P443 (Integrated Physics Lab II)
Singe Photon LED Detection

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A cheap and simple method for photon counting using an LED as an avalanche photodiode in reverse-biased condition is studied during the course of this experiment. We obtain the counting statistics of photon detection, the effective capacitance of the detector and thereby obtain its decay constant. The dead time of the setup was also computed. The temperature dependence of the counting characteristics of the detector setup was also studied.

I. OBJECTIVES

- To assemble and test a single photon avalanche detector using an LED
- To study the counting statistics and its properties of this Single-Photon Avalanche Detector (SPAD)
- To figure out ways to improve the detector by studying variations of counting statistics under temperature, dead time, and decay constant by varying testing conditions

II. INTRODUCTION

Detection of photons play a key role in various branches of science. Different photon detection techniques were developed from time to time. The photomultiplier tube (PMT) which came up in the 1930s, was capable of providing high sensitivity and timing resolution. In recent times the PMT has been replaced by semiconductor-based single-photon detectors. They work on the basis of avalanche effect in reverse-biased mode. These single-photon avalanche photodiodes (SPADs) are capable of detecting single photons with good timing accuracy and less noise at a high rate.

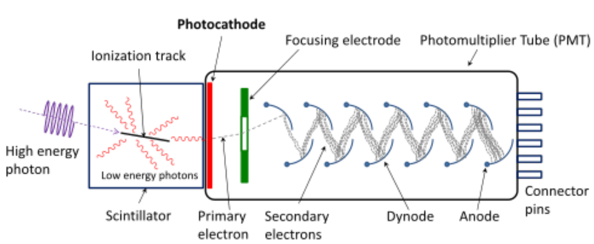

FIG. 1. A schematic diagram for a PMT

III. THEORY

A. Detection of photons using SPAD

In this experiment, the goal is to demonstrate the working of a single photon avalanche detector (SPAD) from a Gallium Phosphide (AND114R) LED under various operational conditions. As the LED is a pn junction diode in the reverse biased condition, it would be able to detect photons incident on it. When a photon arrives at the junction, it generates electron-hole pairs which get separated instantaneously due to the electric field created through biasing. The electron gains kinetic energy once it is accelerated by this field. Upon interacting with an atom in the junction, the kinetic energy of the electron creates yet another e-h pair, leading to 2 electrons being produced in total. This avalanche process goes on leading to a measurable pulse of current. This is similar to the avalanche occurring in a Geiger–Müller tube. Here, the set up is returned to its initial condition by the help of a quenching resistance connected in series to the LED. When a large current flows through the circuit, there would be a huge voltage drop across this resistance which reduces the bias voltage of diode thereby quenching the avalanche. This type of quenching is called passive quenching. Quenching makes the circuit ready to receive a new photon.

B. Dead Time

The time taken for quenching the avalanche initiated by a photon is called dead time of that detector. During this time the detector is insensitive to incident photons. The dead time primarily depends on the value of quenching resistance and the applied bias voltage.

C. Afterpulsing

In non ideal conditions there would be phenomena like joule heating coming into play. This increases the probability of electrons getting trapped into energy states.

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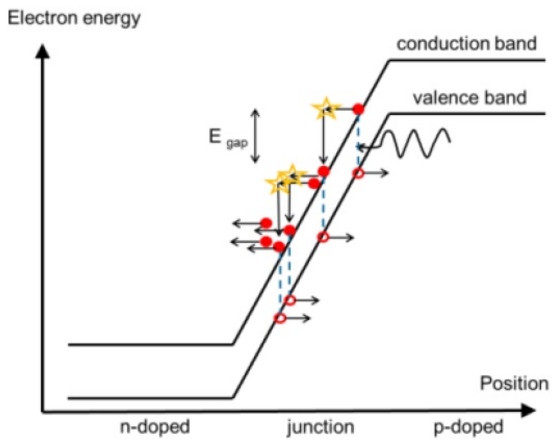

FIG. 2. Apparatus for the experiment

This electron can begin another avalanche which is correlated to the first one. Hence one pulse would beget another pulse within a short span of time. This is called Afterpulsing. This leads to an overcounting of incident photons and also causes the frequency distribution of the counts to show non-poisson distributions.

