit will quickly sense and reduce the bias voltage across the APD. After a certain hold off time, τ_d, the voltage will be subsequently restored. Previous designs have been developed to operate APDs with high breakdown voltages (250-400V)[12]. A new design is proposed using a mixed active and passive quench circuit. Using a method, originally proposed by Nightingale[13], of controlling the hold off time by using a capacitor at the inverting input of the comparator, a new relatively simple design is presented for low voltage breakdown APDs (20-45V) that avoids the disadvantages of high voltage active quench circuits and their associated complexity.

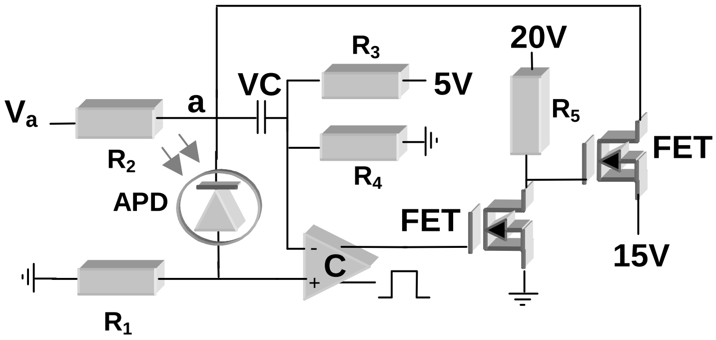

Figure 4. Geiger mode active quench circuit

After the APD has detected a photon, the voltage will be quickly sensed by the comparator, due to the large resistor, R_1. The comparator will turn on the fast FETs which in turn drop the voltage at the APD node (a) and brings the device below breakdown. The device is held below breakdown for a hold-off time determined by the time constant in discharging the variable capacitor VC. The device then quickly resets through R_2 before being ready to detect further photons. This circuit and design has proved very reliable with numerous different APD designs and is capable of detecting well in excess of $10x10^6$ counts per second for long periods. One of the main advantages of the design is the placement of the input of the comparator before the ballast resistor, R_1. This ensures that only a small amount of current is necessary to generate the voltage needed to trigger the fast comparator. Some of the benefits of this are reduced power dissipation, lower dark counts and less afterpulsing.

4. EXPERIMENTAL RESULTS

A number of important parameters are necessary to fully characterize GM-APDs. These include quantifying the dark count rate, excess reverse bias voltage, optimum operating temperature, and hold-off time. As the excess reverse bias voltage increases, the photon detection probability increases. While it would be desirable to have a high photon detection probability by increasing V_{ex}, it is to the detriment of the dark count rate, which also increases. In figure 5, the dark count rate is shown versus excess bias voltage, V_{ex}, at $T=20^oC$.

The dark count rate is as low as 12 counts per second at room temperature with V_{ex} = 4V, 16% above breakdown and with a hold off time of τ_d = 370ns. Table 1 shows the corresponding dark count rate, in counts per second, for different excess bias voltages. Results for three different sizes of GM-APDs are shown. As the diameter of the device increases, so should the dark count and it is mainly this fact that has limited the size of GM-APDs to small areas. However, for the 15μm device the dark count was observed to be significantly lower that the 10μm device.

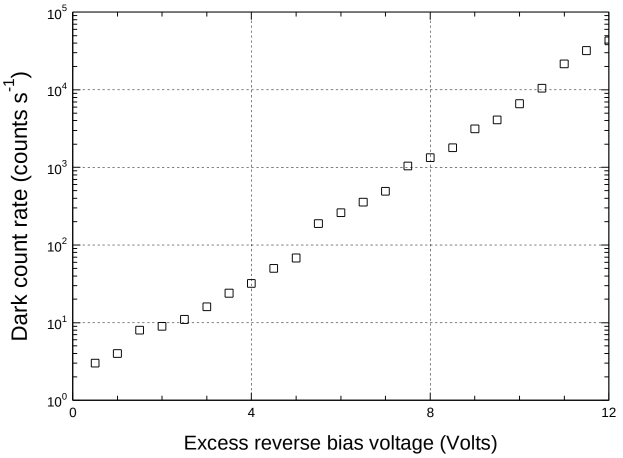

Figure 5. Dark count rate versus excess bias voltage for a 10㎜ GM-APD with a breakdown voltage, V_b= 25V.

