A NbTiN Superconducting Nanowire Single Photon Detector (SNSPD) on a Silicon-on-Insulator Substrate

by

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Abstract

Single photon detectors are essential part of most optical quantum information applications. Among all candidates, superconducting nanowire single photon detectors (SNSPD) have the advantages of low jitter, low dark count rates and high maximum count rate. Commercial systems based on these detector elements currently cost on order $50-100K. In this project a circular meander design of a free-space SNSPD is fabricated and tested in house. Although the absolute absorption efficiency of the detector is low, because it was fabricated on a substrate optimized for other applications, the measured and modelled values for both incident polarizations agree within the uncertainties. The bias current dependence is almost constant from 50% to 100% of the breakdown threshold value, which should allow operation at intrinsic dark count rates extrapolated to be < 1 Hz at 2.05 K.
Preface

For the work in Chapter 2 and Chapter 3, I was responsible for the entire nanofabrication process and design optimization, instructed by related lab notes left by our former postdoc Dr. Mohsen K. Akhlaghi, and was also helped by Dr. Akhlaghi himself via emails.

The idea of experiment method in Chapter 4 is mainly given by my supervisor Dr. Jeff F. Young. I was responsible for all of the optics setup for the measurements and calibration.

Data collection of the cryogenic experiment in Chapter 5 is mainly conducted by Dr. Akhlaghi. I was responsible for experiment preparation, assisting him during the experiment, and post-experiment data analysis.
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Finally, special thanks are owed to my parents, whose have supported me throughout my years of education, both morally and financially.
Dedication

To my parents
Chapter 1

Introduction

1.1 Motivation

A single photon is the known fundamental unit of electromagnetic radiation. The quantum mechanical nature of these photon states opens a whole range of novel applications in the burgeoning field of quantum information (QI). Compared to other candidates for implementation of QI systems, optical or near infrared frequency photons offer many advantages: carrying no charges, there are less unwanted interactions with matter, so they can be transported over macroscopic distances in low-loss waveguides, etc [24].

Most potential applications based on single photons, require detectors that have high-efficiency, low timing jitter, low dark count rates, and high maximum signal count rates. Superconducting nanowire single photon detectors (SNSPD) represent one promising category of such detectors that have been a topic with growing interest in the past twenty years.

1.1.1 Call of Quantum Information

Areas where QI may have an impact ranging from metrology, through secure communication, and all the way to universal quantum computing. Although this application sector is in its infant stage of development, a handful of entry-level commercial ventures already exist.
Quantum key distribution (QKD) [7] is one of most mature QI applications, and is already commercialized by some companies, such as ID Quantique, MagiQ Technologies and so on. It provides unconditioned secure communication that is guaranteed by laws of physics (quantum mechanics). Especially with the BB84 protocol, metropolitan QKD networks have been built and tested [29].

In this protocol, the security stems from quantum indeterminacy and no-cloning theorem. No-cloning theorem states that it is impossible to create an identical copy of an arbitrary unknown quantum state, so that any eavesdropper has to make a direct measurement on the communicating quantum states to learn information about them. Quantum indeterminacy states that a measurement of a quantum state can in general have an indeterministic result and disturb the state, unless the state is an eigenstate of the measurement. BB84 exploits these physics to detect the eavesdropper and distribute secure keys.

For BB84 to work, two pairs of orthogonal basis (of the same 2-dimension Hilbert space) are chosen, for example, the rectilinear basis (horizontal and vertical direction) and the diagonal basis (45°and 135°direction) of photon polarizations. For each pair, the bit information 0 and 1 is encoded by preparing the photon in two basis states respectively, as shown in Figure 1.1.

**Figure 1.1:** Two chosen basis and states for encoding information in single photon states.
There is a conjugation relation (in Dirac bracket notation) between the two sets of basis:

\[
|\uparrow> = \frac{\sqrt{2}}{2}(|\nearrow> + |\swarrow>) \\
|\rightarrow> = \frac{\sqrt{2}}{2}(|\nearrow> - |\swarrow>) \\
|\nearrow> = \frac{\sqrt{2}}{2}(|\uparrow> + |\rightarrow>) \\
|\swarrow> = \frac{\sqrt{2}}{2}(|\uparrow> - |\rightarrow>).
\]

The information can be extracted exactly by measuring the photon with respect to the same pair of states, but measurements with the wrong pair will have a 50-50 probability of getting either 0 or 1 and leave the photon in a corresponding state of the wrong pair.

In practice, suppose Alice (the sender) wants to generate and share a secret key with Bob (the receiver), she encodes random bit information to photons, and for each bit, she uses a random pair of basis from the two discussed above, and sends them to Bob via a quantum channel. Bob measures these photons choosing different basis also randomly. After transmission is finished, they discuss only the basis they used to encode/measure photons through a public channel, and only keep bits that are encoded/measured with the same pair of basis, for these bits held by both parties should be identical in theory.

Then they compare a subset of the selected bits through public channel and check for the error rate (there should be an expected instrumental error rate), and discard these bits afterwards. If a third party Eve (the eavesdropper) intercepted the quantum channel and measured photons, she will have 50% probability altering the photon state when measuring it with the wrong pair of basis, which results in an increased error rate, and thus can be detected. If the error rate remains under a threshold level, then remaining bits
will be subjected to a reconciliation [8] process for error-correction, and then be applied by a universal hash function to generate a shorter key for privacy amplification, such that Eve has negligible knowledge about this final key. Otherwise if the error rate is beyond the threshold level, Alice and Bob will just abort the communication and try with another quantum channel.

Clearly for this protocol to work, detectors capable of reliably recording single photon absorption events are required. Deficiencies in the quantum efficiency and/or significant spurious dark count rates of such detectors will seriously compromise the potential data rate at which this protocol can be operated.

Besides QKD, there are other QI applications that rely on SPDs of good performance, such as linear optical quantum computing (LOQC) [19]. LOQC is one ultimate QI goal. It still remains distant, because it has very strict requirements for single photon sources and detectors. For detectors, it requires scalable SPDs of detection efficiency (ratio between accurately detected photon count rate and photon input rate) of at least 2/3 [33], which is achieved only recently [21].

### 1.1.2 Why SNSPD

Single photon detection is not a new subject, and to date conventional SPDs mainly consist of photomultiplier tubes (PMT) and single-photon avalanche photodiodes (SPAD) [12].

The main body of a PMT is a vacuum tube, inside which is a photocathode followed by a focusing electrode, a sequence of electrodes with increasing bias voltages (called dynodes) and an anode, as shown in Figure 1.2. If photons to be detected have an energy exceeding the work function of photocathode material, photoelectrons (called primary electrons) will be emitted from the photocathode due to photoelectric effect. These primary electrons get focused by the focusing electrode, then accelerated by and collide with the dynodes, which release more electrons (called secondary electrons). Since each dynode is biased at a voltage higher than the
previous one, secondary electrons get multiplied and thus amplify the initial signal and allow single photon detection.

An SPAD is in essence an reversely biased p-n junction (p side negative and n side positive), as shown in Figure 1.3, with a very high voltage, creating a large depletion region at the interface. This high voltage is supposed to be well above the breakdown voltage of the p-n junction, so once an extra single charger carrier is added to the depletion region, it will gain large kinetic energy due to the strong field and knock off other bound charges that will then also get accelerated, thus triggering the avalanche effect, creating a macroscopic detectable current. The triggering primary electron can be either photo-generated by the absorption of a single photon (ideal case), or thermally generated (a source of dark counts).

PMT and SPAD work in a similar way; they both rely on electron cascade and multiplication effect to give a significant amplification of the single photon signal, which inevitably can have large time lag and jitter[31]. Their count rate is also low. Furthermore, the optoelectronic effects ex-
exploited to turn a photon into electric signal depend on the work function (PMT) and band gap (SPAD), which are constrained by materials. It will also be very challenging to detect a telecommunication wavelength photon (with lower energy): with low work function/band gap materials, unacceptable noise (dark counts) due to thermal fluctuations can be an intrinsic draw-back for these detectors. Cooling technology has been applied to help reduce dark count, but temperature is usually restricted to be above 200 K for normal operations. For the reasons stated above, conventional PMTs and SPADs capable of detecting infrared photons usually have a jitter of hundreds of picoseconds, maximum count rate of $KH_\text{z}$ to tens of $MH_\text{z}$, and $KH_\text{z}$ level of dark count rate.