D. Dark Counts

Electrons can also experience thermal excitations, which can push them into the conduction band. This can also initiate avalanches. Hence, there is a temperature dependence to the number of photons that are apparently detected. The effect of dark counts can be reduced by bringing the temperature of the setup way below room temperature. As dark counts are not due to photons, they introduce discrepancy in photon counts. We tried to investigate the nature of this dependence in particular in the course of our experiment.

E. Counting statistics

It is assumed that photons arrive at the detector randomly at uncorrelated times under normal conditions. Thus, it can be said that their statistics would be similar to that of a radioactive decay process. Hence their frequency distribution would also be expected to follow Poisson distribution, which is given as:

$$p(x, \mu) = \frac{\mu^x e^{-\mu}}{x!}$$

where p is the probability of measuring x events in a particular interval; μ is the average events found in that interval.

The time intervals between successive photon incidence is also measured for different resistances and is fitted with exponential function. Taking the natural logarithm of frequency and plotting against time between pulses gives a plot which can be fitted more or less to a straight line, from which we can deduce the dead time of the detector.

Also, we had measured the duration of pulses. By studying its variation with resistance, we can get the time constant of the detector.

IV. APPARATUS INFORMATION

The following components were utilised in the course of the experiment:

- AND114R LED
- LM311 Comparator
- LM741 Opamp
- Resistors
- 10kΩ Potentiometer
- Breadboard
- 5V, 15V, and 0-30V DC power supply
- Oven with PID-controller
- Arduino UNO and computer for recording data
- Connecting wires

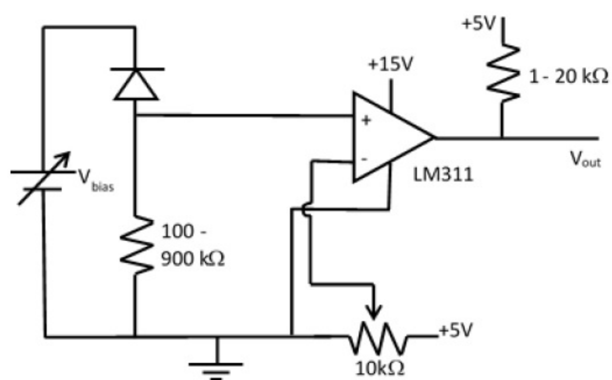

FIG. 3. Circuit for the setup

A. Circuit

As shown in the circuit diagram, the LED was operated in the reverse-bias mode. It was connected in series with a resistance of 150 kΩ. To make the signal measurable, a discriminator (an LM311 IC) was added to the output. The output voltage becomes non-zero whenever the voltage at the non-inverting input is more than that at the inverting input of the LM311 IC. The pull up resistor at the output of the comparator sets the amplitude of the output pulse to 5V. The potentiometer between the inverting input and the 5V supply is used to regulate the voltage that is received at this input. The output of the comparator is usually connected to a microcontroller, which is, in our case, an Arduino UNO board.

The necessary code is run in the Arduino Integrated Development Enviroment (IDE) to record the data. To visualize the pulses, the output of the comparator was also given to a oscilloscope. To check the role of comparator in the circuit, signal input to the comparator is also given to oscilloscope.

B. Software

In Arduino, the code has two main parts - void setup and void loop. The part of the code which is required to be run only once should be inside void setup. This code would be runs at the start. The code which is required to be executed repeatedly until some condition is met is inserted in void loop. Once a piece of code (in Arduino IDE, this is called a 'sketch') is executed, the Arduino board converts the code to assembly level language and continues to execute it when supplied with power.

For recording counting statistics, pulse distance data, and pulse width data from our setup, we have the following three Arduino sketches:

Fetcher_LED.ino

```
int pin = 2;
unsigned long timeRes = 200;
int numPulse = 0;
unsigned long timeEnd = 60000;
unsigned long timeStart = millis();
unsigned long timeReq;

void setup() {
  Serial.begin(9600);
  pinMode(pin, INPUT);
}

void loop() {
  if (timeStart <= timeEnd) {
    if (millis() - timeStart >= timeRes) {
      Serial.println(numPulse);
      numPulse = 0;
      timeStart = timeStart + timeRes;
    }
    timeReq = pulseIn(pin, LOW);
    if (timeReq > 0) {
      numPulse++;
    }
  }
}
```

FIG. 4. Code for recording counting statistics

In the code for measuring pulses in a given interval of time, we changed the timeRes value in accordance with the time interval we need. Also, the timeEnd value is set depending on the number of observations we need for a particular time interval.