Size	V_{ex} (15% above V_b)	V_{ex} (25% above V_b)	V_{ex} (35% above V_b)
10µm	7	73	187
15µm	11	17	46
20µm	54	366	1402

Table 1. Dark count rate for different excess bias voltages.

The dark count rate of the GM-APD will drop exponentially with temperature. At liquid nitrogen temperature, 77K no dark counts were observed at all for numerous devices that were tested. A larger 20µm device at 33% above breakdown was chosen to illustrate this exponential drop in dark count rate versus temperature, figure 6.

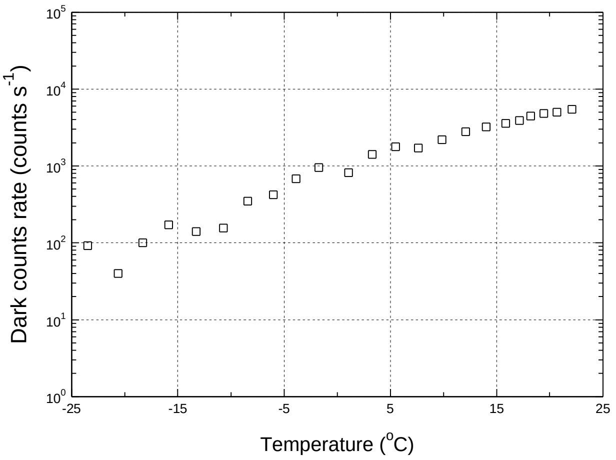

Figure 6. Dark count rate versus temperature for 20㎜ diameter GM-APD, t_d=128.5ns, V_b=30V and V_{ex} =10V.

The photon detection probability was calculated using the equation (1); where P_b is the photon detection probability, x_{apd}, t_{apd}, D_{apd} and A_{apd} are the count rate, dead time, dark count and area from the APD under test; x_{pe}, t_{pe}, D_{pe}, A_{pe} and P_{pe} are the count rate, dead time, dark count, area and photon detection probability from a calibrated comercial APD.

$$P_b = \frac{(x_{apd}(\frac{1}{1-t_{apd}x_{apd}}) - D_{apd})P_{pe}A_{pe}}{(x_{pe}(\frac{1}{1-t_{pe}x_{pe}}) - D_{pe})A_{apd}} \quad (1)$$

The photon detection probability increases with V_{ex} because a higher electric field increases the triggering probability[14]. These GM-APDs were found to have a peak photon detection probability at 650nm, figure 7.

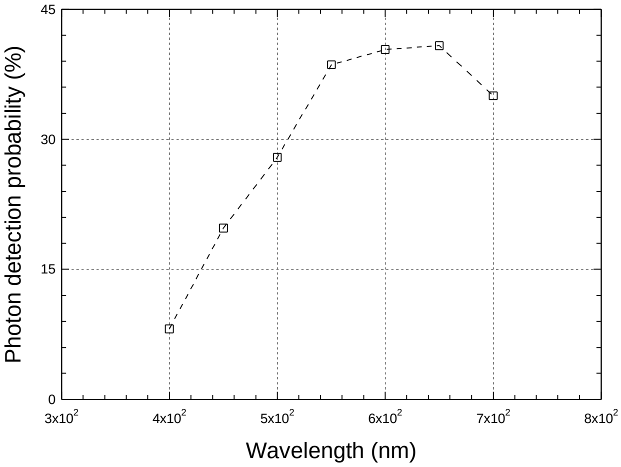

Figure 7. Photon detection probability for 15um APD

In quantifying the effect of afterpulsing, a red LED with a constant current source, illuminated the device under test. A long sweep was then taken by a 125ns bin multichannel analyzer and the data saved. This process was repeated numerous times with the dataset being subsequently analyzed by the normalized autocorrelation function[15] in equation (2) and the results averaged.

$$g^{(2)}{}_{obs}(t) = \frac{< n(t)n(t+t) >}{\bar{n}^2} \quad (2)$$

The results for different excess bias voltages, V_{ex} versus delay are shown for a 15µm device with a breakdown voltage, V_b of 30V, in figure 8. The devices were keep under constant illumination with a mean photon count rate of 100,000 counts per second. As the excess bias voltage was increased to 5V , 10V and 14V, with the hold off time decreased from τ_d =225ns, 150ns to 125ns respectively, the effects of afterpulsing can be clearly seen. For V_{ex} = 10V there is a large excess of correlation counts and therefore high afterpulse probability up to 625ns. Similarly for V_{ex} = 14V, there is a very high afterpulse probability until the normalized autocorrelation function reaches unity at 1µs. There is very little or no afterpulsing at V_{ex} = 5V with the normalized autocorrelation function quickly reaching unity. Due to the resolution of only 125ns, the structure and shape of the normalized autocorrelation function is limited. A higher resolution of approximately 50ns or better, and a larger scan would have been more preferable to obtained a more detailed structure in the correlogram.

