

Development and testing of a photon detector for Quantum optics experiments.

R A Pentz¹ and K Govender²

^{1,2} Department of Electrical, Electronic and Computer Engineering, Cape Peninsula University of Technology, Bellville, Cape Town, 7535, South Africa

E-mail:¹ pentzr@cput.ac.za

Abstract. Quantum communications and computing rely heavily on the use of single photons. Thus there is a need for generating single photons and detecting single photons. In this research, we focus on the detection of single photons. We employ an avalanche photodiode (APD) for this purpose. APD's are special electrical diodes that are operated in reverse bias, beyond the breakdown voltage in the Geiger mode. In the Geiger mode, the device is still non-conducting. Upon receiving a single photon an avalanche breakdown occurs, resulting in a large current. The device then needs to be quenched before it can detect another photon. This can be done using passive or active quenching methods. In this paper, we provide the methodology followed in developing a single photon detector and the challenges associated with developing such a single-photon detector. Some experimental results are also provided.

1. Introduction

Quantum cryptography is currently being investigated at the Cape Peninsula University of Technology with the focus being on developing a quantum key distribution system. The whole project aims to develop and construct a basic, cost-effective, quantum key distribution system, based on the BB84 protocol [1]. One of the main components of such a system is single-photon detectors (SPD). The two main devices that can be used for this application is a photo-multiplier tube (PMT) and an APD. Silicon APD is well researched and well developed, and therefore it is the 1st choice when it comes to selecting a detector [2]. The APD is referred to as a single-photon avalanche diode (SPAD) when it is used to detect a single photon and when it is used in the Geiger mode [3]. Developing a SPAD comes with its challenges and trade-offs.

This paper is organised as follows: The basic theory of developing a SPAD is presented in section 2. Section 3 gives an overview of the experimental setup. The results obtained are presented in section 4, followed by the conclusion in section 5.

2. Single Photon Detection

In a system where one uses photons to communicate, it is important to be able to detect each photon with 100% accuracy. SPAD is used to detect photons, but they have practical limitations, called dead-time and dark-count rates [4].

A SPAD is manufactured with three different types of materials, functioning at different wavelengths: Silicon (Si) (750 nm-900 nm), Germanium (Ge) (1000 nm-1350 nm), and Indium Gallium Arsenide (InGaAs) (950 nm – 1550 nm). These SPAD can be operated in linear or Geiger mode. Geiger

mode is when the diode is operated beyond the reverse breakdown voltage, which results in a huge current gain during an incident photon [5].

The SPAD (D in figure 1) is reversed biased (V_{bias}) to be above the breakdown voltage, V_{bias} , with a DC power supply. At this high V_{bias} , the electric field is so high that a single photon, absorbed within the junction of the SPAD, can trigger a self-sustaining avalanche. When a photon triggers an avalanche, there is a rapid increase in the current to be above the trigger current, I_t , of the diode. In this mode, quenching is required to reset the diode to its original state [3].

Three types of quenching methods are available:

- Passive quenching is achieved by connecting a large resistor (R), 50 k Ω -500 k Ω , in series with the SPAD so that there is a reduction in voltage across the SPAD as soon as the avalanche occurs (figure 1) [6].
- Active quenching utilizes a complex circuit that actively lowers the biasing voltage to a voltage below the reverse breakdown voltage as soon as the avalanche occurs, controlling the dead time and reducing it to a shorter effective quenching time [2].
- Gated mode entails keeping the biasing voltage below the breakdown voltage and increasing it to the required voltage just before an expected photon arrives. The count rate of this method is similar to active quenching but reduces the complexity of the electronic circuit [5].

A Silicon avalanche photo-diode, utilizing passive quenching, will be used, as this is the most cost-effective way to produce a photon detector. Quenching the SPAD is done by introducing a quenching resistor R (figure 1). The quenching resistor will force the voltage across the SPAD to decrease rapidly as the current increases, reducing the current to below I_t , therefore resetting the SPAD to a non-conductive state. The reverse bias voltage, V_{bias} , is chosen to be slightly higher than the V_{BD} .

$$V_{excess} = V_{bias} - V_{BD} \quad (1)$$

V_{excess} is the additional voltage above the breakdown voltage [3].