Pulse_Dist_LED.ino

```
int pin = 2;
unsigned long duration;
int nr = 0;

void setup() {
  Serial.begin(9600);
  pinMode (pin, INPUT);
}

void loop() {
  if (nr <= 10000) {
    duration = pulseIn(pin, LOW);
    Serial.println (duration);
    nr++;
  }
}
```

FIG. 5. Code for deadtime measurement (using pulse distances)

Pulse_Width_LED.ino

```
int pin = 2;
unsigned long duration;
int nr = 0;

void setup() {
  Serial.begin(9600);
  pinMode (pin, INPUT);
}

void loop() {
  if (nr <=10000) {
    duration = pulseIn(pin, HIGH);
    Serial.println(duration);
    nr++;
  }
}
```

FIG. 6. Code for time constant measurement (using pulse widths)

V. ANALYSIS

The bias voltage was set to the minimum value at which the pulses were obtained in the oscilloscope display. It was observed to be ∼22.4V for our setup. In order to check whether the circuit responds to light, we put a dark cloth over the LED. It was observed that the number of pulses decreased somewhat. Then we removed the cap and shone a flashlight, which resulted in a noticeable increase in the rate of pulses. After checking that the circuit was responsive to intensity of light (number of incident photons), data recording was commenced.

A. Counting statistics

We recorded the number of pulses obtained for a particular interval of time, over a period of time under ambient light conditions using the code shown in Figure 4. Data was taken for time intervals of 20, 200, and 600 milliseconds. For these measurements, Bias voltage (22.4 V) and quenching resistance (150 kΩ) were the same. For each of the mentioned time intervals, the data was taken for a period of time in order plot the frequency distribution of counts in an interval. Thus, histogram plots were made, to which, normal distributions were fitted. The goodness of fit was verified using Levenberg-Marquadt method. The covariance matrix for each distribution was taken to compute the error in the parameters in comparison to the fitted curve.

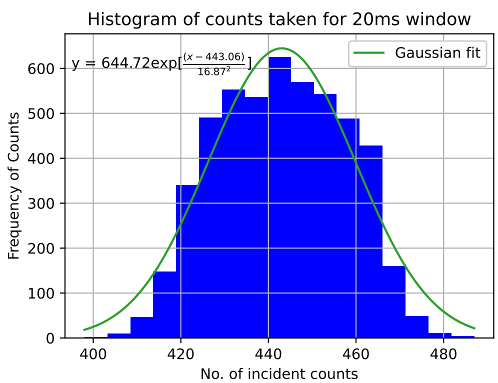

FIG. 7. Frequency distribution of counts for 20ms in ambient light

Below is the covariance matrix for the 20 ms window fit:

	C	μ	σ
C	1.04E+03	-0.01817	-18.3224
μ	-1.82E-02	9.45E-01	1.12E-03
σ	-1.83E+01	1.12E-03	9.62E-01

The diagonal entries of the covariance matrix gives the variance of the value of each parameter. Here, μ is the mean, σ is standard deviation, and C denotes the scaling factor for the Gaussian fit.

The same analysis procedure was repeated for other values of time intervals. All the plots converged to a Gaussian curve in their frequency distribution. The graphs with their best fit curves and values of various parameters are shown in the following figures. The covariance matrices are also given as tables after each distribution's plot.