On the other hand, SNSPDs are made of metallic superconductors that have picosecond level optoelectronic response [30], and connected to fast electronics, which can limit jitter to tens of picoseconds. Short reset time leads to a maximum count rate that can easily reach $GH_\text{z}$ level. Moreover, cryogenic environment guarantees low noise: dark count rates usually at below 100 $H_\text{z}$.
1.2 Detection Mechanism

In contrast to PMT and SPAD, the photon detection mechanism of SNSPD is based on the breakdown of superconductive state of a material. When a superconducting material is cooled below a certain characteristic temperature $T_c$ (critical temperature), the resistivity of the material suddenly drops to zero. However, this state can be destroyed when current density in the material is greater than a characteristic $J_c$ (critical current density). For a nanowire with fixed cross section, $J_c$ corresponds to a characteristic $I_c$ (critical current). For a fixed $J < J_c$ flowing through a superconducting nanowire with $T < T_c$, a single photon can locally disturb the material superconductive state and cause it to go normal in the vicinity of the absorption event [14].

![Formation of resistivity barrier. Arrows indicate current density.](image)

**Figure 1.4:** Formation of resistivity barrier. Arrows indicate current density. Figure taken from [31]

Combining the above two effects allows formation of a detectable resistive barrier on a superconducting nanowire, as shown in Figure 1.4. Firstly, the nanowire is kept at a temperature much lower than $T_c$ so that it is in the superconductive state. Then the nanowire is DC biased at a current close to $I_c$. When a photon is absorbed by the nanowire, a localized non-superconducting 'hot spot' with finite size is generated, which gradually grows and forces super current to go around it. As a result, local current...
densities on both sides of the 'hot spot' become higher, and when they exceed $J_c$, that entire region turns non-superconducting, forming a resistive barrier [31].

Moreover, because of high mobility carriers in superconductor, there is another important physical quantity: kinetic inductance $L_k$. Since charge carriers in the superconductor have inertia mass, it will take a finite time for a change in electromotive force to effect the dynamics of these carriers, which means the wire behaves like an inductor in the circuit.

$L_k$ and the formation of a resistive barrier can be exploited to implement single photon detectors. The schematic diagram in Figure 1.5 shows the basic idea behind the operation of an SNSPD. The SNSPD is represented in circuit form by the green box, and is DC biased by a current close to $I_c$. When no photon is absorbed, the switch is closed, and $R_b$ is short-circuited (superconducting state, no resistance). The case where a photon is absorbed and a resistive barrier formed corresponds to opening the switch. The resulting $LR$ circuit will then have a high frequency signal that can be picked up by the amplifier and fed to the counter. Furthermore, energy relaxation time constants for those resistive barriers are generally in picosecond range, resulting in $GHz$ maximum counting rate [31].

![Figure 1.5: Schematic implementation of SPD using superconducting nanowire. Elements in green dashed box is an analogy to the nanowire.](image)
Given this detection mechanism, there are two main factors for efficient single photon detection: absorption by nanowire and formation of effective resistive barrier. The first factor depends on the geometric structure of the SNSPD and the imaginary permittivity of the material. As for geometry, most SNSPD designs naturally take a meander structure with a detecting area matching the light modal area of a single mode optical fibre at the operating wavelength, for example, Figure 1.6. As for materials, NbN, NbTiN and WSi are often chosen because of their low superconducting energy gap.

![Figure 1.6: A meander design SNSPD. Figure taken from [31]](image)

The second factor depends on the bias current density. Since the formation of resistive barrier starts from the initial 'hotspot', for the same material and bias current density, photons with lower energy (long wavelength) can create a smaller 'hotspot', and thus they are less likely to be detected. However, if the bias current density is brought too close to \( J_c \), intrinsic dark count rate will grow exponentially due to current-assist vortex-antivortex pair unbinding. Therefore, narrow nanowires (usually < 100 nm for NbN/NbTiN) are required to enhance photon detection while keeping intrinsic dark count rate low.
1.3 State-of-the-art

1.3.1 SNSPD in Cavity

As mentioned in the last section, absorption of light is a crucial factor for SNSPD performance. Performance of a simple design as in Figure 1.6 will be largely limited by reflection and transmission of incident light. One way to enhance absorption is to make use of an optical cavity.

An optical cavity traps light. The simplest example is the Fabry-Perot resonator, where two highly reflective mirrors are held close together. Embedding the SNSPD inside such a cavity can boost absorption.

Figure 1.7 shows such a design using silica and gold mirrors to form a cavity, which boosted the detection efficiency of a normal NbN SNSPD from below 10% to 57% at wavelength 1550 nm [28].

![Figure 1.7: SNSPD embedded cavity. ARC is anti-reflection coating. Figure taken from [28]](image-url)

A more recent design of the WSi SNSPD, using stacks of dielectric layers to form the cavity, further increased detection efficiency to over 90%
at a wavelength 1550 nm [21].

1.3.2 Waveguide SNSPD

The SNSPDs discussed so far are all free-space detectors, where the light to be absorbed is incident normal to the plane of the meander detector, either from free space or from a single mode fibre.

![Figure 1.8: Schematic diagram of a TW detector. Figure taken from [26].](image)

In photonic integrated circuit (PIC), conventional bulk optical elements such as beam splitters, resonators, waveguides as well as SPDs, can be integrated to a simple chip, making scalable QI applications possible.

Different from free space or fibre optics, in PIC light propagates in on-chip slab waveguides, or even photonic crystal waveguides [16]. Conventional implementation of a waveguide SNSPD follows a travelling wave fashion (TW detector), where the nanowire simply lies atop the waveguide. An example of TW detector is shown in Figure 1.8. However, most of the light is confined inside the waveguide and only weak evanescent light outside the waveguide can be absorbed by nanowires. Therefore, for such design long enough waveguide and nanowire have to be chosen to ensure a high absorption, resulting in a big footprint, higher dark count rate, etc. For the design shown in Figure 1.8, in order to get a absorption of > 95%,
the nanowire needs to be as long as 20 µm [26].

Figure 1.9: Coherent perfect absorber SNSPD. Superconducting nanowire lies atop a one-dimensional photonic crystal cavity, scale bars are 200 nm for a) and 1 µm for b). Figure taken from [4].

The waveguide SNSPD can also be implemented with an optical cavity. The detector in Figure 1.9 is designed and fabricated in this group earlier by Dr. Mohsen Akhlaghi. The geometry of the nanowire and photonic crystal cavity are carefully chosen to create a coherent perfect absorber (CPA). Such a design ensures a unity absorption of the nanowire, while keeping a compact footprint [4].

Cavity-SNSPDs mentioned previously and CPA-SNSPDs share the similar idea where SNSPDs are put inside cavities to enhance absorption. However, design approaches are different. Cavity-SNSPD cavities are simply Fabry-Perot cavities made with stack dielectrics. CPA-SNSPDs cavities are designed based on temporal coupled-mode theory [16] and can achieve a theoretical unity absorption.

1.3.3 Multiplexed SNSPD Array

The multiplexed SNSPD array bias multiple SNSPDs independently and illuminate light broadly to this 'multi-pixel' detector. This scheme can decrease detector dead time dramatically, since even if one SNSPD 'fired', other SNSPDs can still register photons, which gives a much higher maxi-
Furthermore, multiplexed SNSPD can even count the number of photons incident in one pulse, while SNSPDs described above can only distinguish the state of 'zero photon' and 'one or more photon' of a pulse. In some advanced QI protocols, SPDs should not only be able to detection photons efficiently, but also be photon number-resolvable [20].

Figure 1.10 is an example, which can count up to 6 photons. Recently a 64-pixel multiplexed SNSPD Array has also been reported [5].

1.4 About This Project

In this project, a free-space meander SNSPD is designed, fabricated and tested in house. Commercial single photon detection systems (free-space) based these elements cost the order of $100K. Since we have the in-house nanofabrication capabilities, and the electronic circuitry (designed and made in the earlier CPA-SNSPD project) for building our own detection system, we wanted to see how easy it would be to make good free-space detectors in house. The purpose of this thesis was to sort out the fabrication steps, before getting special, custom-made substrates with cavities as described in Section 1.3.1.

The design is adopted from [3], as shown in Figure 1.11, which is orig-
inally designed for detecting infra-red photons.

