Superconducting Single Photon Detectors
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Preface

After a long hesitation whether quantum mechanics is the right direction for me, I decided to join the Quantum Transport group as a master student. From the beginning I noticed that the group was large, but very friendly and willing to help. I enjoyed this friendly atmosphere and the cooperative attitude very much and I liked the wide variation of research topics, while meeting people from all over the world. That’s why when I was asked to continue as a PhD student it was easy to say yes. Although it was hard working, the past four years were great, also because there can be life besides work. Different skills and knowledge of the people working in the group, helped me for my own research and the good infrastructure makes life in the lab much easier. The work in this thesis has been realized with the help of a lot people and hereby I want to thank them.

First of all Val, I was very lucky to have you as a supervisor during the past four years. Thanks to you we started a number of collaborations with other groups which often led to nice results. In addition, your ideas are very creative and your enthusiasm, especially during your talks, inspiring. I learned a lot and being part of an even bigger growing group was very nice. I am looking forward to continue working together in Single Quantum.

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Leo, thanks for creating the nice QT environment. Your physics knowledge and focus on new and exciting directions is impressive. Your way of running such a large group is I think very nice.

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Today's research is often built on past research. Delft's SSPDs are built on the smooth NbTiN films of the NAF group. It was very nice that the deposition on the oxidized silicon substrates worked so well. Hereby I want to thank Teun for supplying the films and for your input on our papers. I want to thank Tony for the deposition and initial help and ideas on fabrication and Eduard for the deposition during the last stage of my PhD.

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Last, but definitely not least, I want to thank friends for the life outside the lab, it was especially nice to now and then meet with my old Apollo friends. Distracting my focus away from the lab was helpful and relaxing. Jasper, thanks
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Chapter 1

Introduction

1.1 Single photon detection

Single photon generation, manipulation and detection technologies are important for several areas in quantum optics. In the early 1900s it was postponed by Max Planck [1] and later Albert Einstein [2] that the energy of a light beam is distributed in discrete bundles, photons. It was not until 1977 that the first indisputable proof of the quantum nature of light was shown[3, 4]: light generated from fluorescence of a two-level atom exhibit photon count statistics [5] which could only be explained in a non-classical way: the atom emits one photon at a time.

Recent drives to develop technologies using single photon generation and single photon detection are quantum computation, where photons are used as quantum bits[6], and quantum key distribution [7], where photons are used to securely transfer information over long distances. Single photon detection itself has also applications in many fields where high timing resolution and high sensitivity to low photon levels are required, for example in time-of-flight laser ranging [8] and biophotonic applications[9]. Although single photon detectors are highly developed for visible wavelengths (from $\lambda=600$ nm to $\lambda=1.1$ $\mu$m silicon avalanche photodiodes (APDs) can exhibit a peak efficiency of 90%), the short infrared wavelengths of 1.31 $\mu$m and 1.55 $\mu$m are preferred when information is to be transferred over long distances. The reason for this is that optical fibers are commonly used for transporting photons and the lowest optical loss in a fiber is achieved for 1.3 and 1.55 $\mu$m. [10] For these wavelengths different alternative techniques are available, a.o. the Transition Edge Sensor (TES) and InGaAs APDs. TESs have a high efficiency, however only work at very low temperatures (T<1 K), and their recovery time is long. InGaAs APDs can be operated at room temperature, however their efficiency is low and their noise very high.
This thesis is focused on the detection of single photons with a superconducting nanowire (Superconducting Single Photon Detector, or SSPD). They are sensitive to photons over a large wavelength range, with excellent timing properties. Although a temperature below 10 K is needed for operation, this is not a major obstacle anymore. It is possible to use liquid helium to reach this temperature, but in the past years the development of closed cycle cryostats has made them affordable and they can reach low enough temperatures without the need of helium. The work in this thesis is divided in two parts: (1) Properties of the detectors (2) Implementation in experiments. The first part focuses on improving the quantum efficiency, optical properties (polarization and wavelength dependence), and new readout schemes for SSPDs. In the second part the results of implementation in experiments are presented, showing that SSPDs are useful devices with better performance than existing techniques.

Detector performance is often dependent on the application. For example the need for a temperature below 10 K for operation makes SSPDs impractical for consumer applications, however one can define a number of requirements a detector useful for research laboratories and high-tech applications such as quantum cryptography must satisfy:

- Efficient over a broad wavelength range, independent of polarization: In today’s telecommunication applications the wavelength $\lambda=1550$ nm is used mostly because the optical loss in fibers is the lowest for this wavelength. However, a large number of single photon emitters emit at other wavelengths, such as self assembled quantum dots [11], quantum dots in nanowires [12], nitrogen-vacancy defects in diamond[13]. Also efficient detection further in the infrared yields interesting applications [14]. So it is convenient if one detector covers a broad spectrum. In addition, photons can be used to transfer information, which is often encoded in the polarization state of light[15], so it would be inconvenient if detectors can only detect a certain polarization state.

- Low noise: for single photon detectors two types of noise are important: noise in the output signal and dark counts. Noise in the output signal affects the trigger level needed and the timing jitter. Dark counts are detection events when no photon is absorbed. The more dark counts with respect to real counts, the longer the measurement time. Furthermore noise limits the security in quantum key distribution systems.[15]

- Short dead time: dead time is the time it takes after a detection event before the next event can be registered, this limits the maximum count
1.2 Outline

rate.

• Low timing jitter: timing jitter is the accuracy in the timing of a detection event.

• Photon number resolution: a detector that can tell the number of photons absorbed at the same time is needed for linear optics quantum computation. [6]

• Large array: extending the single pixel to an array would allow photon number resolution, shorter dead time and imaging. The challenge for SSPDs lies in a scalable readout circuit and reproducibility of fabrication.

The items mentioned above are all addressed in this thesis with respect to SSPDs.

1.2 Outline

In chapter 2 an introduction to SSPDs is given and relevant previous results are discussed. In chapter 3 the results on the first SSPDs made in Delft are presented along with a method for efficient fiber coupling. We have tried to increase the absorption of photons in the device by investigating the effect of the surrounding materials, this is described in chapter 4. In chapter 5 the polarization and wavelength dependence is discussed and a way to circumvent the polarization dependence. To enhance the efficiency in the infrared we have fabricated SSPDs from a low superconducting gap material (NbSi), the results of which is presented in chapter 6. Alternative readout techniques are introduced in chapter 7: capacitive based readout for avoiding wide band amplifiers, high electron mobility transistor based readout for photon number resolution and a readout scheme for making large arrays. In the second part integration of SSPDs in experiment is discussed, starting with correlation experiments with position controlled nanowires emitting in the infrared (chapter 8). In chapter 9 it is shown that correlation experiments can be simplified by making use of the short dead time of SSPDs. The detection of single surface plasmon polaritons is described in chapter 10. In chapter 11 is shown that SSPDs are not only sensitive to photons, but also to particles, i.e. electrons. In the final chapter conclusions are drawn and applications as quantum cryptography, quantum computation and imaging are described.
Chapter 1. Introduction
Chapter 2

Device and measurement setup

2.1 Introduction to Superconducting Single Photon Detectors

Superconducting single photon detectors (SSPDs) offer single-photon sensitivity from visible to mid-infrared wavelengths, low dark counts, fast recovery times and low timing jitter. The first results on these detectors have been published in 2001 [16] by Gregory Goltsman, Roman Sobolewski and colleagues. They showed that when a photon is absorbed in a nanowire carrying a supercurrent, a resistive hotspot is formed, which could lead to a voltage pulse given that the cross section of the nanowire is small enough. They have also shown that the count rate is linearly proportional to the power of the incident light, an important indication of single photon detection. Their initial detector consists of a NbN superconducting wire, which is 10 nm thick and 200 nm wide. The detector is operated at cryogenic temperatures well below the critical temperature ($T_c$) of the device.

Subsequently it has been shown that decreasing the thickness and decreasing the width (i.e. decreasing the cross section of the wire) improves the quantum efficiency [17]. The length of the wire has also been increased for a larger active area [18]. A scanning electron microscope picture of an SSPD fabricated at TU Delft is shown in figure 2.1a. The wire has a rectangular cross section defined by a thickness of $\sim 6$ nm NbTiN and a width of 100 nm. The length is 500 $\mu$m, the filling factor 50%. The wire is folded in a 10x10 $\mu$m area. The full chip, glued and bonded on a chip carrier, is shown in figure 2.1b.

The operation principle of an SSPD is outlined in figure 2.2. The superconducting nanowire is biased with a direct current ($I_{bias}$) close to the critical current ($I_c$), meaning that the current density ($J_{bias}$) flowing through the wire is near the critical current density ($J_c$), above which the superconductivity of the nanowire breaks down. When an incident photon of sufficient energy is absorbed by the
wire, the superconductivity in that region is disrupted and a part of the detector becomes resistive ($R_n > 1 \text{k}\Omega$). This is modeled as a switch which is closed when the SSPD is superconducting and closed after a photon is absorbed. When the detector is resistive, the current flows through the amplifiers, giving a voltage pulse of $V = I_{\text{bias}} \cdot R_A \cdot A$ (with $R_A$ the amplifier input impedance and $A$ the amplification), provided that $R_n >> R_A$.

![Electrical model of the SSPD setup](image)

**Figure 2.1:** (a) Scanning electron microscope picture of the active area of an SSPD (b) SSPD chip glued and bonded on a chip carrier

**Figure 2.2:** Electrical model of the SSPD setup. The switch together with the normal resistance $R_n > 1 \text{k}\Omega$ and the kinetic inductance, $L_k \approx 500 \text{nH}$, model the detection principle of the SSPD.

### 2.1.1 Detection principle

As mentioned, the detection principle is based on the transition from the superconducting to the normal state. A microscopic explanation of superconductivity...
2.1 Introduction to Superconducting Single Photon Detectors

is found by Bardeen, Cooper and Schrieffer. They argued that even for a very small attracting force between two electrons, an energy gap $\Delta$ would exist between the ground state and the quasi-particle excitations of the system. Spectroscopic measurements clearly showed such a gap. The small attractive force lead to the formation of bound pairs of electrons, which energy is least if they have opposite momentum and anti parallel spins. This leads to an energy gap, which at zero temperature was predicted to be $E_g(0) = 2\Delta(0) = 3.528 \cdot kT_c$. This is the energy needed to break the Cooper pairs into quasi particles. As photons have much higher energy than the superconducting gap it is expected that breaking of Cooper pairs, leading to a reduced $n_s$, is the start of a detection event.

Spatial variation of $n_s$ can be described by the Ginzburg-Landau equations. These equations introduce a complex pseudowave function $\psi$, which is defined as $n_s = |\psi(x)|^2$. By minimizing the free energy, essentially the difference in energy between the superconducting and normal state, which has the form

$$F = F_n + \alpha|\psi|^2 + \frac{\beta}{2}|\psi|^4 + \frac{1}{2m}[-i\hbar\nabla - 2eA]|\psi|^2 + \frac{|B|^2}{2\mu_0}$$

one arrives at the following differential equation for $\psi$:

$$\frac{1}{2m^*} \left( \frac{\hbar^2}{i} \nabla - \frac{e^*}{c} A \right)^2 \psi + \beta|\psi|^2\psi = -\alpha(T)\psi$$

(2.1)

This is analogous to the Schrödinger equation, but with a nonlinear term. It follows that the supercurrent equals to

$$J_s = \frac{e^*\hbar}{i2m^*}(\psi^*\nabla\psi - \psi\nabla\psi^*) - \frac{e^2}{m^*c}|\psi|^2A$$

(2.2)

The Ginzburg Landau equations describe the superconducting state in terms of a thermal equilibrium. The detection of photons in an SSPD is a non equilibrium process in a superconductor carrying a high current density. Generalization of the Ginzburg-Landau equations would lead to a differential equation for the space and time dependence of the order parameter $\Delta$. This time dependent Ginzburg-Landau theory has been solved for situations near $T_c$ (gapless superconductor) and for superconductors with a very clean gap. The time dependence of the order parameter reads then as follows [19]:

$$[(T - T_c)/T_c + \beta(\Delta^2/T_c^2)) - \zeta^2(0)\nabla^2]\Delta = -(\pi/4T_c)\tau_E\Delta \frac{\partial \Delta}{\partial t}$$

(2.3)

No work has been carried out so far to find out whether this equation is applicable for the SSPD situation. The superconducting state has to be treated
as a two dimensional state, as the width of the wire is much larger than its coherence length (5 nm), with a reduced superconducting gap (but non-zero) at low temperatures. The wire carries a high current density and after absorption of light, excitations have to be taken into account, as well as spatial and temporal variations during the diffusion and scattering processes. Theoretical work in this direction could possibly hint towards improving the intrinsic detection efficiency, however in this thesis the focus is on the practical implementation of SSPDs.

### 2.2 Detector characterization

In this section different parameters for the practical implementation of the detectors are described.

