The Effects of Wavelength on an LED based Single Photon Avalanche Detector

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1 Acknowledgements

Thanks to Kobe Chen for assisting with the experiment, Thanks to Dr. Mark Masters for advising us.

2 Introduction

Our original goal is to produce a cost effective Single Photon Counting Machine. Commercial version of SPCMs is over $s1000 making it difficult for students to do single photon experiments. A SPCM consists of a reverse biased diode, known as a Single Photon Avalanche Detector, a circuit that allows for the diode to count a higher rate of photons, and a way to cool the diode to keep its temperature constant. Our first step began with producing the circuit, but without an understand of SPADs this would prove difficult giving us inspiration for the following experiment.

This experiment is a preliminary exploration into the world of single photon detection with the goal of determining the sensitivity of a reverse biased diode based SPAD due to different wavelength photons. The forward biased diodes we use in this experiment will be referred to as source diodes, since they are our source of photons.

2.1 Single Photon Experiments

I was also running another experiment under Dr. Mark Masters and Jucoen Yeater dealing with single photons, but it is not the focus of this paper. This experiment began with me breaking a laser, so I had to get new lasers and build a circuit for them because the new laser needed a different voltage through it. This gave me experience in designing circuit in KiCad and using tools to drill holes into a box. I also had to mill the circuit, so I learned how to use a small CNC machine. While I was fixing the laser, I was also building a list of optics that was needed. Once the list was built I found pieces that we already had and then we bought everything else that was needed. Once the items we bought came in I began aligning optics and began to look into proving the existence of photons. We were going to do the experiment using only a passively quench avalanche diode instead of a SPCM. This would make doing single photon experiments cheaper and cut down significantly on dealing with complicated devices if we were successful. I later talk about coincidence counts because important to single photon experiments.

3 Theory

3.1 Building a Diode

Diodes are electrical components that allow current to flow one way. When diodes are placed in a circuit the low resistance direction this is known as forward biased. When placed the other direction this is known as reverse biased. To create this asymmetric resistance diodes are built by doping a semiconductor crystal. Half the crystal is doped to become an N-type material and the other half is doped to become a P-type material. This combination of the two materials can be done in a myriad of ways, but that is out of our scope for this experiment.

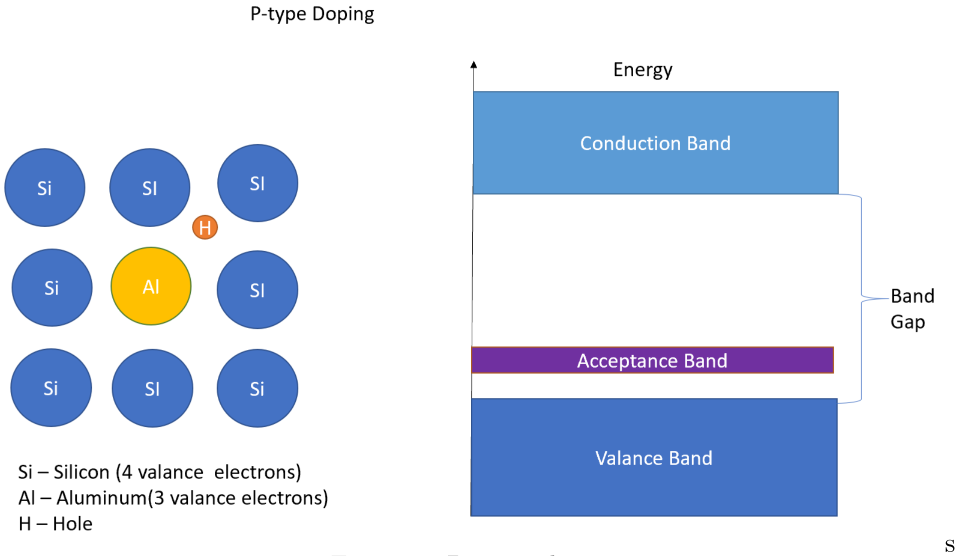

Figure 1: P-Type doping

P-type doping is done by adding impurities to a silicon lattice. Here we are using aluminum because it has one less valance electron than silicon. This means that where there originally were four covalent bonds between two silicon atoms there will only be three with the aluminum atom and a silicon atom. The fact that there is one less bond leaves one of silicon's valance electrons without a bond. This produces the acceptance band in the energy diagram above. It is called the acceptance band because it is produced when the doping atom (aluminum) accepts electrons like it has here.

The energy diagram is depicting the energy level of the valance electrons of the impure lattice. Most of the electrons are in the lowest energy state, depicted as the valance band. A small amount (equal to or less than the number of doping atoms) of them are raised to the acceptor band as a consequence of the impurities. The band gap is the required energy for electrons to enter the conduction band. The number of electrons in the conduction band depends on the temperature or voltage across the material, but electrons will only be there if their energy is great enough [3].