![Meander SNSPD designed by Dr. Akhlaghi. Figure taken from [3].](image)

**Figure 1.11:** Meander SNSPD designed by Dr. Akhlaghi. Figure taken from [3].

In the original design, Nanowires (NbTiN) are 80 nm wide, with a filling factor of 33% and the detecting area diameter was 12.6 µm, fabricated on a silica thin film (with thickness being a silica quarter-wavelength of the target wavelength $\lambda = 1550\,nm$) deposited on a silicon substrate.

This project takes the same nanowire width and filling factor, but decreases the detecting area size to match light spot of visible source (He-Ne laser $\lambda = 632.8\,nm$), and extended the dummy lines area (to be discussed in Chapter 3) to increase the quality of nanowires. The current detector was fabricated with NbTiN coated silicon-on-insulator (SOI) chips (to be discussed in Chapter 2).

The rest of this thesis is organized as follows. Chapter 2 describes the nanofabrication processes of the detector chip, Chapter 3 discusses reasons and methodology of the SNSPD design, Chapter 4 covers experimental set-ups and methods for reliable measurements, Chapter 5 presents the experimental/simulated data and discussions regarding these data, and finally Chapter 6 gives a summary of the project and future work.
Chapter 2

Fabrication

2.1 General Procedure

The SNSPDs were fabricated from SOI wafers (200 nm thick silicon top layer and a 1270 nm thick silica buried oxide layer) coated with 8 nm thick NbTiN layers (STAR Cryoelectronics Inc.), as shown schematically in Figure 2.1. This chapter explains methods and machines that are used to fabricate the detector chip. Chapter 3 will explain the detailed design idea of the detector.

The superconductor coated SOI wafer was spin-coated with acetone-soluble photoresist for protection, and diced into 7 mm x 7 mm chips. From that, all fabrication procedures were finished in house.

![Layer Structure](image)

**Figure 2.1:** Cross section layout out the of superconducting chip (not to scale).
Because of the delicate thin layer of the superconductor, chips must be handled with great care, and most manual processes happened in cleanrooms located within the AMPEL building (one class 1000 cleanroom and one class 10000 cleanroom).

The following subsections outline basic fabrication steps. Detailed explanations on the major steps such as E-beam lithography (EBL), E-beam evaporation and plasma etching are in next three sections.

2.1.1 Sample Preparation

The chip was first blown with a nitrogen gas gun ($N_2$ blow) to remove possible flakes coming from the dicing process. Those flakes may cause scratches on the surface, and thus have to be removed. Then, the chip was soaked in deionized water (DI) water, and underwent a 2-minute ultrasonic wash to further remove possible flakes.

The chip was then given a 2-minute ultrasonic wash in acetone to remove the protecting photoresist, then a 2-minute ultrasonic wash in isopropanol (IPA) to remove the acetone, then a 2-minute ultrasonic wash in DI water to remove the IPA.

After that the chip was taken out and $N_2$ blown to remove residual DI water. Finally, the chip was placed on a hotplate at 100 °C for 1 minute to dehydrate the surface.

At this point, the chip should be visually checked under the optical microscope to make sure no visible dirt or scratches remained on the surface. If there was residual dirt, the previous cleaning sequences were repeated.

2.1.2 Positive Electron Beam Lithography

A schematic flow diagram for this crucial lithography step is shown in Figure 2.2. The dehydrated clean chip was spin-coated with 500 nm of ZEP520A (ZEON Corp.) as a positive e-beam resist. The spin-coating was done using a HEADWAY PMW 32 spinner, operated at 3000 ramps per minute (r.p.m), followed by a 3-minute hard baking on a hotplate at 180 °C.
Since the expensive resist was long passed its expiration date, the r.p.m for the desired thickness was found via trial and error, and it was not consistent with reported value in the original material datasheet.

Twelve sets of contact pads and alignment marks were defined through EBL, with the extra-high tension (EHT) voltage set to 25 kV, and a dose of 120 $\mu$C/cm$^2$ (more details in Section 2.2). Our e-beam lithographer is based on a Zeiss Sigma$^TM$ Field Emission Scanning Electron Microscopy (FESEM), controlled by Nanometer Pattern Generation Software (NPGS) [2] for EBL.

The chip was then developed in o-xylene, followed by ultrasonic cleaning in IPA and DI water for 30 seconds respectively.

2.1.3 Electron Beam Evaporation and Lift-off

Metal needs to be deposited on the uncovered regions from the last step to form real contact pads and alignment marks.

The chip was first rinsed in 40:1 $H_2O:BHF$ (7 : 1 buffered hydrofluoric acid) solution for 1 minute to remove any oxidized layer on the NbTiN surface, so that better Ohmic contact can be achieved later. The chip was then immediately transferred to the evaporation chamber of a DEEWONG-2000 e-beam evaporator, and an 8nm/90nm of titanium-gold bilayer was deposited onto the chip (more details in Section 2.3).

After deposition, the lift-off was performed by soaking in sonicated chlorobenzene for 1 minute. The chlorobenzene could remove unexposed
After e-beam evaporation

After lift-off

Figure 2.3: Schematic process for metal deposition

ZEP and corresponding deposited metals. The lift-off was followed by 30 seconds in sonicated IPA and a 30 seconds DI water cleaning. A schematic summary of this process is shown in Figure 2.3.

2.1.4 Negative Electron Beam Lithography

Meander nanowires were defined using EBL. However, this time the same resist ZEP520A was used as negative resist, i.e., exposed region remains after development (more details in Section 2.2).

Anisole-diluted ZEP520A was spin-coated on the chip at 2200 r.p.m to get a 150 nm thickness, followed by a 3-minute hard baking on a hotplate at 180 °C.

Then nanowires were patterned by EBL at 25 KV EHT and 100 mC/cm², and developed in chlorobenzene. A schematic diagram of the nanowire lithography process is shown in Figure 2.4.

Figure 2.4: Schematic process for positive EBL
2.1.5 Plasma Etching

The final step was to etch through the unprotected NbTiN layer to form superconducting nanowires, using a PLASMAQUEST Electron Cyclotron Resonance (ECR) etcher. The cross section of the final chip is as shown in Figure 2.5.

Since the etch rate at narrow trenches could be slower than a flat surface, the etching recipe was calibrated by etching through 8 nm thick NbTiN and 10 nm thick silicon on a dummy chip. After this step, the nanowires have ~100 nm thick ZEP on top for protection. The gas flow rates were \( CF_4 : O_2 = 15 : 2 \) etch, with chamber pressure 30 mTorr and RF power 50 W, for 75 seconds (more details in Section 2.4).

![Figure 2.5: After plasma etch](image)

Figure 2.6 gives an optical image of part of a final chip.

![Figure 2.6: Optical image of a final chip. 3 out of 12 devices on one chip are shown. Each device has two large contact pads on both sides (blue C marks one set of contact pads) of and connecting to a centre detector (marked in blue circles). Scale bar is 100 \( \mu m \).](image)
Figure 2.6 gives an SEM image of one full meander SNSPD.

Figure 2.7: SEM image of one full detector. Scale bar is 2 \( \mu m \).

2.2 Electron Beam Lithography

Electron beam lithography can pattern custom two dimensional patterns in thin electron-sensitive resist layers by exposing them to a focused electron beam that is scanned over the surface in a computer-generated pattern, with a computer-controlled electron dose. [22]. Compared to traditional photolithography in the silicon industry, EBL has a higher resolution and is maskless. However, EBL is limited by its low throughput and mainly used in research and development.

Typical commercial EBL systems are very expensive, so this project utilized a field emission scanning electron microscope with the beam position and scan speed controlled by a commercial pattern writing software system (NPGS). At an accelerating voltage of 20 \( kV \), the Gaussian electron beam focus has a diameter of nominally <5 \( nm \).

One key parameter in EBL is the dose, as defined by the total charge incident per unit area. The charge is controlled by the dwell time of the e-beam at each pixel for a certain value of beam current. For our EBL system, a square e-beam write field is discretized into \( 2^{32} \) square lattice pixels, which gives a minimum point-to-point spacing. However, this minimum spacing is not always available. For a given beam current and area dose, smaller point-to-point spacing leads to shorter beam dwell time per pixel,
but this pixel dwell time has to be above a lower limit that the system can handle, in our case ~0.2 \( \mu \text{sec} \).