#### 2.2.1 Detection Efficiency

An important characteristic of a detector is its efficiency. For SSPDs it is a measure of the probability that an input photon results in an electrical output pulse. In this probability (DE) different subprocesses can be recognized.

\[
DE = \eta_d \cdot \eta_A \cdot \eta_c
\]  

where \(\eta_d\) is the probability of electrical pulse generation due to an absorbed photon, \(\eta_A\) the photon absorption efficiency of the superconducting nanowire and \(\eta_c\) the optical coupling efficiency between the incident light and the active area of the detector. The first factor is the intrinsic quantum efficiency of the nanowire and it is the probability that a voltage pulse will be generated given that a photon is absorbed. The second factor depends on the absorbing properties of the nanowire (material composition and geometry), which itself depends on the surrounding layers (i.e., substrate and coating layers). Coupling losses are represented by \(\eta_c\). Coupling losses occur when the photon is coupled to the detector. This is usually done with an optical fiber or a microscope objective. As for the ‘end-user’ of the detector the coupling loss is not of interest, often the system detection efficiency (SDE) is defined. This is the probability that the photon is detected once it is in the ‘system’ (before coupling to the detector). The parameters \(\eta_c\) and \(\eta_A\) depend on the surroundings of the detector, they will be treated elsewhere in this thesis. The rest of this section is devoted to a description of \(\eta_d\), which is linked to physical properties of the device itself.

As was mentioned it is generally believed that the energy of a photon \(E_{ph} = h \cdot \nu \approx 1\ \text{eV}\) causes breaking of Cooper pairs, with a superconducting bandgap
energy of $E_g \sim k \cdot T_c \approx 5 \text{ meV}$ (for NbTiN). The increased number of quasi particles leads to a finite resistance in a section of the nanowire, inducing a detection event. It is not presently known how this influences the internal detection efficiency $\eta_d$. However, a number of parameters effecting $\eta_d$ have been investigated experimentally:

### Geometry

The geometry of the device is shown in figure 2.1a. It consists of a long meandering wire. The wire has a rectangular section of approximately $5 \times 100 \text{ nm}$. It has been shown that decreasing the nanowire width, and the nanowire thickness increases the intrinsic efficiency $\eta_d$ of the device [18]. This is likely due to a relative increase in the resistive spot size with respect to the wire cross section, which makes it easier to induce a detection event.

As the wire length is large compared to its cross section, a uniform cross section is extremely important. If a part of the nanowire is constricted, i.e., it has a smaller local cross section, the critical current in this constriction is lower than for the rest of the nanowire. In order to prevent switching to the normal state the SSPD must be biased close to the critical current of the cross section. This will mean that the rest of the wire will be biased far from its critical current, and the internal efficiency in this part is lower than it should be, or in a worst case scenario the detector is only sensitive at a constriction. Constrictions can be identified through electrical measurements [20] and local illumination of operating SSPDs with a focused laser spot [21].

### Bias current

In figure 2.3 the count rate as a function of bias current is shown. It can be seen that the efficiency is minimal at low currents, increases exponentially and reaches a plateau at high bias currents. It has been shown that the curve is shifted towards lower bias currents and typically sharper (steeper exponential region and higher curvature in the transition to the saturated efficiency) for higher energy photons (see section 5.2.3) and narrower or thinner wires [22]. The detection efficiency versus bias current curve for longer wavelength photons is less sharp and shifted toward lower detection efficiencies and higher bias currents.
Chapter 2. Device and measurement setup

Figure 2.3: Bias and temperature dependence of the count rate. The excitation wavelength is 635 nm.

Temperature

The internal detection efficiency increases with decreasing temperatures [23], in large part due to the increased critical current in the nanowires, see also figure 2.3. The critical current can typically increase by $\sim$50\% as the temperature of the detector is reduced from 4.2 K to < 2 K. It can be seen in figure 2.3 that, for the wavelength used in this measurement ($\lambda = 635$ nm), the count rate (and thus the internal detection efficiency) as a function of bias current saturates at high bias currents ($I_{\text{bias}} > 9 \mu A$) and that for $T = 4.2$ K, this bias current cannot be reached. Lowering the temperature from 4.2 K to 2 K yields a higher $I_c$ and a factor of 3 increase in efficiency. When the saturation point is reached, decreasing the temperature further (to $T = 300$ mK) does not result in an additional efficiency improvement.

Photon energy

It has been reported that the internal detection efficiency near the critical current has an exponential dependence on the photon wavelength.[23] The higher the photon energy, the higher the detection efficiency. A detailed description of the photon energy dependence of SSPDs is given in section 5.2.3. In this section we also describe how we perform spectroscopy. A way to make the exponential
dependence less pronounced is presented in chapter 6.

### 2.2.2 Dead time

The primary limitation to the maximum counting rate of an SSPD is the reset time since it determines when a second photon can be detected. The detection response time is set by electrical and thermal properties of the SSPD. The balance between them even determines if the SSPD actually will reset. Reset will only occur if the resistive state in the wire is unstable, for this to happen the thermal time constants (i.e. the time to "cool down" after a detection event) has to be sufficiently fast compared to the electric time constants (i.e. the time it takes for the current to decrease and return in the SSPD). [24, 25] This means that the electrical time constant cannot be lowered indefinitely.

![Figure 2.4: Different approaches to reduce the reset time of SSPDs](image)

(a) A shorter wire has a shorter reset time, however reduces the active area. (b) A parallel geometry has a lower total kinetic inductance, leading to a decreased reset time.

In the usual geometry (500 μm long NbTiN wire) cooling down is much faster than the electrical time constant, so the recovery time $\tau$ is mainly determined by the kinetic inductance $L_k$ of the nanowire and the load impedance $R_L$ to which it is connected $\tau = L_k / R_L$ [26]. The kinetic inductance is proportional to the length of the nanowire divided by the cross-sectional area of the nanowire. The kinetic inductance of a 5 nm thick, 100 nm wide, 500 μm long NbTiN wire is approximately 500 nH and $R_L$ is typically the input impedance of an RF amplifier (i.e. 50 Ω), implying that $\tau = 10$ ns. In figure 2.4 it is demonstrated how a shorter reset time can be achieved. Shorter wires will have lower inductance resulting in faster reset times, though they imply smaller active areas, thus there is a trade-off between maximum counting rates and overall efficiencies. An alternative way
to decrease the kinetic inductance is to put more detectors in parallel. The total kinetic inductance is then $1/L_{k,\text{total}} = 1/L_{k,1} + 1/L_{k,2}...$. A third option to decrease $\tau$ is to increase the impedance as seen by the detector ($R_L$).

As illustrated, it is possible to reduce the electrical time constants, however the thermal constants, dictated by material properties, place a lower limit on the reset time. Alternative substrates and film materials are under investigation [27, 28], but producing faster SSPDs by decreasing the thermal time constants has not been studied in detail.

### 2.2.3 Timing jitter

The timing jitter in SSPDs is not a limiting factor in the counting rate as it is much lower than the reset time. While the nature of the timing jitter is presently not known, it certainly depends on both the electrical time constants and the details of the readout electronics, however there is also an intrinsic timing jitter, most likely produced by the variation in time delay of the formation of the resistive area, which in turn is caused by width variations along the nanowire and the position where the absorption takes place in the meander.

A timing jitter of less than 30 ps has been reported[29]. Timing jitter does not appear to be strongly related to the incident photon energy and the nanowire width (for wires $< 100$ nm in width). It is dependent on the bias current and the amplifiers: high bias currents (close to the critical current of the nanowire) and low-noise, exactly 50 $\Omega$ impedance amplifiers provide the lowest timing jitters. The typical timing jitter of our detectors is 60 ps, see figure 2.5.

![Figure 2.5: Typical timing jitter of NbTiN SSPDs.](image)
2.2.4 Dark counts

Dark counts, detection event when no photon is absorbed, are another important aspect for single photon detectors. For example, they limit security in quantum cryptography applications. Several studies of dark counts have been made. Dark count rate depends on bias current and temperature (see figure 2.6). The rate increases with increasing bias current and increasing temperature. The following origins of dark counts have been considered: (1) Phase slips (2) Current assisted vortex-antivortex pair (VAP) unbinding (3) Crossing of a single vortex (4) Quantum phase slips.

![Figure 2.6: Dark count rate of NbTiN SSPDs.](image)

Scenario (1) can be ruled out, because the nanowire width (100 nm) is much larger than its coherence length (5 nm). Therefore, the formation of phase slips is very unlikely to cause a detection event, as this is a coherent process. As the nanowire width is much larger than its coherence length, SSPDs have to be treated as 2D superconductors. In 2D superconductors there is a possibility of a phase transition called a BKT transition occurring at the critical temperature $T_{BKT}$. Below $T_{BKT}$, the formation of vortices and antivortices is favored energetically and the VAP is spontaneously generated. In the SSPD, the bias current is applied to the device and therefore the vortex and antivortex of a VAP feels Lorentz force in the opposite direction. As a result, the VAP is broken into single vortices, which move in the nanowire perpendicular to the current, the finite resistance appears even below the superconducting critical temperature $T_C$. Scenario (3) refers to a vortex crossing from one strip edge to the opposite one inducing...
a phase slip without creating a normal region across the strip width. This phase slip induces a voltage, leading to a dark count event.

In [30] it was pointed out that the energy barrier for the crossing of a single vortex is much lower than for the unbinding of a vortex-antivortex pair. However experimental data [31, 32, 33] suggest that scenario (2) is a more realistic scenario. For low temperatures (T<1 K) unbinding of a VAP cannot explain the experimental data. Quantum phase slips (scenario 4) have been proposed, but the agreement of this model with the experimental data is not complete.[31, 33]

In general, dark counts are low compared to the SSPDs efficiency with respect to other single photon detectors. For implementation in experiments, detection events because of stray light is a more problematic issue.
2.3 Fabrication

Figure 2.1a shows a scanning electron microscope image of the usual design of the detector. The detector is a 100 nm wide and about 6 nm thick (based on deposition rate) wire, folded in a 10 x 10 μm area. The detector is placed between two gold contacts, which are arranged in a co-planar waveguide with an impedance of 50 Ω.

2.3.1 Layer deposition

NbTiN films (6 nm thick) are deposited on silicon (with a 225 nm thick oxidized layer) substrates by reactive ion sputtering using a single Nb$_{0.7}$Ti$_{0.3}$ alloy target in an environment of Ar and N$_2$ at room temperature. At first the silicon wafer is cleaned (RF clean 2 min, 200 watt, 100 sccm Ar, 8 mTorr), after which the target is presputtered (4 min, 300 watt, 100 sccm Ar, 4 sccm N$_2$, 8 mTorr). Then NbTiN is sputtered (300 watt, 100 sccm Ar, 4 sccm N$_2$, 8 mTorr). Sputtering in this way gives an amorphous layer.

2.3.2 Contact pads

Contacts of 20 nm Nb and 60 nm Au are made using electron beam lithography and lift off. The patterns are written with the Leica Electron Beam Pattern Generator 5000 Plus system, located at the nanofacility of the TU Delft. At first, the gold contacts and markers are defined. For this step PMMA (polymethyl methacrylate), 950 k 4% in anisol, is spinned on the substrate. This resist is spinned at 2000 rpm and baked afterwards at 170°Celsius for 15 minutes. The spinning speed and concentration ensures a layer thickness of approximately 300 nm. Development is done with methylisobutylketon (MIBK), mixed with isopropanol (IPA), with a ratio of MIBK:IPA=1:3 for 1 minute, and stopped with IPA for 1 minute. After development the contacts are deposited on the sample. The sticking layer is Nb, sputtered at 300 W for 1 minute (giving a ~20 nm layer), followed by the evaporation of 70 nm of AuPd. Then the chip is held in acetone for lift-off.

2.3.3 Meander

The resist is a spin-on-glass, called HSQ (hydrogen silsequioxane). The HSQ is fabricated by Dow Corning, formulated as Fox-12. Line widths with this resist can go down to 10 nm [34] or below. The HSQ is diluted with MIBK, with a ratio of HSQ:MIBK=1:1. The HSQ has to be stored at 4°C and can be processed
when it is at room temperature, i.e. it has to warm up before processing. The spinning speed is 6000 rpm for 55 s to get a layer of 80 nm. In [35] a thorough testing of HSQ is performed.

Subsequently we define an etch mask of hydrogen silsesquioxane (HSQ) with electron beam lithography, and the material not covered with HSQ after exposure and development is etched away by reactive ion etching in a plasma of SF$_6$ and O$_2$. The etching is done in an environment of $SF_6$ (13.5 sccm) and $O_2$ (5 sccm), with a power of 50 watt and $V_{bias}$=220 V. The etch time is 30 seconds + 10 seconds overetch for NbN films and 30 seconds + 30 seconds overetch for NbTiN films.