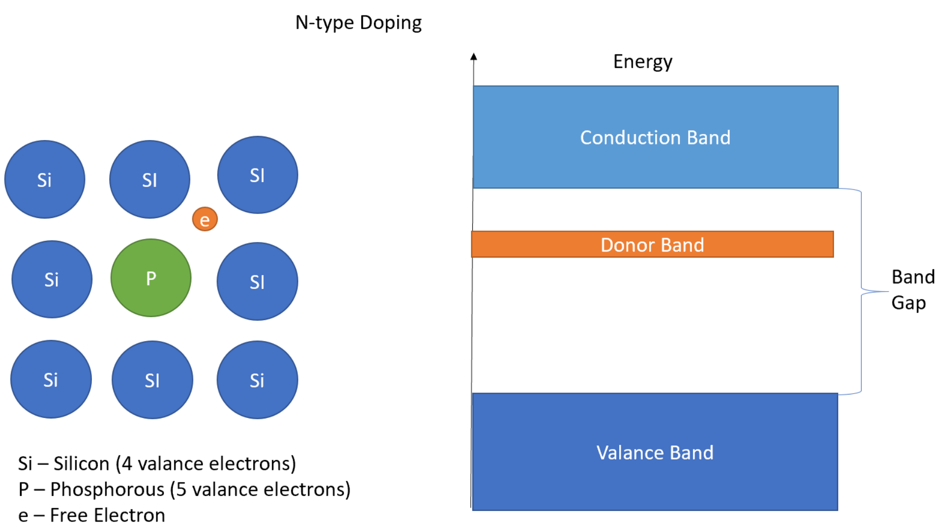

Figure 2: N-type doping

N-type materials are made in much the same way that P-type is done, but instead of doping with an atom that has one less valance electron, an atom with one more valance electron is used. Here we use the example of phosphorous being the impurity added to silicon. This time phosphorous creates all four covalent bonds with the silicon atoms, but it has one more electron floating freely within the lattice. This one electron doesn't take much energy to enter the conduction energy band, creating the donor band in the energy diagram. It is also important to note that both of these material are electrically neutral with equal number of protons and electrons [3].

3.1.1 P-N junction

A P-N junction has three regions of importance. The P-type side, N-type side, and where the two meet. As we recall from above the P-type side has holes, these can be thought of as a positive charge carrier and the N-Type side has free electrons. Where the two meet is called the depletion zone. In the depletion zone, electrons from the N-type side occupy the holes of the P-type region leaving holes on the N-type side, this is known as diffusion. This separation of charge produces an electric field within the depletion zone going from the N-type to the P-type material, Figure 3.

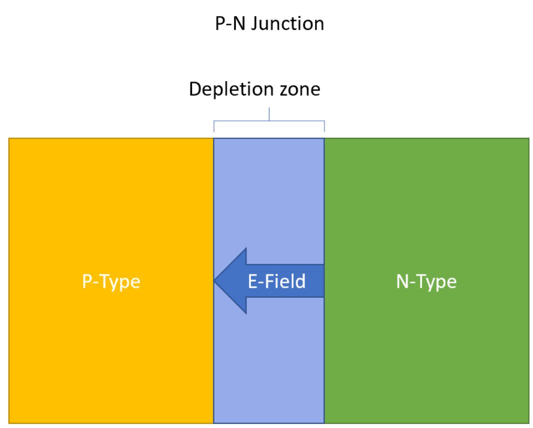

Figure 3: Junction with electric field direction

The energy band diagram of the PN junction can be seen below. The black band through the band gap is known as the Fermi level. The Fermi level being flat like it is in the picture indicates that the system is in equilibrium meaning there is no source of energy for the electrons in the junction (Temp = 0K and the no voltage across the junction).