The write field size were chosen empirically. For writing contact pads, a write field size of 1425 \( \mu \text{m} \times 1425 \mu \text{m} \) was chosen as to include contact pads and alignment marks of 3 devices in a column (as shown in Figure 2.6), which gave a minimum point-to-point spacing of 21.74 \( \text{nm} \). For writing nanowires, the write field size was 71 \( \mu \text{m} \times 71 \mu \text{m} \) to include 1 nanowire detector, corresponding to a minimum point-to-point spacing of 1.09 \( \text{nm} \).

![Figure 2.8: Image of a small part of contact pads and two alignment marks after development. Nanowires will be pattern between contact pads and connect with them. Scale bar is 10 \( \mu \text{m} \).](image)

When first patterning contact pads and alignment marks, ZEP is used as positive resist. The accelerated electrons hit the ZEP and break the polymer into small segments with lower molecular weight, increasing the solubility in the developer (O-xylene in this case).

The fabrication requires two separate EBL processes on the same chip, where patterns from the two process have well defined relative position, i.e nanowires should connect with corresponding contact pads. To align the second write field to the first, only small regions in the vicinity of the gold alignment markers, formed in the first stage of the process, are exposed to the imaging SEM beam. By comparing the imaged regions with the known alignment marker pattern, in three separate alignment marker regions, the offset and rotation of the coordinate system is corrected before writing the second pattern at higher resolution than the first. An image of two alignment
marks is shown in Figure 2.8. This whole alignment procedure can ensure a position precision of submicron level.

When patterning nanowires, it is better to use a negative EBL exposure technique, because of both writing convenience and final etching process. In this process, a much higher electron dose is applied in areas that one wants the resist to remain after development. At these high doses the polymer actually cross-links, rather than fractures, and hence becomes more difficult than the unexposed resist to dissolve in the resist remover (chlorobenzene in this case).

Extra care must be taken when patterning nanowires, since the designed nanowire width of 80 nm is close to the linewidth limit constrained both by the type of resist and the EBL system. Normally, the e-beam will draw a polygon in raster style, starting with one edge, and sweeping parallel to that edge. However, in the nanowire case, such a raster style results in rough edges. Therefore, when patterning a nanowire, the approach is that the e-beam scans along the wire back and forth, as shown in Figure 2.9.

When nanowires encounter a 180-degree bend, more careful considerations are needed, where the design was mainly to account for current crowding effect (to be elaborated in Section 3.2), and the writing scheme to avoid big beam jumps in writing (Section 3.4).

2.3 Electron Beam Evaporation

Thin metallic films are typically deposited using an electron beam evaporator. The target material sits in a water-cooled crucible that resides in a vacuum chamber typically kept below a pressure of ∼5 µTorr. Electrons are extracted from a hot filament and accelerated to bombard the target material at an energy of ∼30 KeV, causing the material to vapourize. The evaporated metal impinges and sticks to the sample which is suspended above the crucible, forming a thin film on the sample surface.

In this project, metals were deposited onto the chip after contact pads and alignment marks were uncovered by the first development process on
Figure 2.9: Raster style schematics. Black dashed line indicates the designed polygon to be write. Blue arrows show the beam sweeps. Red dotted line is the preceding direction of sweeps

the ZEP layer patterned using positive exposure.

Gold does not stick particularly well to silicon, therefore an 8 nm thick of titanium layer is first deposited, to which a 90 nm thick layer of gold bonds well. The total thickness of metal needs to be comparable to or thinner than the thickness of negative resist used in the second lithography step. When patterning nanowire detectors, the nanowire pattern will extend out and overlap with contact pads to make good connections. If contact pads are much thicker than resist, the connection may break and the superconductor underneath the broken area may not be protected and get etched away in the final process, as shown in Figure 2.10.

Figure 2.11 shows an SEM image taken after metal deposition, showing a continuous connection across the resist layer has been achieved.
2.4 Plasma Etching

Dry plasma etching has the advantage of a highly anisotropic etching profile and a small amount of reactants (gaseous) and byproducts, as compared to wet etching [23]. For the PLASMAQUEST ECR etcher used in this project, reactant gases are first ionized in the ECR chamber by electron cyclotron resonance effect, which generates even denser plasma than usual reactive ion etcher (RIE).

The main chamber was first pumped to < $10^{-7}$ torr. Flow rates of reactant gases $CF_4$ and $O_2$ were adjusted to 9 and 1.2 sccm respectively, and the operating pressure was set to 30 mtorr. Microwave power was then applied to resonantly ionize a dense plasma, and then an RF field was applied to the sample chuck to apply a (rectified) accelerating voltage for ions of the plasma to strike surface of the sample to be etched. Figure 2.12.

Plasma ions will be accelerated and drive plasma toward the sample,
where both sputtering (by ions) and chemical reaction (with plasma radicals) contribute to the etching process.

In the etching recipe, $CF_4$ can give effective plasma etching of both NbTiN and silicon, while a small portion of $O_2$ can remove possible byproducts, mostly carbon. The primary reactive plasma components are:

$$CF_4 + e^- \rightarrow CF_3^+ + F,$$

so the superconductor and silicon are removed by reacting with fluorine radicals and volatile chemicals such as $NbF_5$, $TiF_4$, $SiF_4$ and so on.
Chapter 3

Design

3.1 Design Overview

Given the basic detection mechanism as addressed in Chapter 1, one naturally concludes that: (1) the nanowire meander pattern should be as dense as possible, i.e., a very high filling factor (the ratio of nanowire width over meander pitch), to maximize the photon absorption rate; (2) the narrower the nanowire of an SNSPD is, the more likely a single photon absorption event will cause the wire to transition into the normal state, especially for long-wavelength photons that carry less energy to create large enough local hotspots.

The overall layout of the detector design is shown in Figure 3.1, which is a modified version of Dr. Ahklaghi’s design [3], as mentioned in Section 1.4. The active detecting area is the central part, about 10 microns in diameter: it is designed to match the spot size of the focused input laser. Surrounding nanowires are dummy lines included to minimize proximity effects on the perimeter of the main detector meander. The width of the straight sections of the nanowires is 80 nm and the pitch is 240 nm. The 180 degree turns at the ends of the nanowires are carefully designed to avoid current crowding, as discussed in Section 3.2. The input and output ends of the meander wire flare out and connect to large contact pads that are not
shown here.

**Figure 3.1:** Layout of the design.

### 3.2 Current Crowding

Many early meander detectors suffered from a large suppression of the critical current density compared to its bulk value. The cause of this behaviour, which was referred to as 'constriction' [17], was identified in 2011 [2011] when Clem and Berggren pointed out that unless carefully shaped, the 180 degree bends at the ends of the wires will experience "current crowding" [10], or a local increase in the current density over its value in the straight sections of the wire.

Current crowding is not a new concept. In 1963, Hagedorn and Hall showed, by means of conformal transformation, that when current in a strip conductor meets a right-angle turn, the current density is higher on the inside corner of the bend than on the straight strip, for both normal metals and uniform thin superconductors [13]. This fact directly results in the suppression of critical current for SNSPDs.

However, Hagedorn and Hall also showed in the same paper that this suppression at the bend could be eliminated by smoothly shaping the inner boundary, so that the resulting current density is equal or less than that
on the straight strip. The optimal bend shape is usually nontrivial, and it typically limits the maximum practical filling factor. In fact, to avoid current crowding at the 180-degree bend, the filling factor should be no more than 33% [3].

For thin and narrow superconductors, as in this project, the sheet current density $\mathbf{K}$, to a good approximation, satisfies $\nabla \cdot \mathbf{K} = 0$ and $\nabla \times \mathbf{K} = 0$ [10]. In this project, the MATLAB® PDE (Partial Differential Equation) solver is used to numerically find the optimal geometry for a 180-degree bend connecting two 80 nm wide wires by solving the analogous electrostatic problem. The "electric" potential associated with $\mathbf{K}$ is solved for using appropriate boundary conditions, and its gradient yields the desired $\mathbf{K}$.

Figure 3.2: Top view of boundaries of the 180-deg bend. Red boundaries are imposed with Dirichlet boundary conditions and blue boundaries imposed with Neumann boundary conditions. Dashed arrows indicate assumed input/output.