When a sample is etched it is still covered with HSQ. The gold contacts are also covered with an HSQ layer to prevent Au-contamination of the reactive ion etching chamber. To contact the gold pads this HSQ has to be removed. This is done by dipping the sample for 1 second in buffered hydrofluoric acid (BHF), after which the sample is held in water to stop the etching.

### 2.4 Measurement setup

A schematic of the setup for SSPDs is shown in figure 2.7. We use a simple dip-stick design to immerse the detector in liquid He. The detector is positioned well below the liquid He surface, ensuring a stable operation temperature of 4.2 K. The detector is connected to the outside via a coaxial cable. The heat loss (thermal conductivity) and electrical performance has to be taken into account. The material with the lowest heat loss is stainless steel and the material with the best electrical performance is copper.

The electronic readout system is placed outside the He dewar at room temperature. The current supply consists of a computer-controlled data acquisition unit (National Instruments, DAQPad-6015) in combination with a 200 kΩ resistor and the current is applied via the dc-port of a home-made bias tee (bandwidth: 1 MHz - 5 GHz). The detection pulse processing starts after the RF port of the bias tee, which is connected to an amplifier cascade of low-noise amplifiers, ((1) Mini-circuits ZFL-1000LN (2) RFBay LNA 1000). Two attenuators (3 dB), one placed between the amplifiers and the other after the second amplifier, are used for stabilizing the amplifier cascade and to minimize back actions from the pulse counter. The amplified voltage pulse is either fed to a counter (Stanford Research, SR400 Photon Counter) or is monitored with a 1-GHz oscilloscope (LeCroy, LC574AM) or goes to a time to amplitude converter (Picoquant Picoharp 300). The SSPD can be illuminated through an optical fiber.
**Figure 2.7:** Schematic of an SSPD setup. The detector is immersed into liquid He inside a transport He dewar using a simple dipstick design. The bias current is applied via the dc port of a bias tee. The SSPD RF signal is amplified and detected by a pulse counter. The SSPD can be illuminated through an optical fiber. Picture from [36].

In figure 2.8 photographs of the setup are shown. The electrical readout box is shown in figure 2.8a. The data acquisition card, bias tee and amplifiers are placed inside the box. On the right an output pulse of a detector as recorded by an oscilloscope is shown. In figure 2.8b on the right a special SSPD dipstick placed inside a liquid helium transport dewar can be seen. This dipstick allows for operation at 2 K, by pumping on the outlet of the dipstick. A zoom in of this dipstick is shown on the left, the two coaxial cables and two optical fibers going to the SSPD inside the dipstick are visible. To test a large number of devices we have used a low temperature probestation (figure 2.8c). The probestation has several needles and two high frequency probes. In addition it was possible to place an optical fiber in one of the probe arms. A picture of a sample inside the probestation is shown on the left.
Figure 2.8: (a) Electrical readout box and output of SSPD on oscilloscope. (b) (right) SSPD dipstick in transport dewar. (left) Zoom in of top of SSPD dipstick, with two coaxial cables and two optical fibers coming out of the dipstick. (c) Photograph of low temperature probestation. (left) Image of sample in low temperature probestation.
Part 1
Chapter 3

NbTiN SSPDs on an oxidized silicon substrate

3.1 Low noise superconducting single photon detectors on silicon

We have fabricated superconducting nanowire single photon detectors made of NbTiN on a silicon substrate. This new type of material reduces the dark count rate by a factor of 10 compared to identical NbN detectors, enabling single photon detection with unprecedented signal to noise ratio: we report a noise equivalent power of $10^{-19}$ W·Hz$^{-1/2}$ at 4.2 K. The compatibility of our superconducting device with silicon enables its integration with complex structures.

3.1.1 Introduction

So far, NbN has been the material of choice for SSPDs, due to the possibility of depositing very thin films (4 nm thick [18, 37]), required for SSPDs. Here we report on detectors made of NbTiN, a material with critical temperature $T_c = 15 \text{ K}$ and critical current density $I_c = 5.8 \cdot 10^6 \text{ A/cm}^2$, comparable with NbN ($I_c = 2 - 6 \cdot 10^6 \text{ A/cm}^2$, $T_c = 10 \text{ K}$ [38]). Our NbTiN detectors are fabricated on a silicon substrate, enabling easy integration in advanced electronic circuits. For example, an on-chip amplifier [39] could overcome problems of impedance matching. Processing the silicon substrate makes integration of an optical cavity and coupling with a fiber [38] straightforward. We show that an SSPD made of NbTiN gives a lower dark count rate and matches the quantum efficiency of NbN detectors, leading to an improved signal-to-noise ratio.

Figure 3.1: Quantum efficiency versus bias current for different wavelengths and temperatures, with an exponential fit through the data points. Cooling from 4.2 K to 2.4 K exhibits an increase in quantum efficiency. In the inset a time trace of a detection event is shown.

A detailed description of the fabrication process and the measurement setup is given in chapter 2.

3.1.2 Results

Quantum efficiency

In figure 3.1 the quantum efficiency for different wavelengths is plotted as a function of bias current. All measurements shown in this figure were done on the same device. Each point was measured for 1 second. The quantum efficiency increases exponentially with increasing bias current, as seen from the exponential fit through the data points. The best quantum efficiency is achieved for 650 nm wavelength, for longer wavelengths the efficiency gradually goes down. The wavelength dependence of the quantum efficiency can be used to resolve the photon energy. By cooling from 4.2 K to 2.4 K, the critical current of the detector increases from 35 μA to 40.5 μA. The quantum efficiency almost doubles, reaching a value as high as 2.3% for 650 nm wavelength.
3.1 Low noise superconducting single photon detectors on silicon

Figure 3.2: (a) Dark counts as a function of bias current and counter trigger level at a temperature of 4.2 K (Light gray). A dark count trace for an identical NbN detector is shown for 60 mV counter trigger level (Dark gray). (b) Photon counts per second as a function of bias current and counter trigger level. The incident laser power is 0.01 nW, with 650 nm wavelength.

Dark count rate and noise equivalent power

In figure 3.2a dark counts are shown as a function of bias current and counter trigger level for both a NbTiN (yellow) and a NbN (red) detector. The dark counts are measured without fiber coupling.

\(^1\) The NbN
detector was made from a NbN thin film on a sapphire substrate (commercially obtained [18]), following the same fabrication procedure as the NbTiN detectors. The dark count trace for the NbN detector is comparable to literature [40, 41]. From figure 3.2a it can be seen that below a certain counter trigger level (40 mV) the counter mainly detects environmental noise not related to dark counts (detection events without an incident photon) of the superconducting detector. The dark count rate can be measured by raising the trigger level because dark counts have similar voltage pulse amplitudes compared to real detection events (figure 3.1 inset [31]). If the counter trigger level is too high not all photon absorption events are counted, which is not the case for trigger levels up to 100 mV (fig. 3.2b), counter trigger levels of 50 to 100 mV are optimum for our measurements. The measurement time for the dark count rate (fig. 3.2a) was 900 s per point between 0.85·$I_c$ and 0.98·$I_c$ and 1 s per point above 0.98·$I_c$. The lowest dark count rate was $4\cdot10^{-3}$ s$^{-1}$.

While the quantum efficiency of the NbTiN detectors is as high as for NbN detectors made with the same fabrication procedure, the striking feature of NbTiN detectors is their low dark count rate: a factor of 10 lower compared to NbN detectors. This leads to an unequaled low noise equivalent power (NEP). The NEP is defined to reveal the interplay between dark count rate and quantum efficiency [42], and is given by

$$NEP = \frac{h\nu}{QE}\sqrt{2R_{dc}}$$  \hspace{1cm} (3.1)$$

where $h\nu$ represents the photon energy, $QE$ the quantum efficiency and $R_{dc}$ the dark count rate. In figure 3.3 the NEP for different trigger levels is shown.$^2$ It can be seen that an NEP of $1 \cdot 10^{-19}W \cdot Hz^{-1/2}$ can be reached, 2 orders of magnitude lower than the best NbN detectors.$^3$ Note that the NEP reaches $6\cdot10^{-19}W \cdot Hz^{-1/2}$ very close to the critical current (0.97·$I_c$), a desirable behavior, not yet shown for NbN detectors, caused by the fast decrease in dark count rate with decreasing bias current.

$^2$For a counter trigger level of 30 mV, the dark count rate is high, because of noise in the output signal, which explains the decrease in NEP with increasing bias current. For higher counter trigger levels the dark count rate decreases exponentially with decreasing bias current. Although the QE decreases exponentially with bias current as well, the dark count rate decreases much faster, explaining the decrease of NEP with decreasing bias current.

$^3$NbN detectors show $1 \cdot 10^{-17}W \cdot Hz^{-1/2}$ at a comparable temperature [41]
3.1 Low noise superconducting single photon detectors on silicon

3.1.3 Conclusions

We have fabricated superconducting single photon detectors of NbTiN on a silicon substrate. This type of detectors shows a lower dark count rate compared to NbN detectors processed following the same procedure and measured in the same setup. Presumably, this behavior comes from the fact that a thin layer of NbTiN is less affected by the surroundings than other superconductors [43]. We believe that dark counts are caused by the $2\pi$ phase slip of the macroscopic phase [19], supported by the exponential decrease of dark counts with temperature [31]. Grain boundaries would lead to a reduced free energy barrier ($\Delta F_0$), so we explain the lower dark count rate of NbTiN detectors by a better homogeneity of the superconducting parameters in the NbTiN film compared to NbN. As fabrication on a silicon substrate at room temperature is now possible, integration with advanced structures is within reach. It can be noted that the efficiencies presented in this chapter are lower than shown in later sections (ie. section 3.3 and 4.1). This is likely due to an optimization of the fabrication process.
3.2 Analysis of fabrication yield of NbTiN SSPDs on an oxidized silicon substrate

3.2.1 Introduction

In a later part of this thesis it will be shown that SSPDs have proven themselves to be useful devices for a number of experiments, however the number of applications can become even larger by extending the single pixel SSPDs to a large array of SSPDs, eventually resulting in a single photon camera. This could provide a fast and high resolution imaging sensor suitable for applications like medical optical tomography [44] where both temporal and spatial information must be obtained. Another advantage of an array of SSPDs is the possibility of a larger active area, relaxing the requirements for the accuracy of coupling to an optical fiber. Furthermore, the maximum count rate for an individual SNSPD decreases as its active area is increased, due to its kinetic inductance [26], forcing a trade-off between active area and high count rates. Detector arrays will give a larger active area while increasing the maximum count rate, as the pixels can be made smaller and when one pixel is in the off state because of its dead time, the other pixels can still detect. Large arrays could also provide spatial and photon-number resolution. In a later section scalable readout methods scalable for large SSPD arrays will be discussed. In this section another aspect of arrays will be treated. An important condition to produce a large array of SSPDs is the reproducibility of the fabrication. A large variation of detection efficiencies for apparent identical devices has been reported. [29] This is very inconvenient when a large array is produced, as the yield of good devices will become very low. In Ref. [20] a study of the variation in efficiency is made for a large number of devices made of NbN on sapphire. It is demonstrated that these variations can be understood in terms of ‘constrictions’: localized regions where the nanowire cross section is effectively reduced. These constrictions can appear in the thickness or width of the nanowire, limiting the critical current, causing the rest of the nanowire to be underbiased, which yields a lower efficiency. In this section a similar investigation is presented for NbTiN on oxidized Si.

3.2.2 Devices and experiment

Five wafers (with 2 inch diameter) have been fabricated. The fabrication procedure of the detectors has been described in chapter 2. It starts with sputtering a NbTiN layer on an oxidized silicon substrate. Because the layer to be obtained is thin, the sputter time is short (approximately 5 seconds). The timing of the
3.2 Analysis of fabrication yield of NbTiN SSPDs on an oxidized silicon substrate

![Diagram](image)

Figure 3.4: (a) Indication of sheet resistance measurement positions. (b) Sheet resistance of two wafers and resistivity of devices. The two series refer to different device nanowire length. The unknown variation in thickness results in an uncertainty in $\rho$. (c) SEM picture of a low resistance device. (d) SEM picture of a high resistance device. (e) Sheet resistance for different wafers at two fixed positions.

A valve in front of the sputter gun can be automated, in steps of 5 seconds. It was observed that this timing was not very accurate. The valve can also be operated manually, but this would increase the uncertainty in timing. Therefore the valve was programmed at 5 seconds and a sputtering time of respectively 5.5, 7, 6, 7 and 7 seconds was observed. On all wafers the same devices were made: detectors of 10x10 $\mu$m (corresponding to a wire length of 500 $\mu$m) and detectors of $\sim$12x12
\( \mu m \) (corresponding to a length of 847 \( \mu m \)). To measure the critical temperature of the film a strip of 10 \( \mu m \) and 1 \( \mu m \) width (200 \( \mu m \) long) was also fabricated.