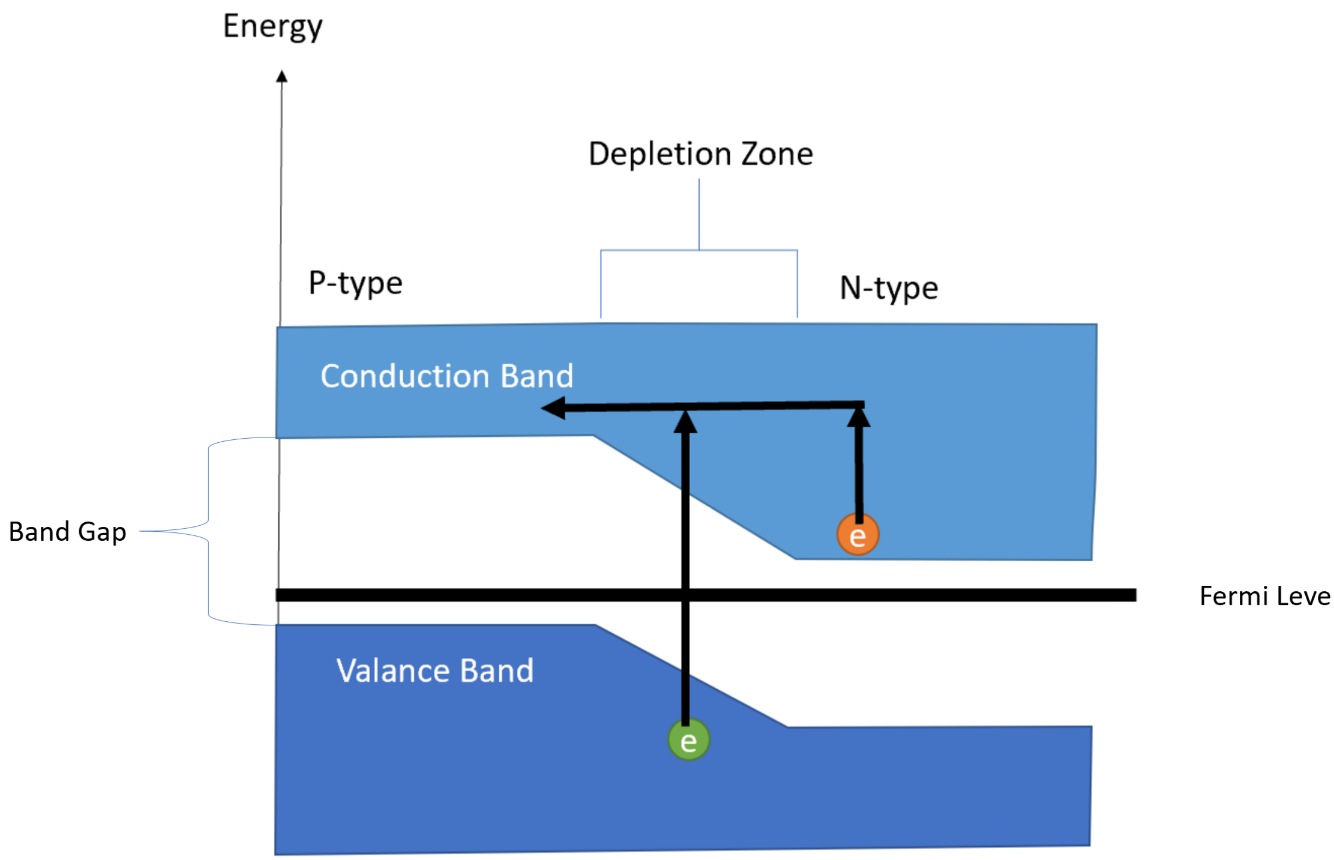

Figure 4: Energy of PN junction with electron entering into the conduction band

3.1.2 Forward biased

In forward bias, meaning the positive terminal of a power source is connected to the P-type material, an electric field is produced opposite to the electric field in the depletion region, if the voltage across the diode is great enough it will create an electric field that cancels the depletion zone's electric field and allow a current to flow. In the energy diagram the strength of the electric field is related to the slope of the energy in the depletion region. When a voltage is applied across the junction the electron's energy in the conduction band are raised, once the slope of the energy is zero, meaning the electric field is gone, a current can flow, indicated by the electron in the conduction band in Figure 4.

3.1.3 Reverse Biased

In reverse bias the electric field produced by the junction and the power source combine together. Once the electric field spans the width of the junction we can produce avalanche pulses, this state is known as Geiger Mode. This electric field being powerful indicates a large slope in the energy diagram. Once the slope is great enough the band gap becomes narrow. The necessary energy for a valance electron to reach the conduction band can be supplied by a photon, producing a photoelectron which is shown by the electron in the valance band jumping up to the conduction band in Figure 4. This photoelectron is accelerated though the electric field colliding with conduction band electrons, giving them enough energy to cause what is known as a avalanche pulse, can be seen in Figure 5.

3.2 Single Photon Avalanche Detector

Single Photon Avalanche Detection is the focus of this experiment and is normally done using a single photon avalanche diode. These are expensive and easy to break so we replaced it with the reverse biased diode. SPADs can be actively quenched or passively quenched. These terms refer to what kind of circuit is built around the diode. An actively quenched diode has a circuit around it that activates when an avalanche pulse is detected and speeds up the rate of which photons can be detected. Passively quenched allow for the pulse to die out at a slower rate. The picture below is an image of a few avalanche pulse from a passively quenched SPAD.

Figure 5: Oscilloscope output for avalanche pulse

3.3 Modeling Photons Produced by Diodes

We need a way to determine the number of photon produced by our source LEDs, so that we can determine how many photons could be detected by our SPAD. To do this we assume that every electron through the LED produces a photon. This can be done using Ohm's law:

$$N_{photons} = N_{electrons} = \frac{Voltage_{system} \Delta Time}{R_{resistor} charge_{electron}}$$

N_{Photon}	Number of photons produced by source LED
$N_{electrons}$	Number of electrons through source LED
$Voltage_{system}$	Voltage across resistor
$\Delta Time$	Length of count interval
$R_{resistor}$	Value of resistor in series with source LED
$charge_{electron}$	$1.6 * 10^-19$ Coulombs

It might be reasonable to consider some of the energy from the electrons is transferred to the air instead of all of them becoming photons. Therefore an improvement on this model would be to subtract off the number of photons that were produced due to heat.

3.4 Poissonian Distribution of Photons

Photons are counted by a Poissonian process. A Poissonian processes follows a few rules.

1. one photon being counted does not effect the possibility of another photon being counted
2. The average number of photons being counted is constant
3. Two photons are not counted at the same time

The first point is not entirely true in this experiment, because while one avalanche pulse is occurring it is less likely for another avalanche pulse to occur. This can be ignored because the time between pulses of the diode is significantly longer than the pulses length. The second point means that if we average counts 100 counts the average should be the same as if we average another 100 counts. This is why using an average is reasonable. Below are graphs showing the distribution of the photon counts for various time lengths. As can been seen the longer the time length the more normal the distribution becomes. The reason for this can be attributed to the central limit theorem for those interested.