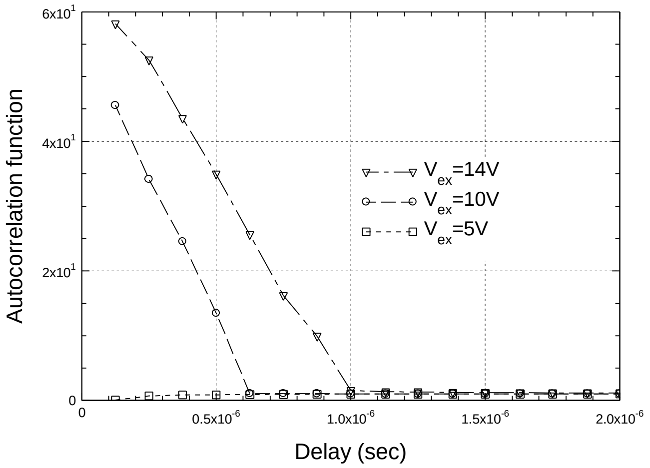

Figure 8. The normalized autocorrelation function at 0.0125 counts per 125ns resolution for different excess bias voltages.

How afterpulsing is affected by the diameter of the APD is shown in figure 9. What is interesting to note that while the 20µm device has the largest afterpulsing probability, the 15µm APD has less correlated counts than the 10µm device. Also the 20µm device has no afterpulsing from 500ns, while the 10µm device continues to have an excess of correlated counts until about 1000ns.

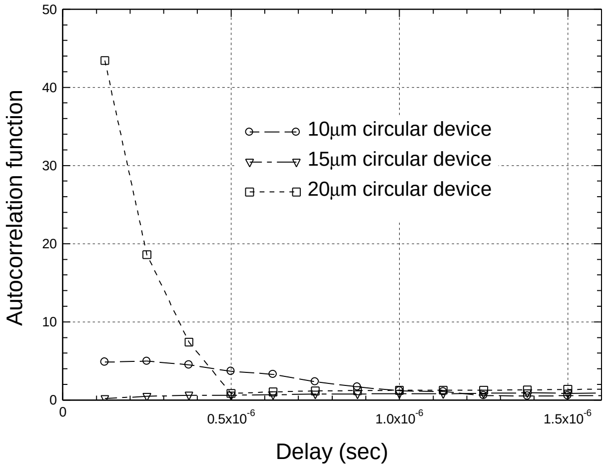

Figure 9. The normalized autocorrelation function at 0.0125 counts per 125ns resolution bin for different excess bias voltages.

Larger GM-APDs have been employed successfully in the detection of labeled proteins in a novel microarray system. Arrays of these new GM-APDs[16], as in figure 10, and other novel devices are currently being tested and characterized for their suitability to the time resolved detection of fluorescence from labeled proteins and DNA.

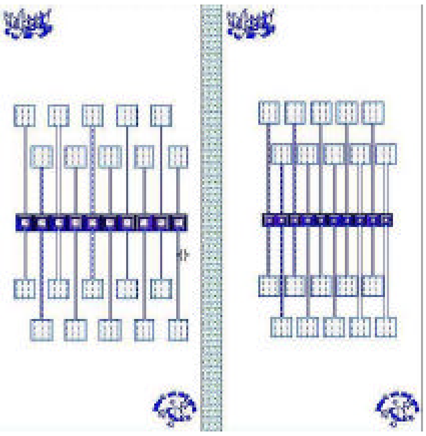

Figure 10. 10x1 arrays of GM-APDs designed specifically for fluorescence detection in microarrays.

5. CONCLUSION

GM-APDs are an alternative to the detection of fluorescence from DNA microarrays. New GM-APDs, together with a new AQC have been presented and characterized to quantitatively ascertain important operating parameters that are essential for the optimal performance of these devices in microarray technologies. These parameters, such as dark count rate, operating temperature, photon detection probability and afterpulsing probability, were calculated so that optimal parameters may be selected, depending on the application.

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