With reference to Figure 3.2, let $\mathbf{n}$ be the normal vector of corresponding boundaries, then we require that $\mathbf{K} \times \mathbf{n} = 0$ on the red (input and output) boundaries, and that $\mathbf{K} \cdot \mathbf{n} = 0$ on the blue (lateral) boundaries. Without loss
of generality, we apply boundary conditions:

\[ V = 1 \quad \text{(upper red edge)} \]  
\[ V = 0 \quad \text{(lower red edge)} \]  
\[ \nabla V = 0 \quad \text{(blue edges)}, \]

where \( V \) is the scalar potential for \( \mathbf{K} \). Streamlines of \( \mathbf{K} \) can then be plotted, as shown in Figure 3.3.

\[ \text{Figure 3.3: Calculated streamlines of } \mathbf{K} \text{ with boundary conditions given in Figure 3.2. Black solid lines correspond to the boundary geometry, and dashed lines (red and blue) are streamlines of } \mathbf{K}. \]

The streamlines in the uniform input and output sections are equally spaced, indicating a uniform current density in the straight wire regions. Inside (outside) the inner red streamline in Figure 3.3, the current density is higher (lower) than in the wire. Therefore, an 80 nm wide wire with boundaries defined by both red streamlines will have the highest current density in the uniform wire regions. The resulting pattern (fabricated example shown in Figure 3.4) has a filling factor in the uniform wire region of 33\% (80 nm wide wires on a 240 nm pitch).
3.3 Proximity Effect

With reference to Figure 3.5, the ideal electron beam for lithography purposes would be focused to the smallest spot size allowed by the machine, on the Photoresist mask material, and all of the modification of the resist by the electrons would be limited to the material within that focused spot (typically just a few nanometres). However, electrons scatter from the resist and backscatter from the underlying substrate, modifying the resist over an area considerably larger than the focused spot size. These scattered electrons thus modify the overall pattern of exposed resist from the pattern that the computer directs the beam to follow. For instance, if trying to write a set of parallel 80 nm lines on different pitches, the closer the pitch approaches 80 nm, the wider the individual wires will become, due to excess exposure from adjacent wires. This phenomenon is known as the "proximity effect".

There are two types of scattering happening when an electron beam is incident on the chip: forward scattering and back scattering. Each of them approximately gives a 2-dimensional Gaussian exposure profile around the incident point, with $1/e$ radii being $\sigma_f$ and $\sigma_b$ respectively [25]. Forward scattering occurs when the beam electrons collide with electrons attached to atoms in the resist or substrate. During the collision, electrons from atoms get excited or even ionized, and the incident electrons lose energy and their
trajectory can deviate from the original direction for some angle. For this kind of rather inelastic collision, the deviation angle is generally small. The effect of forward scattering can be estimated according to the empirical equation [27]:

\[ \sigma_f = 0.9 \left( \frac{R_t}{V} \right)^{1.5}, \]  

where \( R_t \) is the resist thickness in nm and \( V \) is the EHT voltage of the electron beam in kV.

In this case, given the ZEP thickness of about 156 nm and the EHT voltage of 25 kV, \( \sigma_f \) is roughly 14 nm. Since the spacing between nanowires are designed to be 160 nm, there should be little influence of these inelastically scattered electrons from writing one wire, on the adjacent wire. Thus the actual dimensions of the nanowires in the meander pattern should be almost unaffected by this inelastic scattering (i.e. they should retain the dimensions programmed into the beam patterning software).

The real problem comes from back scattering, when the incident electron beam collides with a heavy nucleus, especially those in the substrate. Such collisions are elastic, so electrons retain most of the kinetic energy and scattering angles can be large. Since the associated \( \sigma_b \) depends strongly on
substrate and electron energy, it is usually determined empirically. Based on information in [15], $\sigma_b$ should be around 1 $\mu m$ for the SOI wafer and an EHT voltage of 25 $kV$.

Since this extended area of electron dose is much larger than the wire-to-wire separation in the middle of the detector meander pattern, the wires will typically be wider than the intended width as defined by the pattern followed by the electron beam. This aspect of the "proximity effect" is relatively simple to deal with, by reducing the width of the lines defined by the electron beam.

There is an additional impact of the proximity effect at the extremities of the 9 $\mu m$ diameter meander pattern, since there is a relative lack of backscattered electrons effecting the dose in these regions (no beam is scanned outside the pattern). If only the 9 $\mu m$ diameter meander pattern was written, The size and shape of the wires and 180-degree bend regions would be distorted. To mitigate this problem, a set of dummy lines (not connected to the meander), are written in a circular disk surrounding the detector region (see Figure 3.1).

The dummy lines are meant to ensure that the overall exposure of the wires of the ends is similar to that in the middle of the meander. They are straight nanowire strips designed to have identical width and spacing as the main meander, but not connected to the main meander.

**Figure 3.6:** Two types of scattering. Blue line is an example trajectory of a forward scattering electron. Red line is an example trajectory of a back scattering electron.
As a rule of thumb, the farther the dummy line area extends, the more uniform the exposure at the centre will be, and the uniformity should eventually saturate at some spatial extension of the dummy line area. Given $\sigma_b \sim 1 \mu m$, the width of the dummy line disk was chosen to be 10 $\mu m$ to minimize the overall time required to write the patterns, and the dummy lines had a gap of 160 $nm$ from the ends of the meander wires.

### 3.4 Sequencing Issues

Once the sample is aligned and the translation stage is moved so that the area to be written is centred on the electron beam’s field of view, the computer takes over control of the electron beam position and raster speed. When writing continuous patterns the beam effectively makes small, discrete steps across the pattern, dwelling for a certain amount of time at each point according to the required exposure dose. When jumping from one continuous patterned area to another, a relatively large jump in voltage occurs across the beam steering electrodes. The larger the jump, the more significant “ringing” artifacts may be, thus it is desirable to minimize the need for large voltage jumps. Another practical consideration for choosing the patterning sequence has to do with the potential drift in the system (beam and translation stage). Adjacent objects that require very accurate relative positioning should ideally be written in sequence.

Taking these issues into consideration, the first step in the exposure consists of writing the entire meandering nanowire pattern, from the bottom dummy to the top dummy line, including central meander area and flared input/output wires. As explained in the text associated with Figure 2.9, the individual nanowires are written using multiple raster scans parallel to the wire axis, and the subtlety is to alternate the starting point in each wire, from left to right etc., in order to minimize the voltage jump on going from wire to wire.

The dummy line writing scheme and meander nanowires (particularly at 180-degree bend) are illustrated in Figure 3.7 and Figure 3.8 respectively.
Figure 3.7: Scheme of writing dummy lines in sequence (from bottom to top) to avoid large jumps. Green box indicates nanowire. Blue solid and dashed arrows show direction of beam rastering and jump respectively. Blue circular dots mark the beginning of nanowires.

Once the meander and dummy line sections are completed, the beam must jump by a large amount to start writing one of the relatively wide wires that connects the flared input wire with the contact pad (see the orange outline in Figure 3.1). After writing that connecting wire, the beam must jump a large amount once again, to write the connecting wire from the output flared nanowire to the other contact pad. It was found that the alignment of these final connecting wires with the flared nanowires varied randomly from device to device, and this was attributed to drift (see Figure 3.9). To overcome this, a large rectangular termination to the flared region was added, to ensure that the two would make contact despite this drift issue. This rectangle was written as part of the connecting wire. An example is shown in Figure 3.10.

3.5 Residual Imperfections

While careful control of the beam rastering sequence led to major improvements in the fabricated devices, there still remained unresolved issues. The most significant is illustrated in Figure 3.11, where the shape of some of the
Figure 3.8: Writing scheme for a nanowire bending. Two nanowires (blue and green lines) forming a 180-deg bending. Solid lines with arrows are beam writing path. Dotted lines are beam jump. Grey region is for normal raster style (see Figure 2.9). The number of lines defining a nanowire needs to be odd to avoid big beam jumps (5 lines are illustrated here). Circles and squares are starting and ending points of the nanowire respectively.

Figure 3.9: Improper connection between tapering and tapered nanowire. Blue dashed lines are designed pattern, where triangular tapering part was patterned in the writing sequence of the circular region, while the rectangle tapered part was patterned in the end. The scale bar is 1 µm.

180 degree bends is distorted. The reasons isn’t clear, partly because this was a seemingly random, and infrequent occurrence.