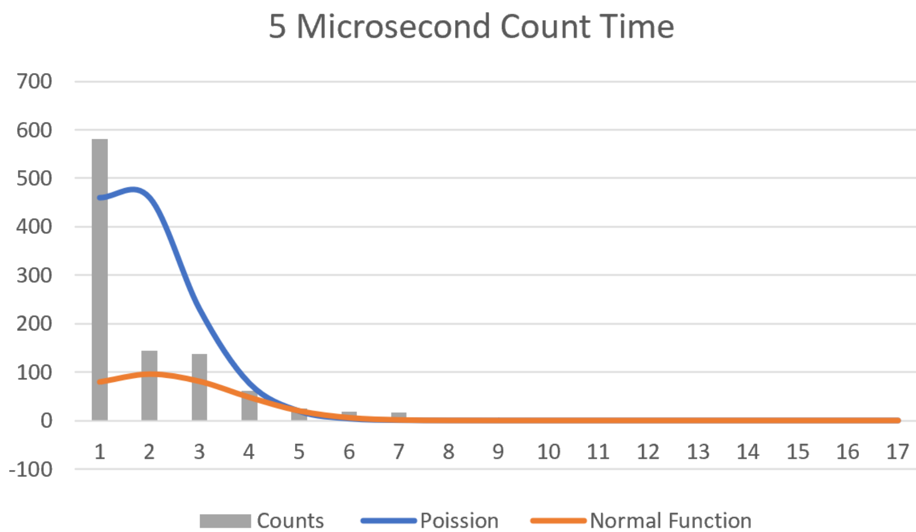

Figure 6: Distribution for photons with a 5 microsecond count window

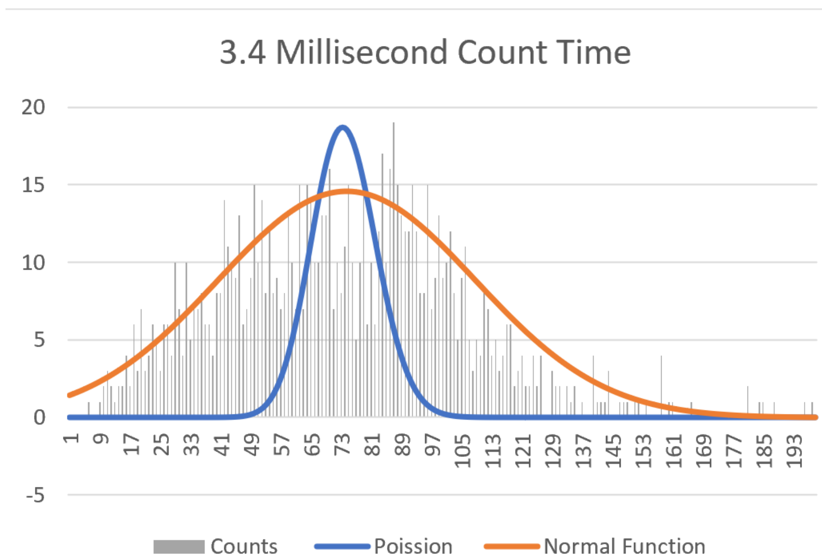

Figure 7: Distribution for photons with a 3.4 millisecond count window

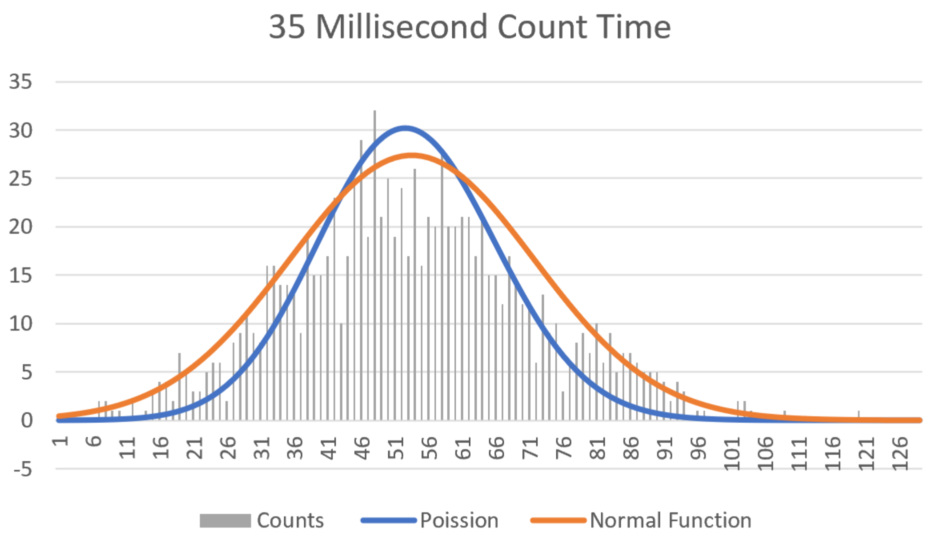

Figure 8: Distribution for photons with a 35 millisecond count window

4 Apparatus

4.1 Circuits

Determining the effects that wavelength has on reverse biased diode was done using the following two circuits. The top circuit has a voltage supply that we kept at 20.5 Volts to put the SPAD in Geiger mode, which is when the diode can release avalanche pulses. The 100k Ohm resistor has two purposes: to keep the current through the diode low and to passively quench the pulses. Without the resistor the current though the diode can become large enough to split it in half, which we achieved to do, and the pulses would not quench. The pulses would be counted by the Cypress PSoC, which is a microcontroller. The bottom circuit was used to produce a known number of photons with various voltages across various LEDs. We could figure out the current through the 1000 Ohm resistor using Ohm's Law because we put a voltmeter across it, giving us a voltage reading. These two circuits are combined inside of a primitive integration sphere.

