Single-Photon Detection
SK2903 - Quantum Technology

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Abstract

In this experiment, we perform single photon detection using a superconducting nanowire. We

1 Introduction

Single-photon detection plays a crucial role in various fields of science and technology, particularly in quantum optics, medical imaging, and communications. We have seen an evolution of devices for single-photon detection over the past century after the discovery of photoelectric effect. The past decade has seen a dramatic increase in interest in new single-photon detector technologies due to its application in quantum information such as quantum key distribution [1]. Among the most common devices used for single-photon detection are avalanche photodiodes (APDs), photomultiplier tubes (PMTs), and superconducting nanowire single-photon detectors (SNSPDs) [2]. In this experiment, we focus specifically on superconducting nanowire single-photon detectors (SNSPD), fabricated from a 6nm thick NbTiN film.

Experimental setup for SNSPD consists of superconducting thin films (thickness 10 nm and below) that are patterned into nanowire structures (width on the order of 100 nm). The detector system is operated at the temperature of around 2.5K. The measurement setup is printed on the circuit board with coaxial RF connectors. Electrical feedthroughs provide electrical connections to the outside of the detector system, while optical fiber feedthroughs allow for light illumination of the superconducting nanowire sample with the help of an optical light source. To measure the voltage pulse a

The critical current I_c and critical current density J_c are two critical properties for the nanowire sample. These are the maximum values the nanowire can sustain before transitioning to a normal-conducting state. According to BCS theory, this change in behaviour is explained by the de-pairing of cooper pairs due to the kinetic energy of cooper pairs exceeding it's binding energy. Our first task is to calculate I_c for the nanowire structures for three different dimensions. We perform this task for 3 cases, one with no input light source and other two with the light sources of 850nm and 1550nm of wavelengths. Then we go on to study how does the detection count rate depends on the power of the light source. We fix the wavelength of the light at 850nm and the bias current in the nanowire at the 90% of I_c for each detector device, while changing the number of photons illuminating the detector via power source.

When the constant DC current close to the 90% of I_c is supplied through the detector device, it becomes sensitive to the external perturbation. In this state, when we hit the detector with the photons via optical fiber feedthroughs, it breaks the cooper pairs present in the detector locally. This results into the creation of a small normal-conducting region, which spreads further across the width of the wire. Once this region covers the whole width of the wire, the DC current temporarily passes through the readout electronics creating a voltage difference. This event of voltage pulse detection in the readout electronics is considered as the photon detection. We analyzed the detection pulse observed in the readout electronics with the help of oscilloscope.[3]

2 Measurements

In the first measurement task, we measure the detection count rate with respect to the bias current in the nanowire. The bias current can be controlled from the web interface of the readout electronics. We keep the range of bias current from 0μA to 50μA with the step size of 0.25μA. Opti-

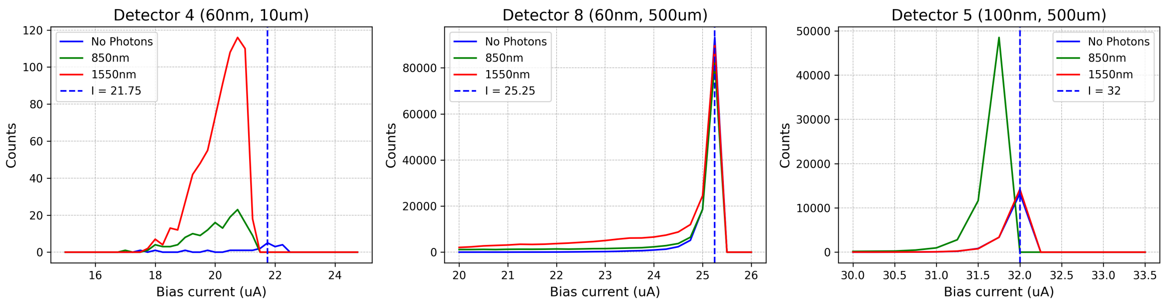

Figure 1: **Count rate as a function of bias current (μA)**. Critical current values found from the no photon case are 21.75μA, 25.25μA and 32μA for detector 4, 8 and 5 respectively.