For all wafers, the sheet resistance of the NbTiN layer is measured with a 4 probe measurement. After fabrication the resistance of the devices is measured with a 2 point measurement. Then the wafers are cooled down in a low temperature probe station. The probe station has a chuck base temperature of 4 K. A high frequency probe is used to measure the critical current as well as dark count rate and efficiency. The efficiency is measured by illuminating the detector with a fiber probe. In this study a relative efficiency is presented, by comparing the count rates of the detectors at a fixed power and fiber position. Finally the \( T_c \) was measured in a dipstick with a heater and temperature controller.

### 3.2.3 Results

In figure 3.4a the positions on the wafer of the sheet resistance measurements (figure 3.4b) are indicated. Also in figure 3.4b the measurements of the resistivity of the devices are shown. The resistivity is extracted from resistance measurements of the devices by dividing the resistance by the length and targeted width and thickness (respectively 5 and 100 nm), the two series correspond to the two different device lengths. The sheet resistance measurement already indicates that the layer thickness is not uniform over the whole wafer. However, the variation occurs for every wafer in the same way (for clarity only the sheet resistances from 2 wafers are shown). So this variation is likely because of the limited dimension of the (3 inch) target and the plasma. The device resistivity measurements show a similar variation, i.e. the devices fabricated at places with a high sheet resistance have a higher resistivity than the devices fabricated at places with a low sheet resistance. This would indicate a high reproducibility of the fabrication procedure, which is underlined in figure 3.4c and 3.4d, where SEM pictures are shown for a device with a low resistance and for a device with a high resistance respectively. It can be seen that the width is similar for both devices. The variation in width along the wire is less than 5%. It is worth to note the percentage of 'failures': devices which have zero or infinite resistance: 24%. The reason for zero resistance devices is incomplete etching, resulting in 'left over' NbTiN between the wires, creating a short. In figure 3.4e the sheet resistance is shown for different wafers at a fixed position. The difference in resistivity is noteworthy, but is probably caused by a difference in sputtering time. A thickness measurement is needed to find the cause for the resistivity variation.

From a number of devices the critical current is measured in the low temperature probe station. The critical current as a function of resistivity is shown in
3.2 Analysis of fabrication yield of NbTiN SSPDs on an oxidized silicon substrate

Figure 3.5: (a) Critical current as a function of resistivity. (b) Critical temperature for different devices. The 'bridges' come from a different place on the wafer and such have a different resistivity. (c) Relative count rate as a function of critical current. The solid line is an exponential fit. (d) Count rate versus $I_c \cdot \rho$, with exponential fit (solid line).

It can be seen that the critical current decreases for higher resistivity, which is probably in large part due to the reduced thickness of the wire. For a smaller cross section, the critical current will be lower. From the data it appears that a maximum resistivity of 400 $\mu\Omega$cm (at room temperature) is needed to have a superconducting device. For lower resistivity devices there is quite some spread in critical current, but in general a lower resistivity yields a higher critical current.

The critical temperature has been measured for different devices. This is shown in figure 3.5b. We have measured the temperature dependence of the resistance of two 'bridges' of 10 $\mu$m width, one with a high and one with a low resistivity (figure 3.5). The bridge from a low resistivity chip has a $T_c$=9.1 K, the bridge from a high resistivity chip has a $T_c$=4.8 K. A device of 100 nm width shows $T_c$=8.3 K.

Finally, the superconducting devices are tested under illumination with a 635 nm laser. This is shown in figure 3.5c. Again there is quite some spread in the results, but it is apparent that the trend is that a higher critical current results in
a higher relative efficiency. In figure 3.5d the count rate versus the product $I_c$ and $\rho$ is shown. As there is no clear correlation we can conclude that constrictions are not the source of device failures in our process[20]. The minimum critical current for a device to respond to light is 5 $\mu$A. The percentage of devices that have a critical current of $> 5 \mu$A is 49%.

3.2.4 Conclusions

We have analyzed the fabrication yield of NbTiN SSPDs on an oxidized silicon substrate. We have observed a variation in sheet resistance and device resistivity over a wafer. Devices with a high resistivity ($> 400 \mu \Omega \text{cm}$) have a low critical current, and are also not very sensitive to photons. It is also shown that a low critical current gives rise to a low efficiency. Low resistivity does not automatically mean a high critical current, but all devices with high critical current show a good efficiency. It is confirmed by SEM that the width of a high resistivity and low resistivity device is similar, but the thickness and composition of the wires should also be investigated to exclude them as a reason for the low critical current. This could lead to a higher fabrication yield. In addition, a precise etch monitor could decrease the number of zero resistance devices.
3.3 Efficient and robust fiber coupled superconducting single photon detectors

e applied a recently developed fiber coupling technique to superconducting single photon detectors (SSPDs). As the detector area of SSPDs has to be kept as small as possible, coupling to an optical fiber has been either inefficient or unreliable. Etching through the silicon substrate allows fabrication of a circularly shaped chip which self aligns to the core of a ferrule terminated fiber in a fiber sleeve. In situ alignment at cryogenic temperatures is unnecessary and no thermal stress during cooldown, causing misalignment, is induced. We measured the quantum efficiency of these devices with an attenuated tunable broadband source. The combination of a lithographically defined chip and high precision standard telecommunication components yields near unity coupling efficiency and a system detection efficiency of 34 % at a wavelength of 1200 nm. This quantum efficiency measurement is confirmed by an absolute efficiency measurement using correlated photon pairs (with $\lambda = 1064$ nm) produced by spontaneous parametric down-conversion. The efficiency obtained via this method agrees well with the efficiency measured with the attenuated tunable broadband source.

3.3.1 Introduction and motivation

At near infrared wavelengths above 1100 nm, i.e. at telecommunication wavelengths, superconducting single photon detectors [16] are an established single photon counting technology. [46] Due to their short dead time[16], low timing jitter [47], good device efficiency, and low dark count rate [48] they have already proved themselves in several experimental applications [49, 50, 51]. Furthermore, they are not only suitable for single photon detection, but also for single electron [52] and single plasmon detection [53]. For optical experiments efficient coupling to an optical fiber is crucial. Because of the low operating temperature and the small active area of the detector, this task remains challenging. To date different techniques of fiber coupling to SSPDs have been shown. A fiber focuser in combination with a micropositioning stage at low temperature enables in situ alignment. However, because of loss in the fiber focuser, drift of the micropositioning stages and mechanical decoupling of the fiber and the detector, it was estimated that the coupling efficiency was only 80%. [54] Another technique which is shown by different groups [47, 55] is to mechanically clamp the fiber close to the detector. This can lead to near unity coupling efficiency, but it is
very sensitive to small shifts, i.e. due to thermal contraction during cool down. Recently a fiber coupling technique was introduced for transition edge sensor devices.[56] This technique utilizes micromachining techniques developed for silicon substrates together with optical fiber techniques. Ferrule terminated fibers can be aligned with respect to each other with a commercially available precisely fabricated sleeve. As the dimensions of these sleeves are very precisely defined, it is possible to use sub-micrometer resolution of lithographic technology to fabricate a detector chip with a shape that fits exactly in the sleeve. By fabricating the detector in the middle of the chip, the alignment of the detector with respect to the core of the ferrule terminated fiber follows naturally.

3.3.2 Chip layout

In figure 3.6 the device is pictured. The chip, which has a circular shape (figure 1b) is placed inside the fiber sleeve (figure 3.6a). The detector (figure 3.6c) is placed exactly in the middle of the circular piece of the chip. The detector itself also has a circular design to minimize the length of the nanowire, as the output of a single mode fiber has a Gaussian shape. Although a smaller active area increases coupling difficulty, it has several advantages. First, a smaller detector yields a shorter recovery time and second a smaller detector has a decreased probability of constrictions, which can severely limit device efficiency.[20] The total length of the nanowire was 847 μm, which results in a recovery time of approximately 10 ns. We have chosen for an 11 μm diameter detector to match to the size of a single mode optical fiber. The rectangular part of the chip extends outside the fiber ferrule, on which contacts are positioned for bonding. In figure 3.6d a schematic of the chip is shown.

3.3.3 Fabrication

The detector is fabricated by sputtering a thin NbTiN film on oxidized silicon and subsequent electron beam lithography and reactive ion etching.[48] The circular chip shape is made by deep etching through the silicon substrate. The deep etching is performed by use of the Bosch dry-etch process[57]. This process provides highly anisotropic etching and a vertical etch profile through the 300 μm thick Si wafer can be obtained. It consists of a longer etching step (with SF₆) and a shorter passivation step (with C₄F₈). The passivation step prevents the side walls from being etched. As a mask for the deep etching a photoresist with a thickness of 5 μm is placed to protect the SSPD. To be able to apply electron beam lithography for patterning the chip, a triple layer mask is used.
3.3 Efficient and robust fiber coupled superconducting single photon detectors

Figure 3.6: Assembly of the fiber coupled detector. (a) Chip carrier with a mounted chip. To fiber couple the detector, a fiber ferrule is slid into the sleeve. (b) Photograph of chip. (c) Scanning electron microscope picture of the active area of the SSPD. (d) Schematic of the chip.

The chip is placed inside a fiber sleeve. The fiber sleeve is glued on a chip carrier, the part of the chip that extends through the opening of the fiber sleeve facilitates the contacts for bonding. After bonding and placing the fiber ferrule inside the connector, the assembly is cooled down by either dipping it into liquid helium or by using a dipstick which allows to cool down to approximately 2.5 K.

3.3.4 Setup

In figure 3.7a the setup for measuring the efficiency is shown, using an attenuated tunable broadband light source. The light source consists of a white light source with filtering performed by an acoustic optical modulator. The white light source is a high power ultra-broadband supercontinuum radiation source with a repetition rate of 20 MHz. The acousto-optic tunable filter system enables selection of a particular wavelength with a linewidth of approximately 6 nm. The setup also consists of different (3) neutral density filters, placed in series in the
Figure 3.7: (a) Attenuated tunable broadband setup, consisting of a wavelength filtered white light source, attenuated by neutral density (ND) filters, coupled into a single mode fiber. The polarization is controlled by a polarizer and a fiber coupled polarization controller. Before connecting the fiber to the SSPD, the power in the fiber is measured with a power meter, without the ND filters in place. (b) Setup for absolute quantum efficiency measurement, consisting of a nonlinear crystal, producing collinear type II correlated photon pairs, which are split by a polarizing beam splitter and sent to two detectors.

optical path. The amount of attenuation is measured with a power meter for all the wavelengths of interest. By measuring the neutral density filters separately a precise value of the attenuation is obtained. As the efficiency of the detector is polarization dependent, a fiber coupled polarization controller is used to change the polarization state of the light. The number of photons in the fiber \( N_{ph} \) can be calculated by \( N_{ph} = A \cdot \frac{P \lambda}{hc} \), with \( P \) the measured power before attenuation, \( A \) the total attenuation and \( hc/\lambda \) the photon energy. The loss at the connection to the power meter is approximated to be equal to the loss at the connection to the detector. The flux of photons in the fiber was between \( 10^5 \) and \( 10^6 \) photons/s, much smaller than the repetition rate of the laser and the maximum count rate of the detector, but much larger than the dark count rate of the detector. The system detection efficiency is then defined as the dark count (\( N_{dc} \) corrected count rate (\( N_c \)) divided by the flux of photons in the fiber.

\[
SDE = \frac{N_c - N_{dc}}{N_{ph}}
\]  

Another method to measure the quantum efficiency of a detector is based on the detection of correlated photon pairs. This method [58] has previously been used to characterize avalanche photodiodes [59] and solid state photomultipliers [60]. The detection of a photon in a trigger detector heralds the presence of another (correlated) photon, to be detected by the device under investigation. The correlated photon pairs are produced by a nonlinear crystal via the process
of spontaneous parametric down-conversion. The setup for this measurement is shown in figure 3.7b. The crystal is a KTP (KTiOPO₄) crystal, from which collinear type-II correlated photon pairs are created. The crystal is pumped with a diode pumped solid state laser, generating photon pairs at a wavelength of $\lambda=1064$ nm with orthogonal polarization. The pair is split at a polarizing beam splitter after filtering out the pump beam. The correlated photons are then sent to two detectors. A time to amplitude converter is used to record the single count rates ($N_{d1}, N_{d2}$) and number of correlations ($N_c$). Without accidental and dark counts the efficiency of detector 1 is: $\eta_1 = N_c / N_{d2}$. In the presence of accidental ($R_A$) and dark counts ($N_{dc}$) and an imperfect collection efficiency ($p_1$) the equation is the following:

$$\eta_1 = \frac{N_c - R_A}{p_1 \cdot (N_{d2} - N_{dc})} \quad (3.3)$$

By exchanging the paths, the collection efficiency ($p_1$ and $p_2$) can be determined.