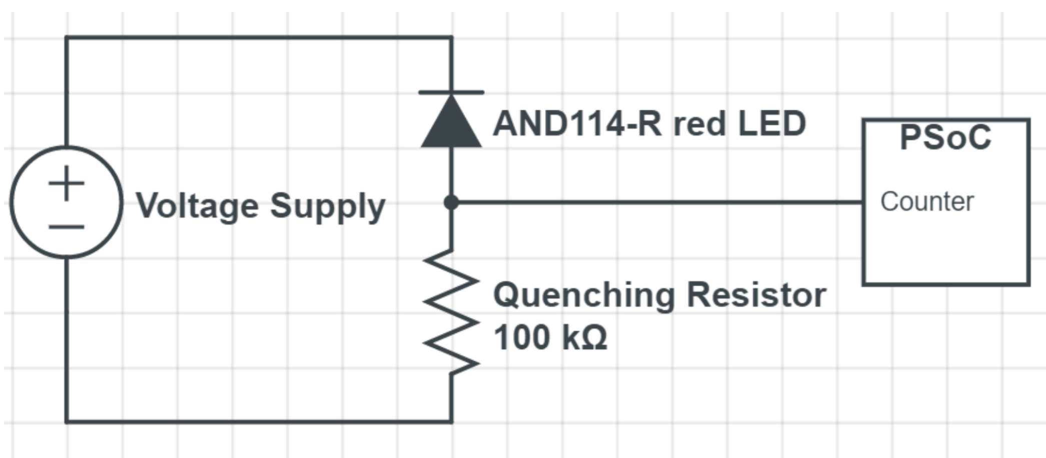

Figure 9: SPAD and counter

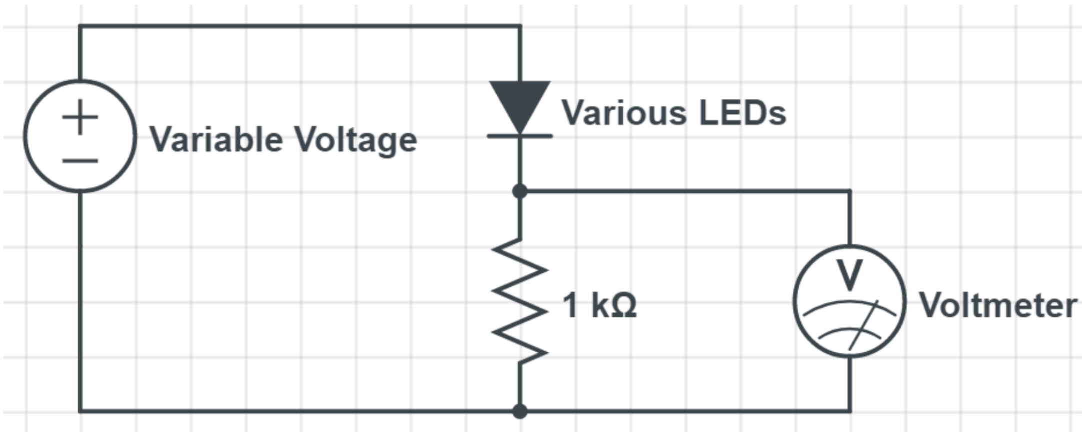

Figure 10: Source LEDs

4.2 PSoC

The microcontroller's purpose was to collect avalanche pulses and send the data to excel through serial communication and Python. This microcontroller contains the ability for coincidence counting, which was not used for this experiment, but will be discussed because these types of counts were important when conducting an experiment that proved the existence of photons which was part of my other experiments with single photons. Below is the schematic of the components used to build the coincidence counter.