cal light source is used to control the wavelength of the light. Before sending the signal we need to first clean the fiber end facet of any dirt particles, if present. Once the signal is sent, we wait for the bias current to increase slowly. We observe a rapid increase in the count rate as the bias current reaches closer to critical current for the detector. As soon as the bias current get past the I_c the count rate drops to zero suddenly. The critical current values obtained from the measurement can be seen in the Table 1.

Detectors	$I_c(\mu A)$	$J_c(\ 10^5 xA/m^2)$
4 (60nm x 10μm)	21.75	362.5
8 (60nm x 500μm)	25.25	8.42
5 (100nm x 500μm)	32	6.4

Table 1: Critical current

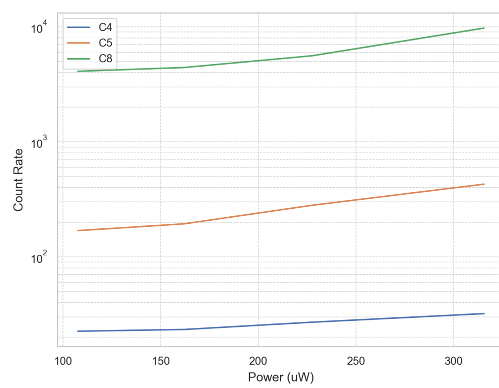

Figure 2: **Count rate as a function of Power (μW)**.

Next we fix the wavelength of the light source at 850 nm and change the power instead, from the same optical light source device. The power values used are -5.01 dB, -6.43 dB, -7.90 dB, -9.68 dB. For each power value we supply 0.9 * I_c as the bias current to the respective detector. We get repeated measurement of count rate to calculate the mean value for each power and each detector device. In fig 2, we can see the almost linear relation between the two. For plotting purpose power values has been converted from decibal to μW using below relation,

$$P = 0.001 * 10^{\frac{P(indB)}{10}} \tag{1}$$

For the third measurement, we capture the photon-detection event data. These detection pulses generates a voltage signal in the readout electronic output to the oscilloscope. We again use the same light source of 850 nm to illuminate the sample at the bias current of 0.9 * I_c. As soon as the photon hits the nanowire, we see a signal rising in the oscilloscope. This means that the nanowire is reaching normal-conducting state or the nanowire is loosing its superconducting properties. The signal reaches the peak and then starts to decay in an exponential fashion representing the return to superconductivity for the nanowire. One pulse represents a single-photon detection event. We capture atleast 200 of such events for each detectors. Although, the voltage signal for detector 4 was low and it was not possible to get a good enough reading. Therefore, we only took the readings for detectors 5 and 8.

To calculate the decay time constant (τ) for the signal pulse we fit an exponential function over the original data from the experiment. [4]

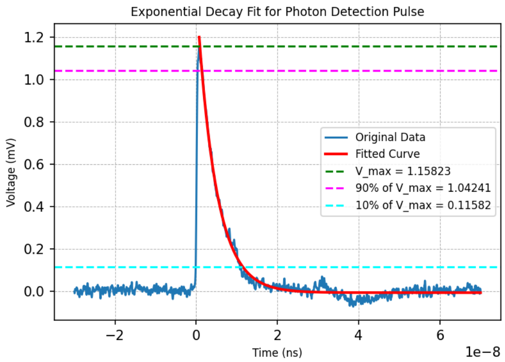

Figure 3: **Single voltage signal pulse for detector 5**.