### 3.3.5 Results

First, the results using the 'attenuated' method are presented. In figure 3.8a the dark count rate and system detection efficiency as a function of current through the SSPD are shown for a wavelength of $\lambda=1310$ nm, for the polarization state which gives maximum efficiency. We show in the next chapter that the interface between the silicon substrate and the silicon dioxide acts a reflecting surface and maximum absorption can be approximated with $d \approx \frac{\lambda}{4n} + m \cdot \frac{\lambda}{2n}$ with $d$ the thickness and $n$ the refractive index of the silicon dioxide and $m=0,1,2...[47]$. With $n=1.5$ and $d=220$ nm, for our device $\lambda_{max} \approx 1300$ nm. As expected, the system detection efficiency increases exponentially with current towards a plateau. It is clear that at a temperature of 4.2 K this device did not show its maximum efficiency, but decreasing the temperature to $\sim 2.5$ K yielded a higher critical current and a higher detection efficiency, with a maximum of 34%. The dark count rate as a function of current showed the well known two slope exponential behavior. Background counts caused by detection of stray environment light coupling into the fiber are the major contribution at low currents. For currents close to the critical current the 'intrinsic' dark count rate takes over. The maximum dark count rate was $\sim 1000$ cps for 4.2 K and $\sim 500$ cps for 2.5 K.

In figure 3.8b the system detection efficiency at 95% of the critical current (where the dark count rate is smaller than 10 cps) is shown as a function of wavelength for the polarization states yielding maximum and minimum efficiency. The operating temperature for this experiment was 2.5 K. The curve shows two
peaks in efficiency with a maximum at a wavelength of 1200 nm, although it has been shown that the intrinsic efficiency of SSPDs is higher for shorter wavelengths.
It is apparent that the absorption efficiency plays a large part in the system detection efficiency, as this is highly increased for the cavity specific wavelength of $\lambda=1200$ nm. To explain the shape of the curve we model the optical system according to [47] to calculate the absorption efficiency $\eta_{\text{absorption}}$. The absorption without optical fiber is simulated in an FDTD simulation, with the optical index $(n,k)$ measured with an ellipsometer. To incorporate the effect of the fiber tip the absorption efficiency is multiplied with a function which describes a Fabry-Perot cavity using Fresnel equations. In order to fit the data of figure 3.8b, we define the system detection efficiency as $SDE = \eta_c \cdot \eta_{\text{intrinsic}} \cdot \eta_{\text{absorption}}$. For the SDE the coupling efficiency $\eta_c$ is taken as unity. We approximate an exponential wavelength dependence of the intrinsic efficiency $\eta_{\text{intrinsic}}$ of the detector. [47] In figure 3.8b the resulting fit through the maximum polarization can be seen. The fit explains the shape well. From the fitting we obtain a fiber tip to detector distance of $l=1.23\mu m$, which is a reasonable value as the fiber ferrule is directly in contact with the chip. The fit also yields a maximum value of $33.6\%$ efficiency at $\lambda = 1200$ nm.

The results of the ’attenuation’ method are verified using the absolute efficiency measurement setup. We have performed a full set of measurements, with two silicon avalanche photodiodes and another self aligned SSPD as conjugate detector. The coincidences are recorded for a fixed time (120 s). By fitting all data sets, the path and detector efficiencies are determined. The efficiencies of the two Si avalanche photodiodes turn out to be $1.52\%$ and $1.57\%$, slightly lower than their specifications (www.optoelectronics.perkinelmer.com). The efficiency of the SSPD under investigation is $11.9\%$. As can be seen in figure 3.8b (circle) this is in good agreement with the ’attenuation’ method.

### 3.3.6 Conclusion

In conclusion, we have applied a technique which reliably couples a fiber to a superconducting nanowire single photon detector. We have shown a high coupling efficiency and peak system detection efficiency of $34\%$ at $\lambda=1200$ nm. In the future we will use fibers with an antireflection coating, which will reduce losses at the end of the fiber. In addition, the optical system can be designed such that it is possible to have the maximum efficiency at any required wavelength.
Chapter 4

Cavity enhanced detectors

4.1 Enhanced telecom wavelength single-photon detection with NbTiN superconducting nanowires on oxidized silicon

We report on the practical performance of packaged NbTiN SSSPDs fabricated on oxidized silicon substrates in the wavelength range from 830 to 1700 nm. We exploit constructive interference from the SiO2 / Si interface in order to achieve enhanced front-side fiber-coupled DE of 23.2 % at 1310 nm, at 1 kHz dark count rate, with 60 ps full width half maximum timing jitter.

4.1.1 Introduction

The 1300 nm wavelength range is important for quantum information experiments using telecom-wavelength quantum-dot single-photon sources [62] and medical applications such as singlet oxygen detection at $\lambda=1273$ nm.[63] In this paper we report on enhanced device efficiency in a Nb-TiN SSPD with a cavity reflection from the oxidized Si substrate optimized for 1300 nm wavelength. The devices are front-side fiber-coupled in a fixed package without the need for nanopositioners or thinning of the substrate used in backside illumination architectures.[29, 55, 54] In this section, we describe device performance as a function of wavelength, with reference to the device architecture. We demonstrate the highest published efficiency in a practically packaged SSPD at $\lambda=1310$ nm with frontside fiber illumination, comparable to results achieved with backside illumination.

Devices used in this study [48] are based on high quality films of NbTiN deposited by reactive dc magnetron sputtering at room temperature on a Si substrate with a 225 nm SiO₂ layer. The devices studied consist of a 10x10 μm² detector, composed of a meander wire 100 nm wide with 200 nm pitch. This was aligned to a single-mode optical fiber with 9 μm mode field diameter as shown in figure 4.1a. The chip-to-fiber spacing was determined through white-light interferometry d=35 μm, at room temperature decreasing to d=10 μm at the operating temperature of 2.8 K. Electrical and optical testing is performed in a Gifford-McMahon cryocooler at a device temperature of 2.8 K, well below the observed device superconducting transition temperature of 8 K. The experimental arrangement for DE measurements is shown in figure 4.1d. The optical attenuation of the laser diode source is varied to control the photon flux while the detector count rate is monitored. Bias current is varied to control the dark counts.

4.1.2 Results

System DE determined from the fiber input to the cryostat was measured by use of calibrated laser diodes at 830, 1310, and 1550 nm wavelength with polarization optimized for both high and low device DE [65] at multiple biasing points, as shown in figure 4.2a. High DE is observed at all wavelengths, at 1 kHz dark count rate DE=8.5%, 23.2%, and 7.8% at 830 nm, 1310 nm and 1550 nm wavelength, respectively. At dark count rates as low as 20 Hz, DE of 7.5%, 10%, and 2.8% are observed for 830 nm, 1310 nm and 1550 nm illumination, respectively. The most striking feature is that DE is higher at 1310 than 830 or 1550 nm wavelength owing to the optical structure discussed below. Without an optical cavity, efficiency will decrease with increasing wavelength [17]. In other respects, the DE versus dark count rate conforms to behavior observed in NbN SSPDs. [51] When dark count rate is reduced from 1 kHz to 20 Hz, the fractional loss in device efficiency is greatest at λ=1550 nm (DE₂₀Hz/DE₁kHz=0.36), and least at λ=830 nm (DE₂₀Hz/DE₁kHz=0.88). At shorter wavelengths, photons have sufficient energy to trigger an output pulse even at low bias current. [17, 61] Inductance and timing jitter are important performance parameters in SSPDs. The absolute kinetic inductance value Lₖ sets the recovery time of the device. [26, 51] Inductance measured as a function of bias, using a vector network analyzer, indicates device uniformity. [20] Lₖ of 342 nH was measured at zero bias current, which agrees well with observed pulse decay time (1/e) of 6.58 ns. A 25% upturn in Lₖ was observed toward I_c. This supports the observation of high DE and indicates that film quality and wire fabrication are extremely uniform. The
4.1 Enhanced telecom wavelength single-photon detection with NbTiN superconducting nanowires on oxidized silicon

Figure 4.1: (a) Full chip and fiber arrangement, not to scale. (b) Simulated probability of photon absorption in NbTiN layer ($\eta_{\text{absorption}}$). (c) Simulated electric field in device layers assuming $10^6$ photons incident in a 10x10 $\mu$m$^2$ device area with $\lambda=1310$ nm. (d) Experimental arrangement for DE measurements. Current is supplied below $I_c$ through the dc line of the bias T, while pulses are read out through the ac line. Laser diodes of different wavelengths are attenuated to provide a controlled photon flux (via calibrated in-fiber attenuation). A manual polarization controller is used to match the optimum photon polarization to the device orientation.

Jitter of the device is the timing uncertainty between the photon arrival and the electrical output pulse, and limits how accurately events can be time-stamped. Measurements at $\lambda=1550$ nm using a 50 ps full width at half maximum (FWHM) diode laser and a time-correlated single-photon counting card, gave 60 ps FWHM jitter, comparable to other 10x10 $\mu$m$^2$ NbN SSPDs.[66] DE can be defined as $\text{DE} = \eta_{\text{coupling}} \cdot \eta_{\text{absorption}} \cdot \eta_{\text{pulse}}$, where $\eta_{\text{coupling}}$ is the optical coupling probability from the fiber to the detector, $\eta_{\text{absorption}}$ is the probability of photon absorption...
in the NbTiN layer, and \( \eta_{\text{pulse}} \) is the probability of an absorbed photon resulting in a measured pulse.\[17, 65\]

![Figure 4.2:](image)

**Figure 4.2:** (a) Device detection efficiency vs dark count rate at three wavelengths. Polarization optimized for high (low) efficiency shown as squares (circles). Note: vertical scales vary. (b) Polarization-dependent measurement of DE over a wide wavelength range with 700 Hz dark count rate. (Main plot) Detection efficiency with fixed input polarization set to maximize (minimize) response at 1550 nm shown as solid (dashed) line. (Inset) Average of the two results from the main plot shown as dashed line. Data taken with the polarization scrambling method shown as solid line precisely aligning with the averaged data. (c) DE with varying wavelength at 1.7 kHz dark count rate. (Main plot) Average of measurements taken with polarization set for high and low response at reference wavelengths to produce a polarization independent result. Vertical dashed line marks the designed absorption maximum. (Inset) Simulated data with \( \kappa = 1 \ \mu m^{-1} \).

In this device, a half cavity is achieved due to the 225 nm SiO\(_2\) (n≈1.45 at
λ=1310 nm) atop the Si substrate (n≈3.5 at λ=1310 nm). Transfer matrix simulations of multilayer reflectivity are used to calculate the absorption of the NbTiN layer, as shown in 4.1b, giving a clear peak at λ≈1310 nm (η_{absorption} ≈65%). This corresponds to a SiO₂ layer optical thickness of λ_{eff}/4 giving an electric field maximum at the NbTiN layer (figure 4.1c. This matches well with the experiment (figure 4.2) in which photons at λ=1310 nm were detected more efficiently than those at 830 or 1550 nm. Without the cavity reflector, η_{absorption} is calculated to be less than 15% at λ=1310 nm; thus the layer structure has significantly increased efficiency in the device. While the cavity is not optimized for λ=830 and 1550 nm, these efficiencies are also increased by the reflection. Without the cavity enhancement (4x at λ =1310 nm, the device would demonstrate efficiencies comparable to those of NbN devices.[51] However NbTiN has shown favorable dark count characteristics and is more versatile in growth conditions enabling the fabrication of the cavity devices. It should be noted that the simulations are based on the optical properties of an unpatterned 10 nm thick NbTiN film measured by ellipsometry at room temperature.