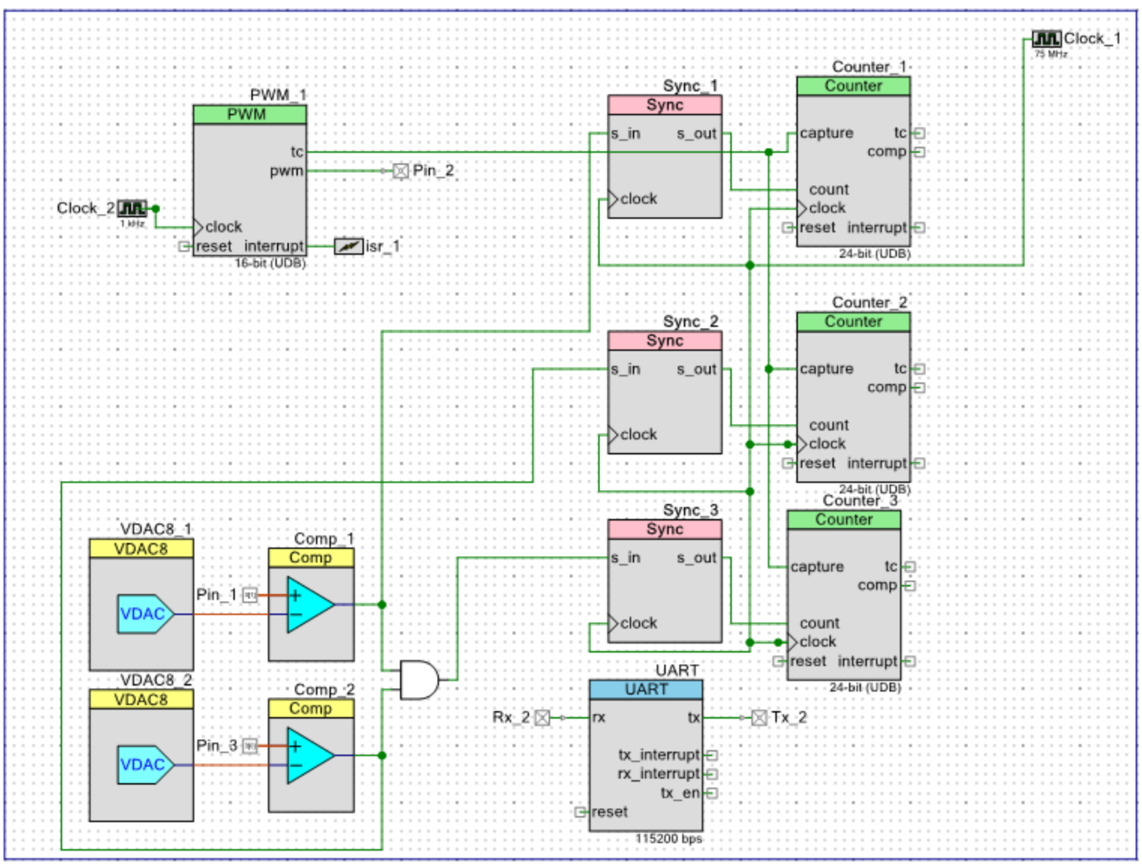

Figure 11: The PSoC schematic

The Pulse Width Modulator (PWM) has the purpose of allowing us to select our count window. The count window consists of the period and compare value of the PWM. The period determines the length of one cycle for the PWM and the compare value determines the duty cycle. We had the period of the PWM be two seconds and the duty cycle be 50 percent for a count window of one second. Connected to the PWM is a one kHz clock and an Interrupt (ISR). The PWM is connected to the capture pin of the counters.

The interrupt (ISR) created system-wide interrupts based on when the PWM has competed one duty cycle.

The Counters were used to count signals. A sync is connected to the count pin of the counter, their clocks are all 75 MHz (this gives a max count rate of near 37 Mhz which is much more than the counts we expect), they all have the PWM connected to their capture pin and counter one is connected to the first comparator, counter two is connected to the second counter and counter three is connected to the and gate. Counter one is used for this experiment and the other two are used for coincidence counting. Counter 1 receives synchronized signals from the first comparator. Those signals are the avalanche pulses. For one second the counter records the number of these pulses and then the code sends those readings to the computer. Counter two acts the same as counter one, but receives its counts from the second comparator. Counter three counts when signals from both comparators are active at the same time, this is what is considered a coincidence count.

The "syncs" synchronize the clock of the counters with the signal from the comparators. This was important because the counter only registers a signal when the counter's clock is high and when the input signal is high as well. The sync lines up the signal with the clock's rising edge allowing the signal to be counted.

The Voltage Analog to Digital Converter (VDAC8) set the reference voltage of the comparator, which has the effect of removing noise. Here we used it to create a DC signal with a specific voltage. In tandem with the comparator any signal from our circuit that was lower than our DC signal would not be counted, thus removing the noisy signals from our counts.

The Comparators had the purpose of removing noise from the system. They have two inputs: the pulses from the SPAD and the VDAC8. If the signal from the pulse has a greater voltage from the signal from the VDAC8 then the comparator will allow a signal through for the counter to register. If the voltage from the VDAC8 is greater than the signal from the circuit then the counter will not receive a signal to register.

The and gate (white symbol connected to both comparators) allowed coincidence counts to be registered. This would allow a signal through when both comparators allowed a signal through. Both comparators would allow a signal through when two SPADs would produce an avalanche pulse simultaneously (within each others avalanche pulse widths).

The UART provides serial communication of the counts to serial ports in a computer.

4.3 Primitive Integration Sphere

To combine the two circuits we built an enclosed box, our attempt at a primitive integration sphere. The box had multiple purposes: to remove photons produced by the room's light and to reflect the photons though the box to be certain that every photon produced would come into contact with the SPAD. Below is a picture of the interior of the box.

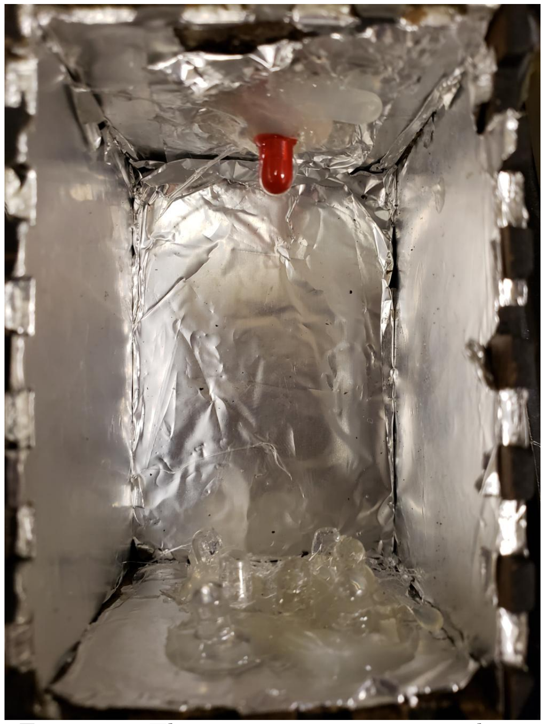
Figure 12: The primitive integration sphere
Dr.