Now, we have the covariance matrix for the 200 ms window fit as follows:

Finally, we have the covariance matrix for the 600 ms window fit:

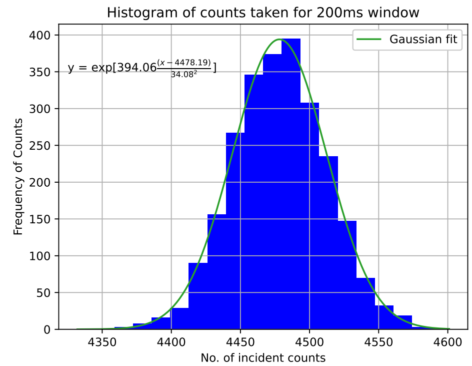

FIG. 8. Frequency distribution of counts for 200 ms in ambient light

	C	μ	σ
C	2.15E+01	-1.28E-05	-1.24E+00
μ	-1.28E-05	2.15E-01	2.63E-06
σ	-1.24E+00	2.63E-06	2.15E-01

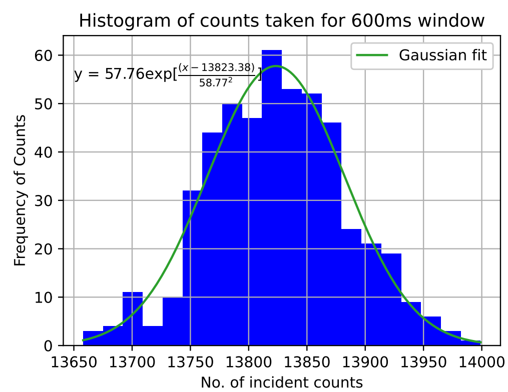

FIG. 9. Frequency distribution of counts for 600 ms in ambient light

	C	μ	σ
C	5.84E+00	3.34E-03	-3.98E+00
μ	3.34E-03	8.05E+00	-7.75E-03
σ	-3.98E+00	-7.75E-03	8.10E+00

B. Deadtime measurements

The distance between pulses were measured using the code shown in Figure 5. Here, the time resolution was kept constant and the quenching resistance was varied. Data taken for 150 kΩ, 300 kΩ, 450 kΩ, and 600 kΩ was used to plot the frequency distribution of occurences. Both plots were observed to exhibit an exponential decay profile. These were fitted to the exponential curve of the form $e^{-\frac{t}{\tau}}$. The time constant of the exponential decay function is in proportion to the dead time of the SPAD.

Therefore, we can study the variation in decay time with different quenching resistances to study how the dead time is affected due to the same. We have taken the natural logarithm of occurrences and plotted against time between pulses to deduce the dead time of our setup. The exponential decay plots and linear fits for the logarithmic graphs are as follows:

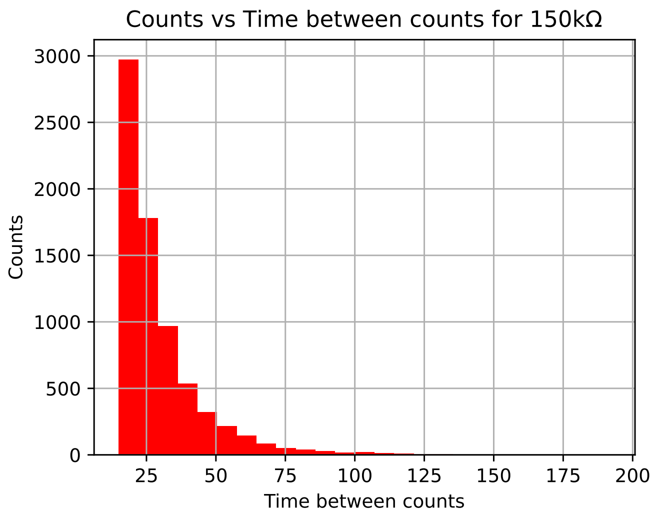

FIG. 10. Pulse distances recorded with 150kΩ quenching resistance

Taking the slope of the plot seen in Figure 11, we get the dead time value as 2.94 ± 0.20 ms

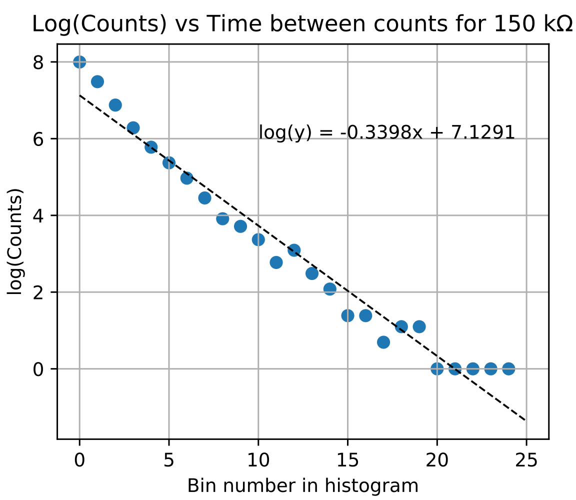

FIG. 11. Deadtime determination for 150kΩ quenching resistance ($R^2 = 0.9312$)

Now, we set the quenching resistance as 300 kΩ and record the pulse distance data.