The real and imaginary parts of the refractive index (n,k) are n=4.17 and k=5.63 at λ=1310 nm. This simulation may not link accurately to the absolute absorption in the nanostructured device but reproduces the trend of absorption versus wavelength and the enhancement due to the cavity. To further test the dependence of DE on wavelength, another NbTiN SSPD device from the same fabrication batch was fiber-coupled and measured in a second experimental setup. The fixed-wavelength source in figure 4.1d was substituted for a white-light source and monochromator with calibrated filters and in-fiber polarization control to produce full spectrum device measurements. Photon count rate was recorded with constant device biasing as wavelength was varied. However, polarization at the device under test varies with wavelength due to birefringence in the fibers if the photon source arrangement is kept constant. The measurements in figure 4.2b have been used to examine this polarization dependence. In the main plot the polarization controller was used to maximize and minimize counts at a reference input wavelength of 1550 nm (dark counts=700 Hz). The higher device response is seen to oscillate between the two measurements as polarization at the device progresses when the input wavelength is swept. The two full spectrum sweeps for polarization set at the reference wavelength were averaged to produce the dashed line in the inset plot. An additional data set was taken with the polarization controller replaced by an automatic polarization scrambler, shown as the solid line in the plot. The two data sets in the inset match very well, within the expected variation in the device response. This confirms that this averaging method is sufficient to produce a polarization-independent result.
when a polarization scrambler is not available. To most clearly observe the effect of the optical cavity on the DE, a higher device biasing was used for the data in figure 4.2c (dark counts =1.7 kHz), as this reduces the variation in \( \eta_{\text{pulse}} \) across the wavelength range, making the dependence on \( \eta_{\text{absorption}} \) more apparent. A peak in DE is seen at a photon wavelength of approximately 1250 nm, lower than the expected absorption peak at 1310 nm. Additional oscillations are present in the data, with a period increasing from 60 to 150 nm across the full wavelength range. These oscillations are due to Fabry Perot interference between the fiber end and the device surface with separation of \( d=8 \mu m \). It is expected that DE is dependent on the \( \eta_{\text{pulse}} \). As observed in figure 4.2, DE is more dependent on device biasing for longer wavelength photons (\( \lambda=1550 \text{ nm} \)), thus photon energy should be accounted for in \( \lambda_{\text{pulse}} \). In order to fit the data of figure 4.2c, we approximate the wavelength dependence of an SSPD at high bias as \( \eta_{\text{pulse}} \propto e^{-\kappa \lambda} \), where \( \kappa \) is a fitting constant.\(^{[17]} \) The expected efficiency of the device is then \( \text{DE}_{\text{sim}} \propto \eta_{\text{absorption}} \cdot e^{-\kappa \lambda} \) if \( \eta_{\text{coupling}} \) is taken to be a constant and the fiber-to-device cavity oscillation is included in \( \eta_{\text{absorption}} \). The simulated efficiency dependence on wavelength is shown in the inset of figure 4.2c with \( \kappa =1 \mu m^{-1} \). The form of the experimental response is recreated and fiber-to-device oscillations are accurately reproduced in scale and period. The energy dependence of \( \eta_{\text{pulse}} \) reduces the wavelength of peak efficiency and causes a greater drop in efficiency at long wavelengths compared to simulated absorption alone, as observed in the experimental result; \( \kappa \) is chosen to give the best fit to both these features. While the form of the simulated absorption matches that of the experimental result, the features are not precisely aligned; this is likely due to (a) the difficulty of accurately obtaining optical data for thin film NbTiN at low temperature, (b) the optical properties of the nanopatterned device, and (c) a more complex dependence of \( \eta_{\text{pulse}} \) on wavelength than that used in this work.

4.1.3 Conclusions

In this section, we have reported the full characterization of a NbTiN SSPD with a quarter wavelength cavity reflection optimized for \( \lambda=1310 \text{ nm} \). We have achieved a well understood increase in DE in a practically packaged front side fiber-coupled system. This gives DE of 23.2% with 1 kHz dark count rate at \( \lambda=1310 \text{ nm} \), with low DE drop-off at lower dark count rates. This is combined with low jitter and fast reset times suitable for use in a variety of timecorrelated single-photon counting experiments. Simulation of superconducting layer absorption with the additional effects of photon energy and FabryPerot oscillations gives a model of the dependence of detector efficiency on incident photon wavelength that
describes all experimental features. The optical architecture is well understood and can be optimized for alternative important wavelengths, such as 1550 nm.
4.2 SSPDs on a DBR substrate

4.2.1 Introduction

The main limitation in the SDE of SSPDs arises from the low absorption of the thin meandering wire. Although NbTiN is a good absorber, with a 6 nm thick continuous film exhibiting about 30% absorption at 1550 nm, this value decreases when the film is structured into a meandering wire with 50% filling factor. It is about 20% for light polarized along the wire, and 10% for light polarized orthogonal to the wire. These values arise from the interaction with the subwavelength and periodic structure of the nanowire [65]. In order to enhance the absorption an SSPD with a mirror was introduced. [67] This concept was extended by adding an anti-reflection coating to minimize reflection losses from the illumination side [29]. In that report a DE ($\eta_{\text{abs}} \cdot \eta_{\text{pulse}}$) as high as 57% at 1550 nm was demonstrated. In both works, the authors added an optical cavity composed of a quarter-wave thick dielectric material and a reflecting metal mirror on top of the detector to enhance the reflection around a central wavelength of interest, which in their case was 1550 nm. Although the DE was high, the requirement of back side illumination can easily result in coupling losses.

So far, most of the efforts to integrate optical cavities with SSPDs have been concentrated in schemes that require back side illumination (i.e. the optical cavity and mirror are deposited on top of the detector). Besides the convenience of post-processing, one of the main reasons for this approach is the difficulty to fabricate high quality and uniform nanowires on top of an optical cavity. The film thickness employed in SSPDs requires good surface quality and lattice matching to ensure film uniformity [27]. Nevertheless an SSPD with an integrated optical cavity for front side illumination is highly desirable due to the simpler methods available to efficiently couple an optical fiber with the detector [68], and the possibility to integrate with on-chip photonic circuits. The capability of fabricating high quality NbTiN single photon detectors on Si substrates is a viable solution to the problem since one can introduce Si compatible technologies into the SSPD fabrication process. Already in this direction, it has been observed in fiber coupled SSPDs (FC-SSPDs) built on oxidized Si substrates, that there is an enhanced absorption and thus an enhanced SDE for photons with a wavelength of $\lambda = 4nd$, where $n$ and $d$ are the refractive index and thickness of the SiO$_2$ respectively (see section 4.1). The enhancement was due to the extra reflection taking place at the SiO$_2$/Si interface and the cavity like behavior of the quarter-wave thick SiO2 layer, leading to constructive interference at the surface of the

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This section is based on E. Bermúdez Ureña, Master Thesis
chip at the corresponding wavelength. The achieved SDE was 23.2 % at 1310 nm with a dark count rate of 1000 c/s. In this system, the absorption of the nanowire was not very high since the extra reflection from just one SiO$_2$/Si interface is not very strong.

In this section we investigate the possibility of improving $\eta_{\text{abs}}$ by fabricating SSPDs on top of highly reflective substrates compatible with Si technologies and suitable for front side illumination, specifically we implemented a distributed Bragg reflector (DBR) as our back mirror. A DBR is a one-dimensional photonic crystal which has a periodic variation of the effective refractive index. It is made of a stack of alternating high- and low-refractive index layers, with each layer in the stack having a quarter-wave optical thickness. This results in a constructive interference and a high reflection band centered around the target wavelength. The shape of the reflectivity spectrum is determined by the layer composition and thickness. The refractive index contrast between the two materials determines the number of layers needed in the stack to achieve a specific reflectivity value. These type of mirrors offer reflectance values above 90% with the appropriate choice of layers, and in the case of silicon based photodetectors they have already been implemented [69]. It was indeed reported that SSPDs based on the same approach, though the full details of the materials used in the dielectric mirror were not specified, showed an enhanced efficiency at the target wavelength of 1550 nm. [70].

### 4.2.2 Simulation

In this section we simulate the absorption efficiency of photons in the wire. The absorption of photons by an SSPD can be approximated by a plane wave interacting with an infinite grating [9]. Both approximations can be justified because in general, experiments are performed with photons at normal incidence and with plane-wave phase fronts (e.g. fiber coupled detectors), and also due to the geometry of the detectors, where the SSPD can be visualized as a periodic array of sub-wavelength strips. The software used in this thesis is different from that used by V. Anant et al., but the method used to calculate the absorption of the SSPD remains basically the same [65]. We used the Lumerical FDTD solutions software (Lumerical Solutions Inc., www.lumerical.com). It uses a Finite Difference Time Domain (FDTD) method for solving Maxwell’s equations in complex geometries. It is a fully vectorial method that provides both time domain and frequency domain information. To simulate the absorption of a periodic grating we have used a two-dimensional simulation with periodic boundary conditions in the x-direction (to simulate the periodicity of the nanowire meander), and as-
sumed the wire to be infinitely long (out of plane direction). The latter is valid since the meandering segments have a length which is longer than the incident wavelength. A snapshot of the simulation cell with the main objects labeled can be found in figure 4.3a.

![Simulation diagram](image1)

**Figure 4.3:** (a) Snapshot of the simulation working space with the main components labeled. (b) Schematic of the simulation cell, with a 100 nm wide nanowire inside a 200 nm wide cell. (c) Extinction coefficient (red) and refractive index (black) of a 10 nm thick NbTiN film.

The simulation cell is defined by the enclosing simulation mesh (in orange), while a smaller mesh surrounding the wire segment (not visible) is placed as an override region where we can ensure a constant small mesh step size in the nanowire area. In our simulations, the smallest mesh step size was set to 0.25 nm. Plane waves are injected from the top of the structure and can have either the electric field polarized along the wire (TM or p-polarization) or orthogonal to the wire (TE or s-polarization). A group monitor is placed surrounding the wire segment and allows us to record the electric field intensity ($|\vec{E}(x,y)|^2$) and the imaginary part of the permittivity ($\epsilon(\omega)$) in order to calculate the absorption of the wire (field and index monitors). A time monitor is placed inside the simulation cell to ensure that the simulation has run for a sufficiently long time to ensure the radiation has left the simulation volume. A close-up look of the nanowire in the cell is schematically illustrated in figure 4.3(b) and represents the standard features of our SSPDs. The simulation cell contains a 100 nm wide wire with a filling factor of 50% (i.e. 200 nm period), in this case on top of a Si/SiO2 substrate. The thickness of the NbTiN layer was set to 6 nm. Since the material database does not include the optical parameters of NbTiN (refractive index...
and extinction coefficient), we added the data after an ellipsometry measurement performed on a 10 nm thick NbTiN film deposited on an oxidized Si wafer, using a J. A. Woolam Inc. ellipsometer inside our Nanofacility. The results are shown in figure 4.3c and are comparable to those of a 12 nm thick NbN film reported in [65]. The total absorption of the nanowire is determined by the integral of the time-averaged resistive dissipation (power loss) over the cross-section of the wire, normalized to the power of the incident source. This can be represented by the following expression:

\[
A = \frac{\int \int \omega \text{Im}[\varepsilon(\omega)]|\vec{E}(x,y)|^2\,dxdy}{\int (\frac{\omega}{\mu_0})^{1/2} |\vec{E}_0|^2\,dx}
\]

(4.1)

where the top and bottom integrals represent the power loss (absorption) in the nanowire cross section, and the source intensity respectively. Here, \(\omega\) is the angular frequency, \(\varepsilon_0\) is the permittivity of air, \(\mu_0\) is the permeability of air and \(\vec{E}_0\) the intensity of the time averaged incident electric field.

As seen in section 4.1, the SSPD absorption benefits from the extra reflections occurring at the interfaces of the underlying substrate. In an oxidized Si substrate though, it is a weak reflection, and it would be desirable to increase it. To do so we can make use of the available semiconductor processing technologies and fabricate high reflectivity mirrors by means of dielectric coatings. In our case we had access to distributed Bragg reflectors (DBRs) especially fabricated for infrared applications [71]. These DBRs consist of SiO\(_2\)/Si\(_3\)N\(_4\) layers grown by plasma enhanced chemical vapor deposition (PECVD). We investigated the effect of the number of SiO\(_2\)/Si\(_3\)N\(_4\) pairs on the absorption of an SSPD in order to choose an appropriate substrate for our interests. A schematic of the unit cell used in the simulation is shown in figure 4.4a for the case of 5 pairs plus a quarter-wave cavity. The thickness of the SiO\(_2\) and Si\(_3\)N\(_4\) layers was 270 nm and 190 nm respectively, and 6 nm for the NbTiN wire. The width of the nanowire was 100 nm with a filling factor of 50%. The plane wave source was set to TM mode (light polarized along the length of the wire). In figure 4.4b, results for 1 (black), 2 (orange), 3 (green), 5 (blue) and 7 (red) pairs are shown. Special attention should be given to the right side of the spectrum where a systematic increase of the absorption maximum as a function of increasing pair number can be observed. Already at 5 pairs, the absorption reaches a value of 84% at 1550 nm, which is almost a factor of 1.8 higher than with a Si substrate with a 270 nm SiO\(_2\) layer. Increasing the number of pairs to 7 would increase the maximum absorption only to 85.8%. From the technical point of view, this requires 4 more layers in the stack, making the growth process more complex, so we decided to
proceed with the 5 pair DBR substrate. These high absorption values give a lot of promise to increase the SDE of SSPDs fabricated on Si substrates. With the samples reported in section 4.1, where a maximum absorption of 44% is expected at 1550 nm, a SDE of 10% was measured. Assuming that the quality of the nanowire would be the same for the SSPD on a 5 pair DBR, we can expect a SDE of 19% at 1550 nm, which would be comparable to the recently reported values[54] for a SSPD with back side illumination (24 % at 1550 nm).

![Figure 4.4](image)

**Figure 4.4:** Simulation of the SSPD absorption on top of distributed Bragg reflectors. (a) Schematic of the simulation cell for the case of an SSPD on top of 5 pairs of SiO2/Si3N4 plus a quarter-wave cavity. (b) Absorption as a function of wavelength of an SSPD with increasing number of underlying SiO2/Si3N4 pairs (TM polarization).