The dark box was laser cut from Masonite using a template from makercase.com, then glued together. The top was left unglued so we could have access to the interior of the box. Aluminum foil coated in interior of the box to reflect the photons produced by the source LEDs and it provided an extra light protection. The diode with the red filter over it is the SPAD and the clear cover one's on the other side of the box are the source photons. There are 7 source LEDs: red, pink, green, ultraviolet (UV), orange, pink, infrared (IR); the pink LED was not used because it is a combination of the red and blue LED. These wavelengths were picked to cover a broad spectrum. The LEDs had their leads lengthened by soldering wires to them to make it possible to breadboard them. After soldering the wires, we heat shrunk the exposed metal of the leads to cut down on shorting. To keep the LEDs from moving and to cover the holes that the leads made we surrounded the LEDs with hot glue. Then we closed the box and covered the edges in electrical tape adding a third layer between the room's photons and the SPAD.

5 Experiment

Our experiment was designed to determine the effect that wavelength has on the sensitivity of the SPAD. The variables we were interested in are the wavelength of the photons being counted and the current through the source LEDs. We suspected that higher energy photons would cause more avalanche pulses to happen because this could make the interaction between the photons and electrons more likely to produce a pulse.
For each of the six diodes we put a voltage across the 1000 Ohm resistor of zero to ten volts incrementing by one volt. The microcontroller collected data for one second count windows, which was repeated 100 at each voltage. Then after collecting the data for the 11 voltage values, we repeated the same process on the next wavelength diode until we finished all 6 source LEDs. We got the current through the source diodes by measuring the voltage across the 1000 Ohm resistor and applying Ohm's law we solved for current.

5.1 Improvements

When we first began we had a circuit with looped wires, and exposed leads from the LEDs. These acted as antennas which increased the noise of our system. To fix this we cut wires to be a shorter length to fit snuggly on the bread board.

The output of the system was only displayed on an LCD screen, it grew tedious to read the numbers off of the LCD screen and write them down. This prompted the use of serial communication and PuTTy is a software that displays the output of the serial communication. This was nice because we could save this output as a file. Though this had issues because we could not tell it how many data points to collect, so we developed a scripted in Python that could take the output of the serial communication and send it to excel. I noticed what seemed to be random fluctuations in our count numbers. This turned out to be due to the power supply having fluctuations. When near the reverse bias break down voltage there is extreme sensitivity to voltage changes, so fluctuation of 0.1 volts is problematic. This led us to finding a power supply that did not fluctuate, which fixed this problem.

The SPAD has a cover over it which acted as a red filter. This caused serious issues with counting photons of all wavelengths. We assume this is the reason for the low photon counts in the regions that are not in the red or orange wavelength region. It would have been nice to analyze the spectrum of the LED with a spectrograph to see if our assumptions were correct. Then we could try to remove the cover of the SPAD.

We were getting counts even when the source diodes had a voltage difference across them below their turn on voltage. Meaning they were not producing photons yet! Dark counts are when the SPAD releases avalanche pulses from thermal excitations. Removing the pulses from thermal excitations would have been an improvement because we would know which counts were from photons, instead of the counts being a combination of thermal excitations and photon counts. We had the idea of using a thermoelectric cooler which uses a potential difference to create a temperature difference to keep the SPAD's temperature constant.

6 Results

Below is a Histogram of 100 counts with a 1 second count windows.

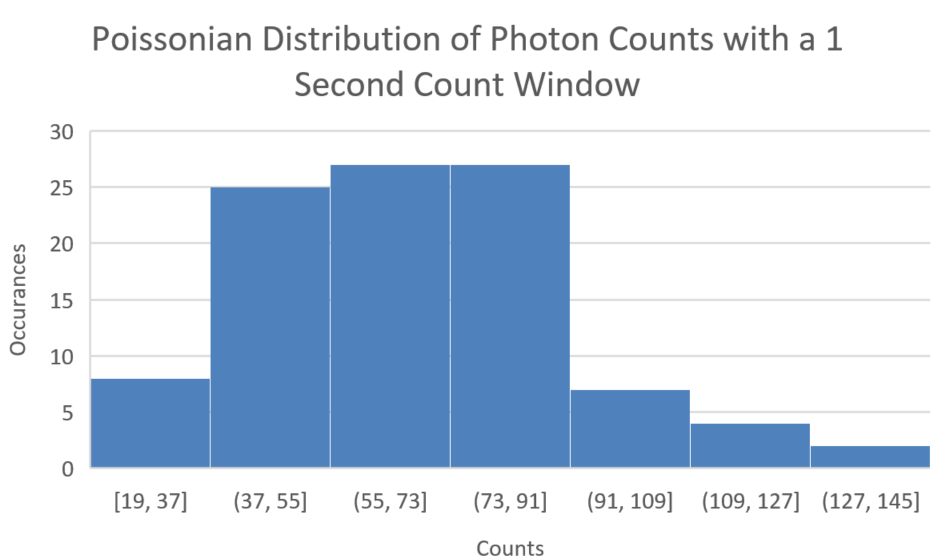

Figure 13: Histogram of photon counts

Below are dark counts of the LEDs. These were gathered with a power source that was on, but below the LED's turn on voltage. This means there was 0 volts across the resister in series with the source LED, implying no current through the circuit. That means there should be no photons being produced. The reason the dark counts could have different values for different LEDs is because the LED could been transferring thermal energy to the air due to the power supply being.