The value of R can be calculated as follows:

$$R = \frac{V_{bias} - V_{BD}}{I_t} \quad (2)$$

The value of R is normally large and is in the order of hundreds of k Ω .

The recovery time is the time required for the SPAD to change from a conduction state to a non-conduction state. This recovery time is also referred to as the dead time, as during this time the SPAD can't detect the next photon. The recovery time τ is a product of the total capacitance C , consisting of the junction capacitance C_j and the stray capacitance C_s , of the SPAD and the quenching resistor R [3].

Dark-counts can be created due to two main causes: Firstly, thermal energy contained within the SPAD can cause an avalanche to occur, creating a current pulse, without an incident photon [3]. Secondly, dark-counts can occur due to after-pulse. After-pulses occur, due to carriers trapped within the junction's depletion layer and when released, an avalanche can occur [3]. High dark-counts will decrease the accuracy of the detector to detect when a photon is arriving. There is also an increase of dark-counts with the increase of V_{bias} . Dark-counts can be reduced by a factor of 50 by cooling the SPAD down to -25 °C, as the dependence of dark-count rate on temperature, is exponential. Dark-current is the current due to dark-count and therefore this current also increases with the increase of V_{bias} [7]. According to Robert Brown *et al.* a V_{excess} of 3-3.5 V is an acceptable voltage to be used when the SPAD is cooled [8].

3. Experimental Setup

The basic setup, depicted in figure 2, is used. The photon source is pulsed with optical switches, which are mechanically synchronized. The photons are channeled via free air into the SPAD and photodiode (PD). The SPAD is an APD10-8-150-T52 from OSI Optoelectronics with a trigger current, I_t , of 10 μ A and a breakdown voltage, V_{BD} , 156.6 V was used. V_{excess} of 1.4 V was used to determine $R=142$ k Ω . V_{excess} was selected to be small, as the dark-current should be as little as possible and the SPAD is not cooled and was used at room temperature.

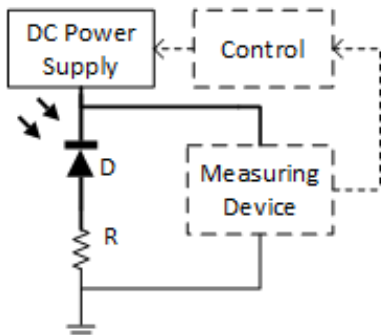


Figure 1. Circuit diagram and setup of the single-photon detector.

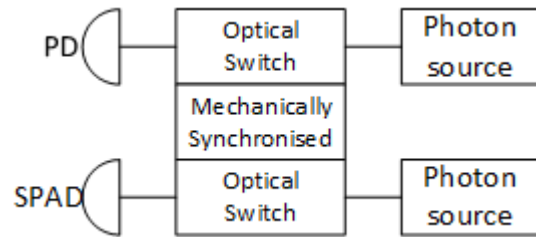


Figure 2. Experimental setup to characterize a single-photon detector.

A reference pulse was created, by measuring the voltage across the limiting resistor of the led. This reference pulse will show us how the current through the led changes and will be used to determine the position of the pulse generated by the SPAD. The wavelength for the photon source for the SPAD is 780 nm and the power of the photon source was reduced to a point where the photon source can just produce light. The light power was measured to be 0.65 nW and a light power meter was used. The electrical pulses generated by the SPAD was measured by an oscilloscope. The purpose of the reference pulse is to determine when a pulse is expected from the SPAD, as the pulse is very small and can be embedded within the noise. The passive quenching circuit and DC power supply are illustrated in figure 1. The current measuring device is an oscilloscope and will be replaced by a comparator circuitry, that will detect any pulses from the SPAD. This will be done in conjunction with a control circuit, as it is crucial to obtaining maximum gain and a low dark-current from the SPAD.

4. Results

4.1. Gain and Dark-current

The gain of the SPAD and the dark-current was measured by varying the intensity of the photon source so that the entire range of measurements can be done without saturating the SPAD. The optical switch was set to function at a steady rate of 50 Hz. The biasing voltage was increased from 0-160 V, in steps of 1 V, while documenting the voltage across R. The voltage measured with a biasing voltage of 0 V, was used as a reference, as the SPAD will produce a gain of one at no biasing voltage, and function like a normal photodiode.