It may possibly be related to the ”charging effect” common in EBL applications involving insulators. When electrons are incident on resist, they can accumulate on exposed areas. The negatively charged resist can gener-
Figure 3.10: Rectangle junction to tolerate shift. Blue dashed lines are designed pattern. The scale bar is 1 $\mu m$.

Figure 3.11: Distortion at the bend. Scale bar is 200 nm.

...ate a repulsive electrical force on the electron beam resulting in a distortion of the pattern. In order to reduce the effect when patterning nanowires, the smallest e-beam aperture ($\phi = 10 \mu m$) was used to minimize the beam current, and thus maximize the dwell time of the beam at each pixel. The aim was to give more time for any accumulated charges to dissipate.
Chapter 4

Experiment Method

4.1 Experiment Design
The experiment set-up consisted of an electronic part and an optical part: these are described separately in the following subsections.

4.1.1 Electronic Part
Figure 4.1 shows a schematic diagram of the electronic components in the system, all of which were designed, assembled, and tested by Dr. Ahklaghi prior to the start of this thesis work. The SNSPD is DC-biased, and when it absorbs photons, the resulting high frequency signal is capacitively coupled to a low noise amplifier LNA, and further amplified before being input to the counter.

The counter used here is a PicoHarp 300. The SNSPD chip is wire-bonded to the circuit board which was placed in a liquid He bath within an optical cryostat (SVT-300, Janis Inc.). An Edwards mechanical vacuum pump was used to pump on the liquid He reservoir, reducing the temperature to 2.1 K. This is well below the superconducting critical temperature of NbTiN (8.4 K in bulk form), and the He critical temperature, so there were no bubbles in the chamber to scatter incident radiation.

Figure 4.2 shows photos of the final chip and electronics.
Figure 4.1: A schematic diagram of the electronics set-up. Parts enclosed by the blue dashed line are inside the cryostat. The SNSPD is in series with an inductor L (100 nH) and resistor R (100 Ω). C is capacitor (122 pF) and LNA is low noise amplifier.

(a) Final chip with a quarter coin. The chip is mounted on a cryostat sample holder, and wire-bonded to electronics.

(b) Our customized circuit board outside the cryostat.

Figure 4.2: Photos of the final chip and electronics.

4.1.2 Optical Power Calibration Approach

The purpose of the optical system was to deliver a calibrated optical power of HeNe laser radiation (lambda=632.8 nm) on the 9 µm diameter active area of the detector. Two possible schemes were considered, as shown in
Figure 4.3: Two possible schemes for obtaining actual input power on the detector area. The schematic of the detector only shows the active area, (dummy lines are omitted). Blue circular shade indicates laser spot.

The first scheme is to focus the laser to a spot considerably smaller that the 9 µm diameter detecting area. In this case, one would only have to measure the laser beam power hitting the sample to know the incident photon rate on the detector. The main reasons for abandoning this approach were i) getting an $\sim 5 \, \mu m$ diameter beam focused on the sample, inside the cryostat using external optical components is challenging, and ii) vibrations in the laboratory would cause the beam to move randomly on and off the detector area during the experiment.

The second scheme involves a focused light spot much bigger. In this case, if the concentrically focused laser is known to be Gaussian with a well-defined beam waist and total power, the fraction of that power incident on the small detector can be easily calculated. If sufficiently oversized, uncertainty/variation in the incident power due to vibration-caused beam shifts can be largely reduced. Therefore, the second scheme was adopted in this project.

Suppose the laser has been centred at one SNSPD, with on-chip laser beamwidth $w$, the optical intensity profile of the on-chip fundamental TEM$_{00}$ Gaussian is then given by [32]:

$$I(r) = I_0 \left(\frac{w_0}{w}\right)^2 \exp\left(-\frac{2r^2}{w^2}\right),$$

where $r$ is the distance from the point of evaluation to the Gaussian centre,
$I_0$ is the maximum intensity (at $r = 0$) and $w_0$ is the beamwidth at beam waist. The optical power within a radius $R$ can be obtained by integrating $I(r)$:

$$P(R) = \int_0^R I(r)2\pi rdr.$$  \hspace{1cm} (4.2)

Setting $R = \infty$, we can calculate the total beam power:

$$P_{tot} = \int_0^\infty I(r)2\pi rdr = \frac{I_0}{2}(\pi w_0^2).$$

Setting $R = r_d$, the detecting area radius of the SNSPD that sits at the centre of the beam, we can calculate the actual input power:

$$P_{rd} = \int_0^{r_d} I(r)2\pi rdr = P_{tot}[1 - \exp(-\frac{2r_d^2}{w^2})].$$

From the above, a ratio of $P_{rd}/P_{tot}$ can be calculated:

$$P_{rd}/P_{tot} = R_p = 1 - \exp(-\frac{2r_d^2}{w^2}).$$ \hspace{1cm} (4.3)

The Laser power $P_{tot}$ can be easily measured with a optical power meter, $r_d$ can be directly measured from SEM images of the SNSPDs, and the beamwidth $w$ can be measured using the knife edge technique (see Section 4.3).

4.1.3 Optical Set-up

Figure 4.4 shows the optical set-up for the cryogenic experiment. Two knobs for tilt adjustment on mirror M2 allow the laser spot on the sam-
ple chip to be repositioned, along the x and y directions respectively. In the actual experiment, M2 is used to sweep the laser spot and find the position that maximized the count rate of the detector signal. Then the SNSPD is considered to be at the centre of the laser spot. Uncertainties associating with this part will be further discussed in Section 4.3.

Figure 4.4: Optical set-up. HeNe laser ($\lambda = 632.8$ nm) is through neutral density filter set (NDF1) and directed via mirrors M1 and M2 to a polarizer plrz. Power meter PM is used to measure the power of polarized light. The meter is then removed and light goes through another pre-calibrated set of neutral density filters NDF2 for precise attenuation. Then light goes through cryostat windows and normally incident on the sample.

The adjustable polarizer plrz polarizes the input laser. The two polarizations of interest were parallel and orthogonal to the nanowires. The power meter PM is a detector head (Spectra-Physics Model 404) directly fed into an oscilloscope (Tektronix TDS 350), giving a sensitivity of 10 nanowatt.

The choice of NDF1 and NDF2 is not trivial, but is decided according to the constraints of both the PM range and the maximum count rate of the counter (up to 10 MHz, which corresponds to a power of $\sim 3.14$ picowatt of red photons).

Based on this set-up, a calibrated input power for an SNSPD can be obtained:

$$P_{in} = P_{PM} \times T_{NDF2} \times T_{window} \times R_p,$$

(4.4)
where $P_{PM}$ is the power measured by power meter PM, $T_{NDF2}$ is the transmission of neutral density filters set NDF2, and $T_{\text{window}}$ is the transmission of the cryostat windows.

### 4.2 Measuring Cryostat Window Transmission $T_{\text{window}}$

The set-up for measuring the cryostat windows transmission is as in Figure 4.5.

![Diagram](image)

**Figure 4.5:** Measuring cryostat windows transmission. BS is beam splitter. Reflector is a silicon chip.

Suppose the readouts from power meter PM in Figure 4.5a and Fig-
ure 4.5b are $P_1$ and $P_2$ respectively. They can be expressed as:

$$P_1 = P_0 \cdot T_{BS} \cdot T_{\text{window}} \cdot R_{\text{ref}} \cdot T_{\text{window}} \cdot R_{BS},$$

$$P_2 = P_0 \cdot T_{BS} \cdot R_{\text{ref}} \cdot R_{BS},$$

where $P_0$ is the power of the laser measured right after mirror M2, $T_{BS}$ and $R_{BS}$ are the transmission and reflection of the beam splitter respectively, and $R_{\text{ref}}$ is the reflection of the silicon reflector chip.

The transmission through the windows can then be calculated as:

$$T_{\text{window}} = \sqrt{\frac{P_1}{P_2}}. \quad (4.5)$$

Using this method, a transmission of $T_{\text{window}} = 0.85 \pm 0.01$ is observed. There are two windows (outer and inner) in the light path, which have identical thickness of $\sim 0.48 \text{ cm}$. The simulation based on normal incident Fresnel equations suggests a transmission of $0.933^2 = 0.87 \pm 0.08$, as averaged for wavelengths around $\lambda = 632.8 \text{ nm}$, for the window material SUPRASIL™2. The measure transmission is therefore reasonable.