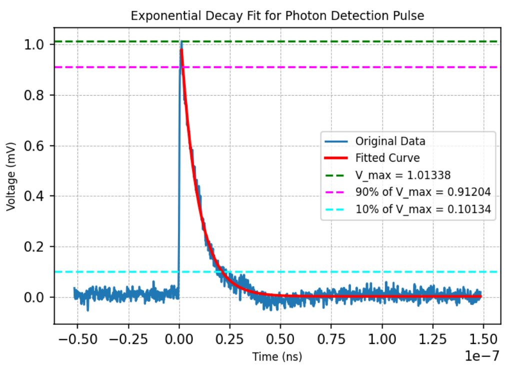

Figure 4: **Single voltage signal pulse for detector 8**.

$$V(t) = V_0 \cdot e^{\frac{-t}{\tau}} + C \tag{2}$$

Values we get for the decay constants from the fit are $\tau = 4.69$ns for detector 5 and $\tau = 8.69$ ns for detector 8. Detector 8 takes almost twice as much amount of time to decay by the same percentage as detector 5.

3 Analysis

In superconductors energy stored in the motion of charge carriers can cause the significant inductance effect. This type of inductance is called as kinetic inductance. To calculate this inductance we need to equate the total kinetic energy of the charge carriers present in the material with the energy relation for inductance.

$$\frac{1}{2} \cdot L_k \cdot I^2 = \frac{1}{2} n_s \cdot A \cdot l \cdot m \cdot v^2 \tag{3}$$

Considering,

$$I = nAvq, q = 2e^-, m = 2m_e \tag{4}$$

$$\frac{L_k}{l} = \frac{m_e}{n_s A 2e^2} \tag{5}$$

where:

- n_s is the charge carrier density of the material,
- A is cross-section area of the nanowire,
- l is the length of the wire,
- v is the velocity of the charge carriers,
- m is the mass of the charge carriers,
- L_k is the Kinetic inductance of the nanowire,
- q is the total charge of the charge carrier,
- I is the current passing through the nanowire.

Now using, eq. (5), we can calculate Kinetic inductance per unit length for any wire. If cross-section area is 100nm x 6nm and carrier concentration of $5 \cdot 10^{22} cm^{-3}$, we can use the previous equation,

$$\frac{L_k}{l} = \frac{9.1 \cdot 10^{-31} Kg}{2 \cdot 5 \cdot 10^{22} cm^{-3} \cdot 100nm \cdot 6nm \cdot 1.6^2 \cdot 10^{-38} C^2} \tag{6}$$

$$\frac{L_k}{l} = 0.592 \cdot 10^6 \frac{pH}{m} \tag{7}$$

Lets assume, to achieve a kinetic inductance of 500nH from this material we need a wire of length l. Then, from previous relation

$$\frac{500nH}{l} = 0.592 \cdot 10^6 \frac{pH}{m} \tag{8}$$

$$l = \frac{500nH}{0.592 \cdot 10^6} \frac{m}{pH} = 0.85m \tag{9}$$

In the first measrurement, the graphs obtained for 3 different illumination conditions shows a relationship between detector geometry and the count rate. Dark count rate increases when we decrease the detector width and (see fig. 1). Larger width reduces sensitivity to larger wavelength, for example detector 5 has significantly lower count rate for light source of wavelength 1550nm when compared to detector 8. The critical current values showed a proportional relation with the dimensions of the sample nanowire, which states that wider and longer wire will always have a bigger critical current. In the signal pulse measurements we saw that the detector 8 has a bigger decay constant which is actually thinner when compared to detector 5. This tells us that thinner wire takes longer to return to superconducting state than the wider nanowire. So, for shorter pulses we should aim for a wider wire.

4 Methods

The python code used for data analysis can be found in the github link.

References

[1] Hadfield, R. Single-photon detectors for optical quantum information applications. Nature Photon **3**, 696–705 (2009). https://doi.org/10.1038/nphoton.2009.230

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[4] https://docs.scipy.org/doc/scipy/reference/ generated/scipy.optimize.curve$_fit.html$