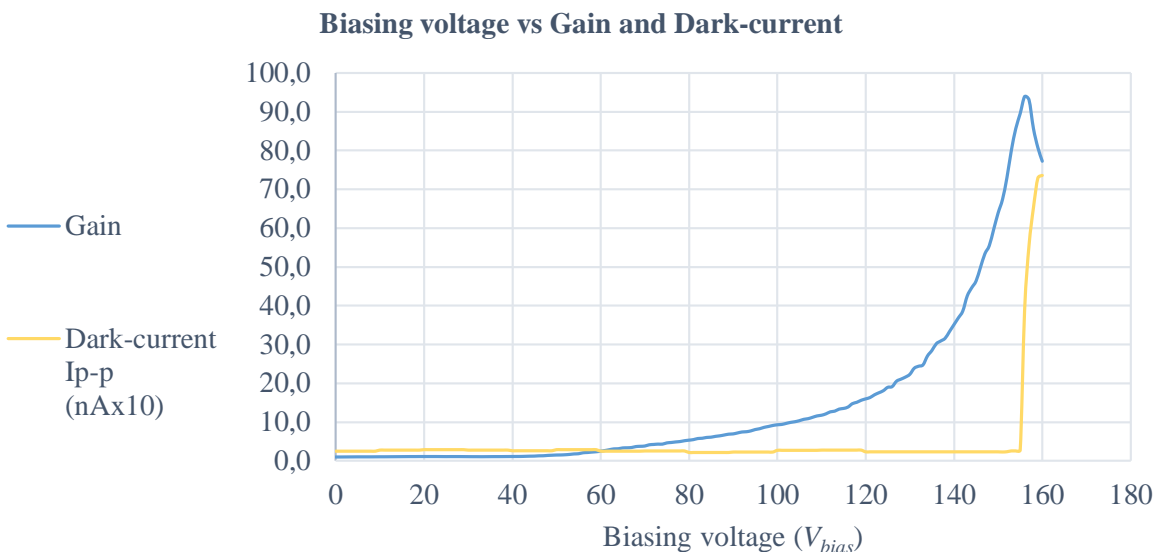


Figure 3. Graph representing biasing voltage vs gain and dark-current.

Gain is the ratio of the output voltage and the reference voltage. The photon source for the SPAD was switched off and the voltage across R was measured and converted to a current, which represents the dark-current. Figure 3 shows the results of dark-current and gain, versus biasing voltage.

The SPAD, according to the manufacturer, has a maximum gain of 100, but in practice, a gain of 93.9 was achieved. Observe the increase of dark-current while the gain is at a maximum. Take note that the gain reduces after reaching a peak. This shows that selecting V_{bias} incorrectly will result in low gain and an increased dark-current.

4.2. Photon Counting

Figure 4 shows the pulses measured from the APD (orange, top) and the reference signal from the PD (blue, bottom).