### 4.3 Measuring Beamwidth $w$: Knife Edge Measurement

In order to calculate $R_p$ in equation 4.4, it is essential to measure the beamwidth of the focused laser spot on-chip.

#### 4.3.1 Knife Edge Measurement

The Knife edge technique [1] is a common way to measure beamwidth and to evaluate the quality of a Gaussian beam. The basic set-up for such a measurement is shown in Figure 4.6.

Rewriting the optical intensity equation 4.1 in Cartesian coordinates (origin at beam centre), and supposing the knife edge in Figure 4.6 is placed at position $x$, the unblocked power can then be evaluated by this integral:
Figure 4.6: Knife edge experiment. Straight knife edge translates along x-axis, cutting through Gaussian beam and blocking a part of it. Resulting unblocked power is measured by a power meter.

\[ P(x) = P_{tot} - I_0 \left( \frac{w_0}{w} \right)^2 \int_{-\infty}^{x} \exp\left(-\frac{2x^2}{w^2}\right) dx \int_{-\infty}^{+\infty} \exp\left(-\frac{2y^2}{w^2}\right) dy \]

\[ = P_{tot} - I_0 \left( \frac{w_0}{w} \right)^2 \sqrt{\frac{\pi}{2}} \int_{-\infty}^{x} \exp\left(-\frac{2x^2}{w^2}\right) dx \]

\[ = P_{tot} - I_0 \left( \frac{w_0}{w} \right)^2 \sqrt{\frac{\pi}{2}} w \left[ \int_{-\infty}^{0} \exp\left(-\frac{2x^2}{w^2}\right) dx + \int_{0}^{x} \exp\left(-\frac{2x^2}{w^2}\right) dx \right] \]

\[ = P_{tot} - I_0 \left( \frac{w_0}{w} \right)^2 \sqrt{\frac{\pi}{2}} w \left[ \sqrt{\frac{\pi}{8}} w + \int_{0}^{x} \exp\left(-\frac{2x^2}{w^2}\right) dx \right] \]

\[ = P_{tot} - \frac{I_0}{4} (\pi w_0^2) - \int_{0}^{x} \exp\left(-\frac{2x^2}{w^2}\right) dx \]

\[ = \frac{P_{tot}}{2} - \frac{I_0}{4} \left( \frac{w_0}{w} \right)^2 \sqrt{\frac{\pi}{2}} w \int_{0}^{x} \exp\left(-\frac{2x^2}{w^2}\right) dx \]

The remaining integral in the above result is essentially an error function. With a change of variable:

\[ I_0 \left( \frac{w_0}{w} \right)^2 \sqrt{\frac{\pi}{2}} w \int_{0}^{x} \exp\left(-\frac{2x^2}{w^2}\right) dx = \frac{I_0}{4} (\pi w_0^2) \int_{0}^{\frac{\sqrt{\pi}}{2}} \exp\left(-u^2\right) du \]

\[ = \frac{P_{tot}}{2} \text{erf} \left( \frac{\sqrt{2x}}{w} \right). \]
Therefore,

\[ P(x) = \frac{P_{\text{tot}}}{2} \left[ 1 - \text{erf}\left( \frac{\sqrt{2}x}{w} \right) \right] \]  

(4.6)

Finally, we have a fitting model for determining beamwidth \( w \):

\[ P(x) = \frac{P_{\text{tot}}}{2} \left[ 1 - \text{erf}\left( \sqrt{2}\left( x - x_0 \right) \right) \right] \]

(4.7)

where \( x_0 \) is an offset parameter such that \( x \) coordinates don’t have to be measured from the beam centre.

By translating the knife edge over a series of \( x \) coordinates, recording the corresponding power \( P(x) \), \( P_{\text{tot}} \), \( x_0 \) and \( w \) can be obtained by fitting with this model.

### 4.3.2 Measuring Beamwidth

Since the sample is located in the cryostat, where it is impossible to perform a knife edge measurement, the procedure shown in Figure 4.7 was devised.

![Figure 4.7](image)

**Figure 4.7:** Beamwidth measurement. The laser is pulled back a distance \( d \) and the beamwidth of a position at distance \( d \) from the sample position is measured.

**Figure 4.8** shows the data and fitted curve of the knife edge measurement. According to the measurement, a beamwidth of \( 1.025 \pm 0.009 \text{ mm} \) is obtained. From Equation 4.3, this means \( R_p = 3.93 \times 10^{-5} \). It should be
noted that although the 'sample point' and laser are both pulled back at distance $d$, the light path is different. In the actual experiment, light has to go through the cryostat windows described above. The thin windows slightly shift the position of the beam waist axially, but calculations show the net impact on the above estimate is negligible.

### 4.3.3 Uncertainty Summary

The overall uncertainty of the incident power on the detector due to the measurement uncertainties of the laser power, window transmission, and beam waist at the sample is $\sim 5\%$. This is negligible in comparison to the noise in the detected count rate, due to vibrations of the cryostat from the vacuum pump, as documented in the following chapter.
Chapter 5

Results

5.1 Absorption Simulation

![Simulated Structure Diagram]

Figure 5.1: Simulated structure

The absorption of the nanowire array is simulated using Lumerical® FDTD Solutions, with the geometry the unit cell shown in Figure 5.1, on a 240 nm pitch. The refractive indices of ZEP ($n_{ZEP} = 1.5539$) and NbTiN ($n_{NbTiN} = 1.7 + 2.8i$) at wavelength $\lambda = 632.8 \text{ nm}$ are calculated from the ZEON product data sheet and [9] respectively. This cross section of an infinite (into the page) nanowire was periodically replicated in the simulation, and it was excited by a normally incident plane wave.
The exact widths of the wires, the etched silicon depth, the residual ZEP layer thickness, and the silica layer thickness are not known, since it would be necessary to destroy the detectors to measure them. As described in Chapter 2, a number of detectors were made with slightly different doses chosen to bracket the target wire width of 80 nm. From detector 1 to 12, nanowire width was designed to gradually increase. The SEM images shown in the previous chapter are all taken of the largest wire width detector 12. Its measured width is $\sim 90$ nm, which roughly indicates a range of widths for all detectors of between $70 \sim 90$ nm.

Apart from the bracketing design, some other variations due to fabrication uncertainty should also be taken into consideration in simulations. The three most important variations are: (1) $\pm 10$ nm of residual ZEP thickness (under go spin-coating and plasma etch); (2) $\pm 5$ nm of silicon etch depth; (3) $\pm 10$ nm of silica (BOX) layer thickness.

Given all of these uncertain, but bounded parameters, the absorption of the structure was calculated as a function of wire width, silicon etch depth, ZEP layer thickness, BOX layer thickness, for plane waves polarized parallel and perpendicular to the wire axis. The results are shown in Figure 5.2 - Figure 5.5 respectively.

For each of the absorption simulations, a range of parallel and perpendicular polarized absorption values, and their ratios can be calculated for each of the independent unknown device parameters in the simulations. By taking the average of the mean values and adding uncertainties quadratically, the overall simulated absorption values and their ratio are:

$$P_\parallel = 3.34\% \pm 1.01\% \quad (5.1)$$
$$P_\perp = 2.91\% \pm 1.05\% \quad (5.2)$$
$$\text{ratio} = 1.1562 \pm 0.1643 \quad (5.3)$$

The absolute values of the absorptions are very low because the structure of the SOI wafer on which the meander wires were fabricated results in there
Figure 5.2: Simulated absorption of nanowire versus its width. Blue solid and dashed lines correspond to a source polarization that is parallel and perpendicular to nanowire respectively. Red line is the ratio of two absorption (parallel over perpendicular).

Figure 5.3: Simulated absorption of nanowire versus ZEP thickness. The colour coding is the same as the previous figure.

being a near anti-node of the incident plus reflected (from the multi-layer, high refractive index stacked structure) field right at the silicon surface (see Figure 5.6 and Figure 5.7). These wafers were originally designed and used to fabricate SNSPDs on silicon waveguides carrying light in the plane of the silicon device layer. Others have designed substrates optimized to produce a
Figure 5.4: Simulated absorption of nanowire versus silicon etch depth. The colour coding is the same as the previous figures.

Figure 5.5: Simulated absorption of nanowire versus BOX thickness. The colour coding is the same as the previous figures.

near node in the incident plus net reflected field in the nanowire plane [28], and the current detectors could readily be fabricated on such substrates, increasing their absorption considerably.