Taking the slope of the plot seen in Figure 13, we get the dead time value as 1.32 ± 0.05 ms

Setting the quenching resistance as 450 kΩ, we thus record the pulse distance data.

Taking the slope of the plot seen in Figure 15, we get the dead time value as 1.43 ± 0.08 ms

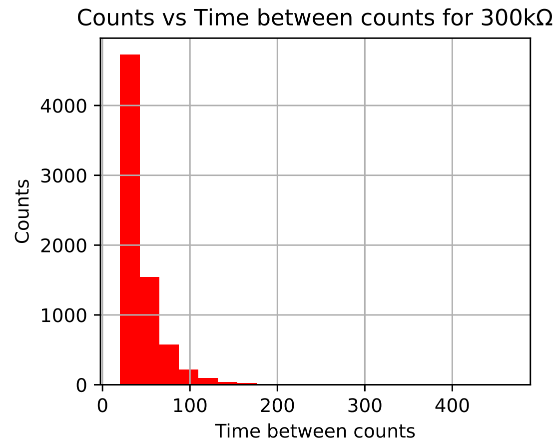

FIG. 12. Pulse distances recorded with 300kΩ quenching resistance

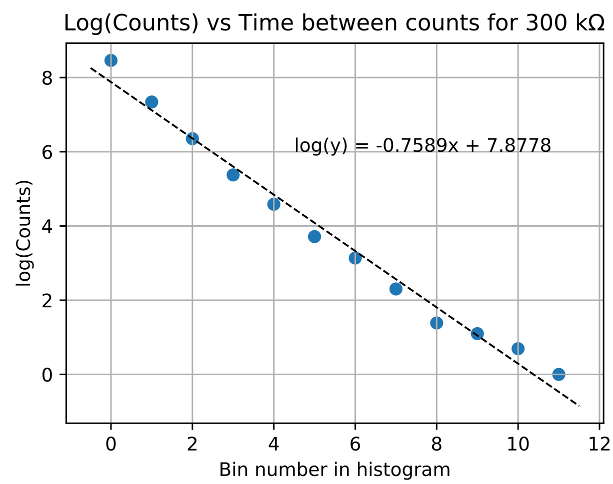

FIG. 13. Deadtime determination for 300kΩ quenching resistance ($R^2 = 0.9631$)

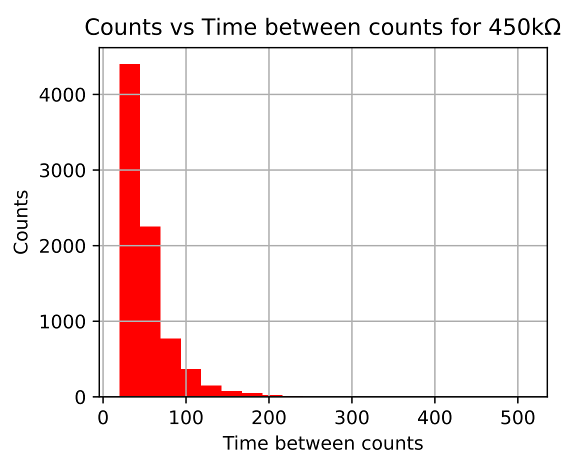

FIG. 14. Pulse distances recorded with 450kΩ quenching resistance

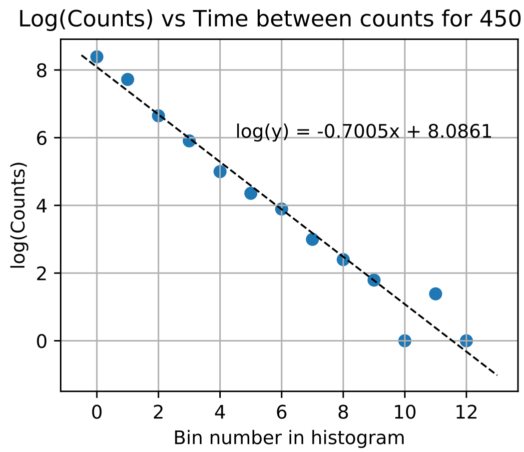

FIG. 15. Deadtime determination for 450kΩ quenching resistance ($R^2 = 0.9456$)

And finally, with the quenching resistance as 600 kΩ, we fetch the pulse distance data.