Wavelength	IR	Red	Orange	Green	Blue	UV
dark counts	0.59	0.77	0.62	0.66	0.29	0.01

The raw counts are color coded to the color of the LED that produced them. In case colors are difficult to see for you; from most to least counts: red, orange, UV, green, blue, then IR. Due to the cover on the SPAD, it counted wavelengths in the red region the best. As the current increases the trend of the counts become asymptotic indicating either saturation in the SPAD or the source LED is converting more energy to thermal energy. The orange LED produces some photons in the red wavelength region; that is why the SPAD gets more counts out of that LED than the others.

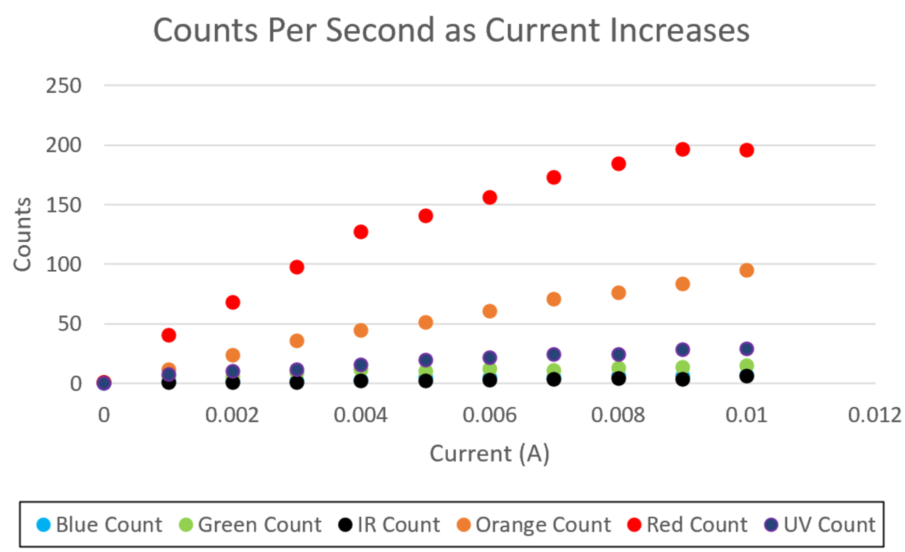

Figure 14: Average counts of photons with 1 second count window

The sensitivity of the SPAD due to each color source LED, follows the same trend as the above graph. Though this time, as the red source LED produces more photons the SPAD becomes less sensitive. This could be due to the source LED producing less photons than we calculated so the SPAD could not detect the projected number of photons in those ranges.

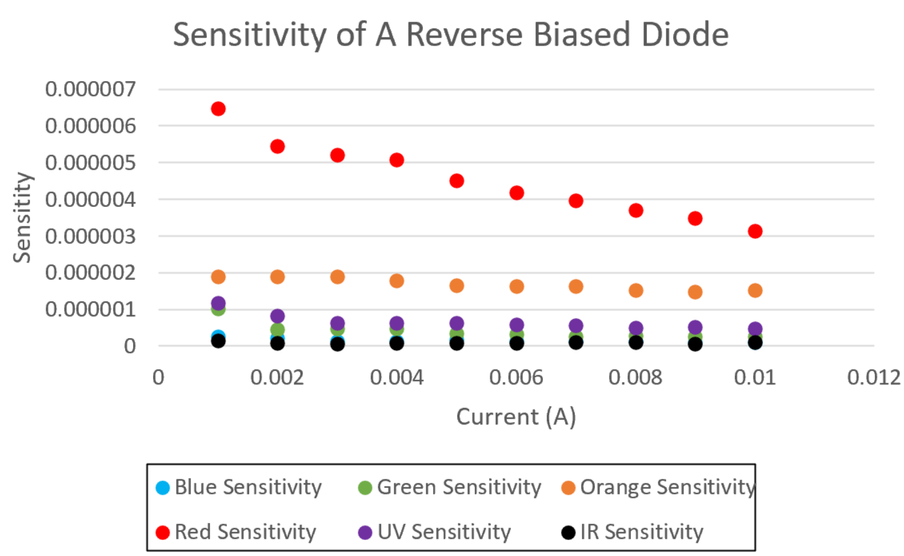

Figure 15: Sensitivity of reverse biased diode as current increases

7 Conclusion

Determining the sensitivity due to wavelength of a reverse biased LED based SPAD is a useful experiment for learning about single photon detection and diodes. Unfortunately, the cover over our reverse biased diode did not allow for accurate detection of all wavelengths of photons, so we were unable to come to a conclusion about how wavelengths effect the sensitivity of our SPAD. Removing the cover and reproducing this experiment would be the next step in this preliminary exploration of producing a cost effective SPAD.

References

[1] Spencer Kelham, and Dr. Mark Masters. *Development of a Low Cost Single Photon Avalanche Detector* . Purdue University, Fort Wayne, 2019.

[2] Majeed Hayat , Mark Itzler , David Ramirez , and Graham Rees. *Model for Passive Quenching of SPADs.* SPIE Vol. 7608

[3] Harold Stokes. *Solid State Physics for Advanced Undergraduate Students.* 117-119. Brigham Young University, 2007.