The absorption efficiency is basically the upper bound of the QE, since the detection mechanism explained in Chapter 1 shows that the absorption of a photon does not necessarily results in the detection of it. Biasing the nanowire at a current closer to critical current can increase the QE for a
Figure 5.6: Simulated E field of source polarization along z axis, parallel to nanowires.

Figure 5.7: Simulated E field of source polarization along x axis, perpendicular to nanowires.

fixed absorption efficiency, but this also increases the intrinsic dark count rate, as shown below.

5.2 Experiment Results

Figure 5.8 shows the IV curves of the two detectors in super fluid Helium. The curves indicate good electrical connection of detectors, and the turning points show clearly the breakdown of superconductivity at slightly dif-
different critical currents of 5.24 $\mu A$ and 8.28 $\mu A$ for detector 1 and 4 respectively. Because of the bracketing in fabrication, detector 4 has a wider nanowire and thus higher critical current, as expected. However, the supplementary information of [4] shows a value of $\sim 29 \mu A$ is measured from a short straight 80 nm wide nanowire at the same temperature, of the same material and with the same set-up. The most likely explanation is a residual current crowding effect due to fabrication imperfections in the 180 degree bends of the meander. A similar detector with a nominal nanowire width of 80 nm in [3] has a critical current of $\sim 14 \mu A$

\[
\text{Figure 5.8: IV curves of detector 1 (blue curve) and 4 (red curve), at temperature } T = 2.05K.
\]

\[
\text{Figure 5.9 shows an electric pulse detected using detector 4 and a fast oscilloscope. The negative polarity of the pulse is set on purpose to make it compatible with the counter, and the frequency cut-offs of the chain of amplifiers results in an under-damped shape, and cannot provide an estimation of detector reset time [4].}
\]

In this project, timing performance is not directly measured. However, the reset time can be roughly estimated using a calculation from [11]. Our SNSPD has a kinetic inductance of $L_k \sim 300 \, nH$ and with the resistor and inductor integrated as in Figure 4.1, the reset time can be estimated as $\tau = (L_k + L)/R = 4ns$. A 4 ns reset time corresponds to a count rate of 250
Figure 5.9: Electric pulse picked up by fast oscilloscope. Vertical scale is 50 mV/div and horizontal scale is 5 ns/div.

Figure 5.10 and Figure 5.11 show measurements of the QE for two source polarizations: parallel and perpendicular to the nanowires respectively, where error bars are due to fluctuations of counts read from the counter.

As can be seen from the figures, the QE versus bias current shows an early saturation for both polarizations. When increasing bias current, the SNSPD becomes more sensitive to photons, but the measured photon count stops increasing. This is not an artifact of an incident photon rate that exceeds the detector count rate, since the maximum count rate was estimated to be 250 MHz, while the maximum incident photon rate was \( \sim 10 \) MHz.

According to Figure 5.10 and Figure 5.11, the measured QEs are:

\[
QE_{||} = 2.30\% \pm 0.63\% \quad (5.4)
\]
\[
QE_{\perp} = 2.57\% \pm 0.72\% \quad (5.5)
\]
\[
\text{ratio}' = 0.90 \pm 0.35 \quad (5.6)
\]

The measured QEs and the polarization ratio therefore agree with simu-
lated results in equation 5.1, 5.2 and 5.3 within the (relatively large) mutual uncertainties.

The saturation of the QE suggests that in that saturated range of bias currents, every single photon that is absorbed by the nanowire is detected. Furthermore, the saturation happens when the bias current is about $4.5 \, \mu A$, with the critical current being $8.28 \, \mu A$.

As a comparison, Figure 5.12 shows the QE and intrinsic dark count rates measured for the detector reported in [3], from which the design is adopted for this project. Recall from Section 1.4, that these detectors are very similar in structure to those made in this thesis project, but they were fabricated on a substrate designed to maximize the absorption of $1.55 \, \mu m$ wavelength photons. While the optimized substrates result in much higher maximum QEs of these detectors, note that they do not exhibit saturation with bias current. This difference in saturation behaviour can be at least qualitatively explained by noting the nearly factor of two difference in energies of $1.55 \, \mu m$ and $632.8 \, nm$ wavelength photons. Recall that the cause of a detection event is the formation of a resistive barrier, upon the local

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig5_10.png}
\caption{QE and background count rates versus bias current for parallel polarization.}
\end{figure}
absorption of a single photon which depends on the significance of photon-induced local 'hot spot'. If the incident photon has weak energy (long wavelength), the induced 'hot spot' will be less significant, which is more likely to fail in formation of resistive barrier. Therefore, to enhance detection of longer wavelength photons, the bias current has to be set closer to the critical current. In other words, the saturation bias current is expected to be closer to the critical current for 1550 nm photons, as compared to 632.8 nm photons, which is at least qualitatively consistent with the data in Figure 5.12.

The significance of the saturation of the QE with bias current can best be understood from Figure 5.12. Both the QE and the intrinsic (no background (eg. black body) photons present) dark count rates increase with bias current below the critical current. The intrinsic dark count rate increases exponentially, so the more saturated the QE curve, the lower the bias current you can operate at, and hence the lower the intrinsic dark count rate. The data in Figure 5.10 and Figure 5.11 does not show the exponential behaviour of the dark count rate because it was impossible to sufficiently shield the detector
from black body radiation. However, assuming that the dark count rate due to this black body radiation also saturates for our detectors, a constant value can be subtracted off of the total dark count rate to obtain an estimate of the intrinsic dark count rate. The results of doing this subtraction for both polarization data sets is shown in Figure 5.13. Within the uncertainties, the results are independent of incident polarization, as they should be.

The relation between SNSPD dark count rate ($DCR$) and ratio of bias current over critical current $I/I_c$ has been studied in detail: [34] gives a rigorous explanation of the origin of dark count based on current-assist vortex-antivortex pair unbinding rate. Empirically, a relation $DCR \propto \exp I/I_0$ is observed [18]. Figure 5.13 shows estimated dark count rates, curves are fitted with exponential functions.

**Figure 5.12:** QE and dark count rate (of photons with wavelength 1550 $nm$) versus bias current of the detector shown in Figure 1.11. Dashed lines mark optimal bias current. Figure taken from [3].
Figure 5.13: Estimated dark count rates. Blue and red lines correspond to a source polarization that is parallel and perpendicular to nanowire respectively. Curves fitted with an exponential function.
Chapter 6

Conclusion

6.1 Project Summary

In this project a circular meander design of a free-space SNSPD was fabricated and tested in house. Although the absolute absorption efficiency of the detector is low ($\sim 3\%$ at temperature $2.05\; K$), because it was fabricated on a substrate optimized for other applications, the measured QE and modelled nanowire absorption efficiency for incident polarizations both parallel and perpendicular to the wire axis agree within the uncertainties.

The absorption efficiency remains flat (saturated) for bias currents above $0.5\; I_c$. The intrinsic dark count rate at a bias current of $0.7\; I_c$ was measured to be $\sim 100\; Hz$ at $2.05\; K$. Assuming a continuing exponential falloff at lower bias currents, the detectors should operate at maximum absorption efficiency down and an intrinsic dark count rate of $< 1\; Hz$ at a bias current of $0.5\; I_c$. These results suggest that using the same patterning techniques and electronics, very useful in-house detectors at a wavelength of 632 nm could be fabricated on appropriate substrates.

The total cost of the SNSPD element including the chip, circuit boards and nanofabrication equipment usage is conservatively estimated to be $< \$10K$, which is significantly lower than the commercial element cost (on the order of $\sim \$50-100K$).
6.2 Future Work

The highest priority extension of this work is to design and source or fabricate a substrate that would locate an antinode of the total field in the plane of the superconducting layer. Based on the literature, it should be possible to obtain QEs on the order of 90\%. Once this problem is solved, then the next highest priority is to develop a robust packaging scheme to convert these detectors into useful laboratory instruments.

A longer term project would involve exploring the potential benefits of alternate superconducting materials, such as WSi.

For example, to date a new material WSi is spreading its influence in the field of SNSPDs rapidly. The lower superconducting gap energy of WSi compared to NbN/NbTiN makes WSi nanowires more sensitive to photons (larger 'hot spot'), resulting in a higher QE and earlier saturation [6]. Most of the work in this thesis should carry over directly to samples made from WSi rather than NbTiN.
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