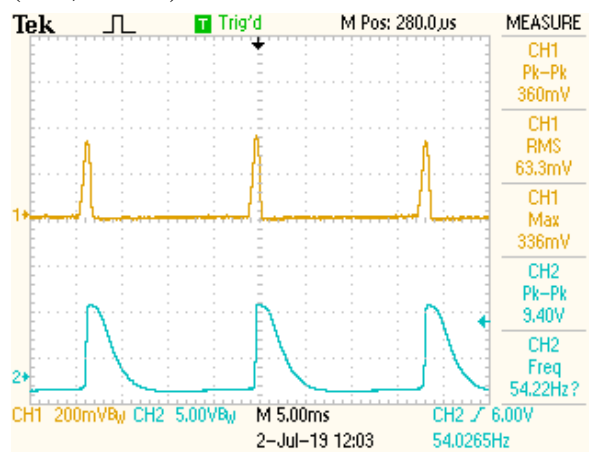


Figure 4. Output waveforms from the APD and PD

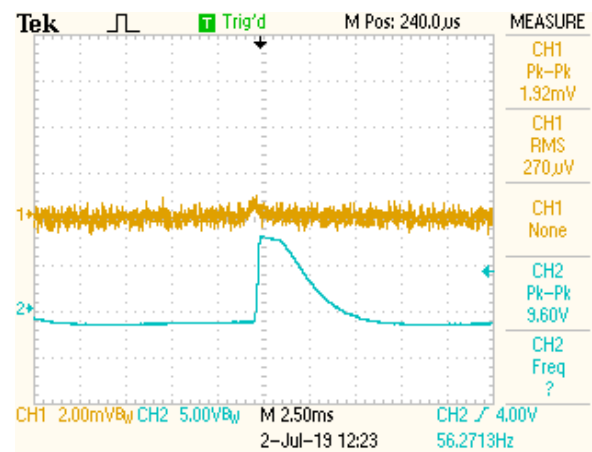


Figure 5. Smallest pulse measured from the APD

Selecting V_{bias} as 158 V, as determined above, will result in a voltage gain of 85.6, with a dark-current of 652.78 nA. Using figure 3, one can reduce the dark-current by selecting a lower biasing voltage of 155 V, and therefore reduce the dark-current to 27.78 nA, with a gain of 89.5. By doing this, one maximizes the gain, while keeping the dark-current to a minimum. It should be mentioned that the manufacturer included a specification sheet for the device, stating that V_{BD} was 156.6 V. Figure 5 shows the reference pulse (blue, bottom) and therefore the position of the output pulse of the APD (orange, top) is identified, even though it is hidden by the noise. The power of the light was measured with a light power meter and, with the aid of the following equation, the number of photons could be calculated:

$$N = \frac{P \times T \times \lambda}{h \times c} \quad (3)$$

N is the number of photons, P is the power measurement of the light, T is the period of the pulse, λ is the wavelength, h is Planck's constant, and c is the speed of light. The number of photons calculated was 51.01×10^6 photons. Therefore, each pulse in figure 5 represents a large number of photons. We still need to optimize the setup to be able to detect just one photon.

4.3. Quenching

The junction capacitance of the SPAD is 6 pF from the datasheet, and the stray capacitance, measured of the circuit, is 0.5 nF. The resistor, R , has a value of 142 k Ω , and therefore a quenching time (or dead-time) was calculated to be 71.85 μ s. Figure 6 shows the pulse of the SPAD (blue, bottom) with the measurement of a fall time of 80.8 μ s, which is a good approximation of the time taken to quench the APD.

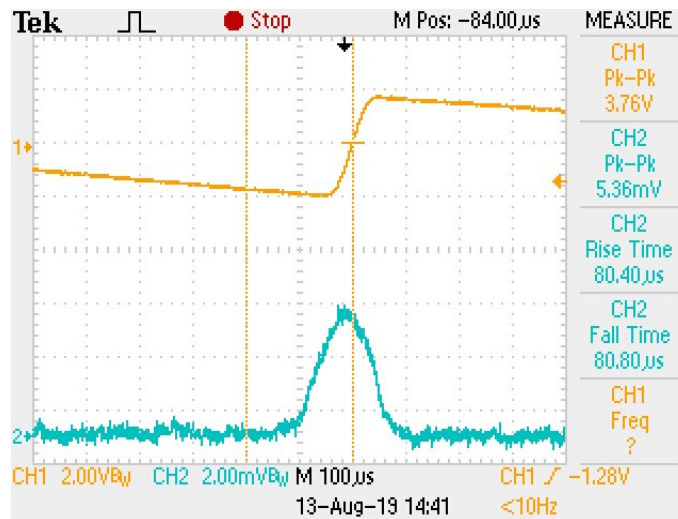


Figure 6. Measurement of the quenching time for an APD

5. Conclusion

A simple photon detector was developed to get acquainted with the challenges, related to such a device. While it is still necessary to optimize the circuit so that we can detect single photons, we have demonstrated the operation of the detector at very low light levels. The detector was constructed, characterised and measurements were shown. It was shown that, by applying attention to the gain/dark-current versus bias voltage, one can select an optimal reverse biasing voltage to obtain a maximum gain, with minimum dark-current. It is still a challenge to obtain single-photon results, due to the rising noise floor and a lack of sufficient gain. Care should be taken to keep circuit and radiation noise to a minimum.

References

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