### 4.2.3 Optical setup

To investigate the frequency response of the SSPDs on DBRs we used a supercontinuum white light source (Fianium SC400) coupled to a monochromator (Acton SpectraPro-150), which enables experiments over a broad wavelength range, from 400 nm to beyond 2 μm. The 'Fianium’ is a high power fiber laser generating supercontinuum radiation in the 400-2400 nm spectral band with an average power of 2 W and spectral density of >1.5 mW/nm. It consists of three main parts: a master source, a power amplifier and a supercontinuum generator. The master source consists of a low-power fiber laser which provides light pulses of approximately 5 ps at a repetition rate of 20 MHz. The power amplifier is based on a double-clad Yb-doped fiber pumped by a high power laser-diode pump module. The supercontinuum spectrum is generated by means of a highly-nonlinear optical fiber. The output beam of the Fianium is coupled into the entrance slit of the monochromator.
4.2 SSPDs on a DBR substrate

The SpectraPro-150 monochromator has a focal length of 150 mm. It features an astigmatism-corrected optical system and interchangeable grating turrets. We used a set of two plane ruled gratings (Newport Corporation) with different groove density and blazing angles, specifically one with 1200 g/mm blazed at 750 nm and the other one with 600 g/mm and blazed at 1.6 μm. The blazing angle determines the wavelength of maximum efficiency. In our experiments, when working in the range of the telecom wavelengths (1.3 μm and 1.55 μm) we used the grating blazed at 1.6 μm, while for the visible range we worked with the grating blazed at 750 nm.

An important feature to consider when working with diffraction gratings is the existence of different diffraction orders. Light diffracted at a grating satisfies the grating equation:

\[ m\lambda = d(sin(\alpha) + sin(\beta)) \]  

where \( m \) is an integer and represents the diffraction order, \( \lambda \) is the incident wavelength, \( d \) is the groove spacing, and \( \alpha \) and \( \beta \) are the incident and diffracted angle respectively. We implemented long pass filters after beam collimation at the output of the monochromator in order to eliminate the higher order contributions of the monochromator.

4.2.4 Results

The first attempts to grow NbTiN on DBR substrates were based upon the already established growth process on oxidized Si wafers, where a sputtering time of 5 seconds is typically used to achieve films with 4.5 nm in thickness (0.9 nm/s growth rate). The superconducting nanowires obtained with these parameters exhibited low and unstable critical currents (\( I_c \)) below 1 μA, hinting that the film quality was not optimal, with one of the possible reasons being that the film had a non-uniform microstructure leading to constrictions in the nanowire and thus limiting the critical currents [20]. In a subsequent batch, the sputtering time was increased to 7 seconds in order to obtain thicker films (6 nm). With this approach we were able to obtain superconducting nanowires with higher critical currents (\( \approx 5 \) μA) and were able to detect photons.

To study the spectral response of our devices we separated our wavelength range of interest in two regions, below and above 1000 nm, to separate effects arising from the gratings in our monochromator. For the 500 nm to 1000 nm range we used the grating blazed at 750 nm without long pass filter. For wavelengths above 1000 nm we used the grating blazed at 1.6 μm and a long pass filter at 800 nm. The power was measured by connecting a power meter directly to the output.
Chapter 4. Cavity and grating enhanced detectors

of the fiber (Thorlabs S154C and S120C above and below 1000 nm respectively). The detection counts and power sensor scans for a given wavelength range were taken consequently to avoid discrepancies in the efficiency calculation.

The system detection efficiency (SDE) is again calculated as:

$$SDE = \frac{N_c - N_{dc}}{N_{ph}}$$  \hspace{1cm} (4.3)

where $N_c$ is the detection count rate, $N_{dc}$ the dark count rate and $N_{ph}$ is the photon rate at the fiber output, calculated by $N_{ph} = P/E_{photon}$, with $P$ the measured power.

We coupled the detector to a fiber to have effective overlap between the light from the output of a single mode fiber and the active area of the detector. This means that the scaling between detection counts and photon number measured at the end of the output fiber should yield an accurate value of the maximum SDE possible with these detectors. The fiber coupled detector on a DBR substrate (FC-DBR) was operated at a current of $I_{bias} = 0.9 \cdot I_c$, where $I_c \approx 11 \mu A$ and the dark count rate was 100 c/s. The SDE of this device is shown in figure 4.5. The dashed line at 1100 nm marks the boundary between the two scans. The red trace is the simulated SDE for our device based on the simulations presented in section 4.2.2. The small shift in the position of the peaks between the simulation and the experimental data can arise from discrepancies in the actual material properties and precise DBR layer thicknesses versus the ones used in our FDTD simulations.

Even though the SDE exhibits the expected wavelength dependency due to the absorption properties of the nanowire imposed by the DBR substrate, the overall values are low. At 1550 nm we obtained an SDE of just 0.02%, at least two to three orders of magnitude lower than expected, assuming that the quality of the nanowires is as good as in the case of SSPDs on oxidized Si substrates. Evidently this is not the case, the low measured SDEs are most likely a consequence of non-uniformities in our nanowires. Since our fabrication process yields uniform wire widths, our suspicion was that the growth of NbTiN films on DBR substrates gives rise to films with less uniformity than those grown on oxidized Si wafers, most probably due to a difference in the surface roughness between the two types of substrates.

We did not carry out detailed surface studies in our samples; but the kinetic inductance measurements on our FC-DBR device carried out at Herriot Watt University in Edinburgh, support the suspicion about the bad quality of our nanowires. In short, by measuring the kinetic inductance of the SSPD at different bias currents and with a suitable model [20], a characteristic value (labeled
4.2 SSPDs on a DBR substrate

Figure 4.5: System detection efficiency as a function of wavelength of the fiber coupled SSPD on a DBR substrate. The experimental data points are plotted in black while the red trace is based upon absorption simulations and a scaling factor to account for the energy dependence of the internal quantum efficiency.

as $C$) can be extracted, which provides information about the ratio of the constricted cross sectional area to the unconstricted superconducting cross section of the wire. A value of $C = 1$ corresponds to a theoretically perfect device (unconstricted), while lower values imply that there are constrictions present in the nanowire. Typically, the kinetic inductance in a nanowire is observed to increase as the critical current is approached, due to the increased current density. In devices with constrictions, the increase is weaker because at high bias the current density in most of the device is still far from the critical current density of the unconstricted segments. Figure 4.6 shows the results obtained in our FC-DBR (red) as well as the results of an SSPD on an oxidized Si substrate from a previous batch fabricated in our group (blue). It can be seen that the inductance increases with current. This is due to the depletion of Cooper pair density and the consequent local increase in pair velocity necessary to maintain the current. The total kinetic inductance of the wire therefore provides a way to determine if $I$ is indeed near $I_c$ over the whole wire or only at one localized place. The solid line is a fit according to Ginzburg-Landau theory with no free parameters solid line.

If we consider a transmission line in which the total current changes due to a small ac current, the electric field response to the inductance is given by $E = (L/l)dI/dt$ where $l$ is the length of the superconducting strip and $L$ is the total inductance which is the sum of the magnetic and the kinetic inductances.
From the first London equation \( \frac{dj_s}{dt} = n_s \cdot e^2/m \cdot E \), we can derive the inductance as 
\[
L = (-ml/e)\frac{dv_s}{dI}
\]
where \( v_s \) is the velocity of the superconducting electrons. The current corresponding to the Ginzburg-Landau equations in the case of sufficiently thin superconducting strips is expressed as
\[
I = -Aen_s(1 - \frac{v_s^2}{3v_m^2})v_s
\]
where \( A \) is the cross-sectional area of the superconducting strip and \( n_s \) is the density of the superconducting electrons in absence of currents, \( n_s = n[1 - (T/T_c)^\alpha] \). The value of \( \alpha \) is an exponent which determines the variation of \( n_s \) with temperature. From these equations the inductance can be derived as a function of the temperature and the bias current
\[
L(T, I) = L_0[1 - (T/T_c)^\alpha]^{-1} \cdot [1 + \frac{4}{9I_c^2} \cdot I^2]
\]  
where \( L_0 = ml/Ae^2n \). Therefore, equation 4.4 allows the determination of the temperature dependence of the inductance at fixed bias current and the bias current dependence of the inductance at fixed temperatures. The data in figure 4.6 is fitted with \( L = L_0 \cdot C \cdot I^2 \), with \( C \) a scaling factor. For a constricted device the inductance increases less than predicted, due to a constriction: \( I \) is only near \( I_c \) at one localized place whereas everywhere else \( J \) is lower, producing a smaller total increase in inductance. This can be quantified in a value, which is the factor \( C \) by which \( I_c \) must be rescaled for a given device so that the \( L_k/L_0(I_{bias}/I_c) \) data match the curve for a perfect device. The low value of \( C \) measured in our device is a reliable proof that our detector was highly constricted. Our FC-DBR device exhibited a value of \( C = 0.3 \), which was lower than the \( C = 0.67 \) value obtained for a previously fabricated SSPD on an oxidized Si substrate.

### 4.2.5 Conclusions

Increasing the absorption efficiency of SSPDs loses relevance if the internal detection efficiency of the detector is poor. Now, if a highly reflective mirror and an optical cavity are to be implemented in SSPDs for front-side illumination, special care needs to be addressed to keep the quality of the NbTiN film as high as possible. One option is to optimize the growth parameters in both the DBR and NbTiN process to achieve uniform thin films. Also a lattice matching layer can be introduced after the DBR growth to improve the growth of NbTiN. An alternative direction would be to use a DBR with a high quality SiO\(_2\) top layer, for example using silicon-on-insulator based substrates. The number of Si/SiO\(_2\) pairs required for high reflectivity is less than in Si\(_3\)N\(_4\)/SiO\(_2\) based DBRs since the refractive index contrast is higher in the former (Si has a higher refractive index than Si\(_3\)N\(_4\)). Once the issue of film quality on DBR substrates is solved, the potential of a bottom cavity/mirror substrate can be fully realized. One
4.2 SSPDs on a DBR substrate

Figure 4.6: Normalized kinetic inductance as a function of the normalized bias current. The black trace represents a theoretically unconstricted device (C=1) while our FC-DBR device showed a very low C=0.3 value, implying high number of constrictions (red trace). For comparison the blue trace represents a standard SSPD on an oxidized Si substrate previously fabricated in our group, that device had a high C value and also good detection efficiencies.

An important step that can be introduced when testing new substrates is to perform roughness measurements with an atomic force microscope to correlate the influence of substrate uniformity with the detector performance.
Chapter 4. Cavity and grating enhanced detectors
Chapter 5

Polarization and wavelength dependence

5.1 Polarization dependence

SSPDs are usually fabricated in such a way that a polarization dependence of the quantum efficiency is inevitable. Their meandering nanowire leads to a preferential polarization absorption, this is undesired in experiments where the polarization degree of freedom is used. We have designed two new geometries for which the polarization dependence is minimized: a detector with two meander-type parts oriented perpendicular with respect to each other and a spiraling detector. For these designs the polarization dependence of the quantum efficiency is minimized.

5.1.1 Introduction

It has already been reported that the quantum efficiency of SSPDs is dependent on the polarization of the incident light [72, 65]. This effect is usually unwanted as the polarization degree of freedom is often used in quantum information experiments. Here we present a solution to the problem by exploring two new geometries.

There are two reasons for the polarization sensitivity of SSPDs, both arising from the geometry of the detector, consisting of a long narrow wire (100 nm wide and approximately 500 μm long) typically arranged in a meander-type geometry to maximize the active area of the device (fig. 5.1a, lower part). This geometry leads to an increased quantum efficiency for light polarized parallel to the wire with respect to light polarized perpendicular to the wire. The first reason for this effect is that light polarized parallel to the wire has a higher probability of being

absorbed. This originates from the fact that a large number of parallel wires acts as a wire-grid polarizer [73]. Light polarized perpendicular to the wire grid causes surface charges which screen the field and reduce the electric field intensity at the wire edges, leading to a decreased absorption. For light polarized parallel to the wire-grid the electric field intensity is uniform across the wire [65]. Anant et al. suggested a second reason for polarization sensitivity of SSPDs as they found that the optical effect was not enough to describe the polarization dependence: also the intrinsic detection probability of polarization parallel to the wire is larger with respect to light polarized perpendicular to the detector.

Building an SSPD consisting of two sub-parts of the original meander-type design, where the sub-parts are oriented perpendicular to each other, two preferential polarization absorption directions and detection probabilities are created, giving an equal quantum efficiency to all polarization directions. When we let the nanowire run in a circular geometry (figure 5.1b) no single preferential direction is left: this detector is minimally polarization dependent.