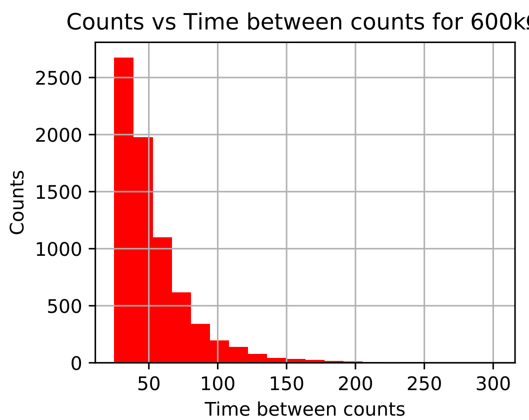

FIG. 16. Pulse distances recorded with 600kΩ quenching resistance

Taking the slope of the plot seen in Figure 17, we get the dead time value as 2.25 ± 0.10 ms.

Thus, it is seen that there is no clear trend in the variation of the time constant with the quenching resistance.

C. Time constant measurements

The time constant of the detector is obtained by taking the average pulse widths for various values of quenching resistance for the SPAD. We do this using the code shown in Figure 6. This quantity will tell us about the nature of the decay current. The slope for the average pulse width vs resistance plot allows us to find the capacitance of the detector. We multiply the quenching resistance of the circuit to this value (as $\tau = R \times C$) in order to get the time constant of the circuit.

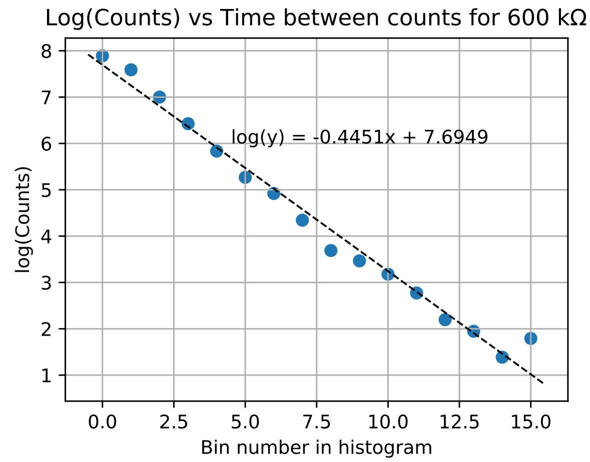

FIG. 17. Deadtime determination for 600kΩ quenching resistance ($R^2 = 0.9539$)

FIG. 18. Dead time for various quenching resistances

The average pulsewidths are plotted against quenching resistance in the following figure, wherein a linear trend is observed.

The slope is computed as $C = 0.01336 \times 10^{-9}$ F $=$ 13.36 pF. Then the time constant of our circuit, where we took the resistance to be 150 kΩ, is found to be $\tau =$ 2.004 ms.

D. Temperature dependence

The time constant of the detector is obtained by taking the average pulse widths for various values of quenching resistance for the SPAD. We do this using the code shown in Figure 6. This quantity will tell us about the nature of the decay current. The slope for the average pulse width vs resistance plot allows us to find the capacitance of the detector. We multiply the quenching resistance of the circuit to this value (as $\tau = R \times C$) in order to get the

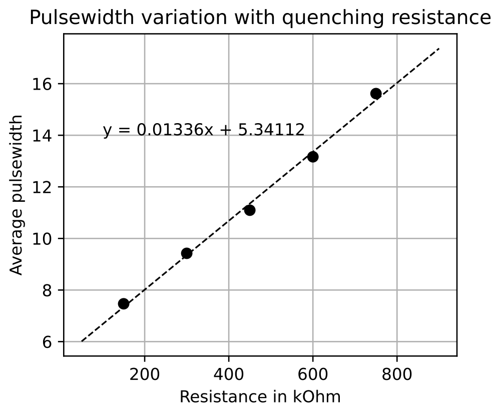

FIG. 19. Average pulse width for various quenching resistances ($R^2 = 0.9953$)

time constant of the circuit.

The average pulsewidths are plotted against quenching resistance in the following figure, wherein a linear trend is observed.

The slope comes out to be C = 0.0179 × 10-9F = 17.9 pF. Then the time constant of our circuit, where we took the resistance to be 620 kΩ, is $\tau = 11.098$ ms.

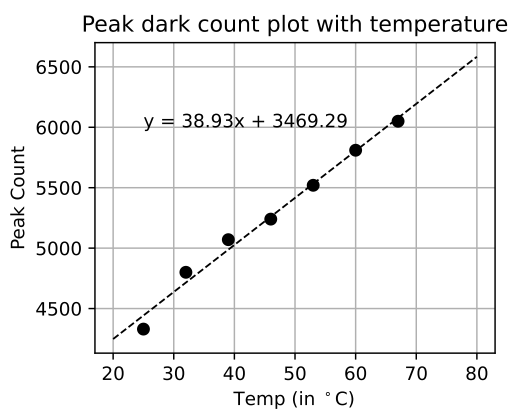

FIG. 20. Dependence of counting characteristics upon temperature ($R^2 = 0.9867$)

VI. RESULTS

- The pulse width was found to be directly proportional to the value of the quenching resistance in the circuit. The slope of the graph of pulse width vs resistance gave the effective capacitance of the circuit (calculated as 13.36 pF). The time constant (τ) was calculated to be 2.004 ms with a 150 kΩ quenching resistance.
- The variation of dead time of the detector with quenching resistance was also studied. There was no visible trend in the data.
- In the counting statistics, the frequency plots for the time intervals of 200 ms, 350 ms and 5000 ms converged to Gaussian distributions. None of the plots were able to converge to Poisson distributions.
- For the temperature variation experiment, it was seen that the average of the distribution for the counting statistics taken at each temperature varied in a linearly increasing manner with a per degrees celsius increase of 38.93 ± 0.52 counts.

VII. DISCUSSION

A. Improvements

As seen from the temperature dependence of the SPAD in our experiment, we should set the temperature lower if we are to get less thermally initiated avalanches, as these counts are, in effect, false positives. This would lead to a more reliable photon counting device.

To improve the convergence of the plots to Poisson fits, a lower biasing voltage and short time intervals can be set to record pulse counts.

Recording data for longer time intervals seems to have better results, as can be seen from the counting statistics data.

B. Further work

One could potentially try seeing the dependence of the dark counts in case of colder temperatures (0°C and below.

For investigating the behaviour in case of hotter temperatures, modifications would have to be made to the setup, since a lot of the components do not perform optimally above 100°C.

The spectral response of the SPAD can also be investigated using coherent light sources from LASERs with varying wavelengths. However, getting more than 2-3 such wavelengths is expensive using LASERs, hence one would have to improvise.

C. Tips and Precautions

- Check for loose connections, warnings from the DC supply, and for short circuits when the circuit fails to work as expected.
- Keep the bias voltage at the minimum possible value wherein pulses can be detected by the setup.
- If square pulses are not obtained at the output of the comparator, the reference voltage should be varied by changing the resistance value of potentiometer until square pulses are seen on the oscilloscope.

- Reducing the quenching resistance beyond a limit tends to introduce noise in the data, hence, 900 kΩ is usually taken as a limit when working with this LED.
- With the PID-controlled oven (or, any heating device in general), always be sure to understand in advance which surfaces get hot so that mishaps are avoided.

VIII. CONCLUSION

We explored the technique of developing an inexpensive SPAD from a reverse biased LED to some extent. Main characteristics of the setup was studied. By calculating the decay constant and dead time of the detector we traced out its behaviour in different conditions. We also studied the counting statistics of the setup at various temperatures and observed that the average count increases linearly in the temperature regime of interest.

IX. REFERENCES

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