**5.1.2 Device**

Detectors are made from two different materials: NbN, the material typically used for SSPDs, and NbTiN, a material that was recently shown to detect single photons with a very high signal-to-noise ratio (see chapter 3). A sapphire substrate with a thin NbN layer (approximately 4 nm) was commercially obtained [40]. The NbTiN detectors are made from a 6 nm layer of NbTiN sputtered on a silicon substrate at room temperature, a description of the fabrication procedure can be found in chapter 3. Scanning electron microscope (SEM) images of the unpolarized detectors are shown in figure 5.1a and 5.1b. The first detector type consists of two sub-parts, oriented perpendicular with respect to each other, each orientation filling half of the detector. The wires are 100 nm wide and 4-6 nm thick, with 50 % fill fraction. The active area is 10 x 10 μm. The second type consists of spiraling wires, first going towards the center of the detector, after which they spiral out. The width of the wires is again 100 nm, with 50 % fill fraction, and the diameter of the detector is 10 μm.

**5.1.3 Measurement setup**

The measurement setup is shown in figure 5.1c. The detector is placed in an exchange gas in a helium bath cryostat (tube length 1 m, with a coaxial feedthrough and optical window) on XYZ piezo translators, allowing scanning and focusing. White and laser light are collimated outside the cryostat and focused in situ with
5.1 Polarization dependence

Figure 5.1: (a) SEM image of a perpendicular NbN detector. (b) SEM image of a spiraling NbTiN detector. (c) Readout system: the detector is placed on XYZ piezo translators. Optical access is provided by a window. The electrical part consists of a bias tee, amplifiers (46 dB) and a pulse counter. (d) White light image of the perpendicular detector, the contours are indicated. The two directions give distinct reflections of the white light (horizontal: dark, vertical: bright). The bright spot is the laser.

A white light image of a perpendicular (figure 5.1a) detector is shown in figure 5.1d, revealing the exact position of the laser spot (diameter 1 μm) on the detector. The two different parts of the detector can be distinguished by the different reflection of the polarized white light (horizontal wires: dark, vertical wires: bright). The laser polarization is controlled with a polarizer and a half wave plate. The zero position of the half wave plate is set such that it gives a maximum (minimum) count rate, corresponding to the parallel (perpendicular) direction of the polarization to the horizontal (vertical)
wires, i.e. the reference polarization angle is fixed with respect to the setup.

The measurements reported here were performed at 4.2 K. The device is biased from the outside via a bias tee through the coaxial connection with a constant current source and voltage pulses are led, via the bias tee again, to an amplifier cascade (total amplification: 46 dB) and measured with a pulse counter. The quantum efficiency for a wavelength of 650 nm (without polarizer) is determined to be 2.6% for the NbN perpendicular detector, 1.8% for the NbTiN perpendicular detector and 0.6% for the NbTiN spiral detector.

5.1.4 Results

In figure 5.2a we show the polarization dependent count rate for the NbN perpendicular detector. Focusing on the two distinct (horizontal and vertical) parts of the detector give count rates shifted by 90 degrees with respect to each other. When we illuminate the entire detector by defocusing the beam to a diameter of 8-10 μm the dependence on the polarization nearly vanishes. The count rate is then the mean of the maximum and minimum count rate when one sub-part is illuminated, i.e. minimum polarization sensitivity can not be achieved together with maximum detection efficiency. For consistency with literature about polarization dependence in SSPDs ([65, 74] we use the following definition for the degree of linear polarization

\[
C = \frac{N_\parallel - N_\perp}{N_\parallel + N_\perp}
\] (5.1)

where \(N_\parallel\) is the number of counts for light polarized parallel and \(N_\perp\) the number of counts for light polarized perpendicular with respect to the wire. For clarity we note that this corresponds to the maximum \((N_\parallel)\) and the minimum \((N_\perp)\) countrate. The degree of linear polarization versus wavelength of the perpendicular detectors made of NbN or NbTiN is shown in figure 5.2b. It is measured by rotating the \(\lambda/2\) waveplate over 360 degrees (corresponding to 720 degrees of the polarization direction), and fitting a sine through the data points. When the laser is focused on one of the two sub-parts of the perpendicular detector the degree of polarization ranges from 0.31 to 0.45 for a detector made of NbN and from 0.12 to 0.28 for a detector made of NbTiN. However, when we illuminate the whole detector uniformly the degree of linear polarization is 0.03 ± 0.02.

The results for the spiraling detector are shown in figure 5.3. For this measurement we focused the laser spot (1 μm diameter) on different regions of the detector (called South, East and South-east). Although the wires are not straight, sub-areas still show a polarization dependence, but the polarization angle at which

\[
C = \frac{N_\parallel - N_\perp}{N_\parallel + N_\perp}
\] (5.1)
5.1 Polarization dependence

Figure 5.2: (a) Count rate versus polarization angle for the perpendicular detector made of NbN. The laser spot (wavelength 650 nm) is focused on respectively the horizontal wires (red triangles), the vertical wires (green squares) and the entire detector (orange circles). $I=0.9I_c$ and the laser power is 0.1 nW (b) Degree of polarization versus wavelength for the perpendicular detectors, made of NbN and NbTiN, with one sub-part (squares) or the entire detector (triangles) illuminated.

A maximum count rate is measured differs for each region of the detector. The direction of the wires can be recognized, e.g. the maximum count rates for the South region is shifted by 90 degrees with respect to the East region. The count rate versus the polarization angle for three regions is shown in figure 3. The degree of linear polarization is $0.19 \pm 0.03$ for the South, $0.13 \pm 0.01$ for the
Figure 5.3: Polarization dependent count rate for a spiraling SSPD. The laser spot (wavelength 650 nm, diameter 1 μm) is focused on different regions (indicated in the lower part). When the entire active area is illuminated uniformly, the count rate exhibits almost no polarization dependence (red curve).

East and 0.19 ± 0.02 for the South-East region. When the entire detector is illuminated the degree of polarization reduces to 0.02 ± 0.01 and also for this detector the count rate is then averaged. The fabrication yield and performance of the opposite and spiraling detector was almost equal. The spiraling detector has the advantage that it is more robust against alignment because of its intrinsic symmetry.

5.1.5 Conclusions

In conclusion we have fabricated two new SSPD geometries to overcome the problem of polarization dependence of the quantum efficiency. By using geometries with either two perpendicular preferential directions or no preferential direction the polarization dependence can be significantly reduced.
5.2 Resolving the wavelength using a statistical method

5.2.1 Introduction

In this section, we investigate the energy resolving property of SSPDs. Due to the fact that the QE depends on the wavelength of the absorbed photon the photon energy can be determined with the help of a statistical method. Being able not only to count individual photons, but also gain information about their energy opens new experimental possibilities. It should also result in a design of novel, compact single-photon spectrometers, as no additional refractive device has to be placed between the source and the detector, and hence optical losses can be minimized.

5.2.2 Experimental setup

The nominal strip width of the SSPD is 100 nm. The SSPD is pigtailed with a single-mode fiber (Thorlabs, P1-SMF28, single mode: 1310 nm to 1550 nm). Assuming that the resistance of the SSPD when it is in its resistive state, $R_{SSPD}$, is much higher than the 50 Ω input impedance of the amplifier, the measured amplitude of the voltage photoresponse pulse is expected to be $V_{pulse} = I_b \cdot 50Ω \cdot G_{sig}$, with $G_{sig}$ the total gain of the amplifier system within the amplifier passband [25]. The measured $I_c$ of our SSPD is 11.8 μA and a typical photoresponse shows a voltage amplitude of 250 mV, when the SSPD is biased with $I_b/I_c = 0.8$. For demonstrating the energy resolving properties, we use a tunable Ti:sapphire laser (Coherent, MIRA900) with a wavelength range between 700 nm and 1000 nm as photon source. The laser is operated in a continuous-wave mode. To monitor the laser stability and to be able to compensate for possible laser fluctuations, a beam splitter is positioned between the laser and the single-mode fiber and the laser intensity is simultaneously detected by a power meter (Thorlabs, S120A), together with the SSPD readout. No fiber collimation optics is used to focus the laser light on the fiber input, with the effect that the coupling is less position-sensitive with respect to the laser spot. This is expected to give lower variations in the coupling efficiency, when changing the wavelength of the laser. In addition, we have sufficiently high laser power to obtain high-count rates. The laser intensity is varied using a laser stabilization system (Brockton Electrooptic Co.) and a

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calibrated attenuator wheel in front of the beam splitter.

### 5.2.3 Photon energy resolving property

![Figure 5.4: Bias current scans for different incident photon wavelengths. The SSPD system DE depends strongly on the energy of the absorbed photons. It is highest for 700-nm photons due to the large diameter of the generated non-superconducting hotspot and lowest for the longest wavelength of 1000 nm, as illustrated schematically by the two insets. The right-hand axis corresponds to the dark-count rate of the SSPD, represented by black dots.](image)

In this part, we investigate the energy resolving properties of SSPDs. To gain information about the energy of absorbed single photons, we use the fact that for a given thickness of a NbN nanowire, the area of a non-superconducting hotspot depends linearly on the energy of the incident photon. In the case of a 10-nm-thick SSPD, the difference in the diameters is 30%, when comparing hotspots corresponding to the 700-nm (hotspot diameter \( \sim 25 \) nm) and 1000-nm (\( \sim 32 \) nm) wavelength photons. For 4-nm-thick devices used in our experiments, we will follow the dependence presented in Ref. [17] for a 3.5-nm-thick SSPD, assuming the actual differences between the nominally 3.5- and 4-nm nanowires are negligible. Figure 5.4 presents a family of the system \( DE \) curves versus the normalized applied bias current, collected for different incident photon wavelengths. Clearly, it can be seen that for shorter wavelengths, larger \( DEs \) are obtained for the same
5.2 Resolving the wavelength using a statistical method

$I_b$ because highly energetic photons create larger hotspots and the condition for the PSC generation in the sidewalks can be exceeded at lower bias current values. E.g., at $I_b/I_c = 0.7$, the difference in $DE$s for the 700 nm and 1000 nm photons is approximately two orders of magnitude. For the 700 nm wavelength, the $DE$ is almost saturated, whereas for 1000-nm photons, the $DE$ can still be further increased by going closer to $I_c$.

For the studied SSPD, the overall system $DE$ presented in figure 5.4 is quite low. One apparent reason is that the optical coupling of the laser light to the SSPD is far from the best-reported value of 30% [38]. In addition, the QE of the SSPD might be reduced, possibly due to variations of the nanowire strip width. Nevertheless, despite the low absolute $DE$ values, the $DE$ curves collected for different wavelengths show the strong dependence on the energy of the photons, which is crucial for our approach of single-photon energy resolution. On the right-hand axis in figure 5.4 the dark-count rate (black dots) of the SSPD, measured when the laser light is completely blocked, is shown. We note that the dark counts are only relevant for $I_b/I_c > 0.85$. But even then, they are relatively low, despite the fact that we did not properly shield our device from the thermal background radiation (there were no cold IR filters in our optical beam line).

For our proposed fitting procedure the second criterion, which has to be fulfilled is the linear dependence of the SSPD photon-count rate on the incident photon flux (laser intensity). As we assume that we cannot fully control the intensity of the light source for which we want to determine the wavelength, the actual measured photon-count rate has to be normalized with respect to the calibration curves, which are obtained at a known wavelength and at a given intensity. In figure 5.5, the linear dependence of the SSPD count rate is shown with the laser power varied over two orders of magnitude. This linear dependence is expected, unless the laser power is increased to very high values where we leave the one-photon absorption regime [17]. In fact, the linear dependence of photon-counts on the number of incoming photons for very weak photon fluxes is a direct confirmation of the single-photon counting nature of our detectors [16].

**Fitting procedure**

Calibration curves were taken for different laser wavelengths over the whole tunable wavelength regime of our laser, from 700 nm to 1 μm in steps of 50 nm, as presented in figure 5.6. The laser intensity of each calibration curve was chosen in such way that at 10.2 μA bias current (voltage setting of 4.5 V), the obtained photon-count rate was approximately 1 MHz. The $I_b$ step size was 45 nA. For each point, the count rate was measured for 1 s. Several calibration curves for
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Figure 5.5: Measured photon-count rate dependence on the laser intensity. The linear dependence is a prerequisite to be able to recalibrate test curves taken at arbitrary intensities and compare it to the calibration curves.

For demonstrating the energy resolving property, we have taken test curves at the same wavelengths as the calibration curve, but measured for arbitrary intensities of incident photons. The photon-count rate of the SSPD was measured at four different $I_b$ settings, applying 3.0 V, 3.5 V, 4.0 V and 4.5 V to the bias current setup. Each point was an average over 20 measurements, each one taken for 1 s. The total time needed for taking one test curve was about 1-2 min. The value at 4.5 V was used to normalize the test curve with respect to the calibration curve to $10^6$ cps. In figure 5.6, both the original and the normalized points of one test curve are plotted. It can be easily assigned by eye to the calibration curve of 1000 nm wavelength.

Fitting results

For a quantitative assignment, we calculated the sum of the squared differences of all points of one test curve ($x_i$) with respect to all calibration curves ($\text{cal}_i(j)$),

\[
\sum (x_i - \text{cal}_i(j))^2
\]
5.2 Resolving the wavelength using a statistical method

Figure 5.6: Calibration curves. For wavelengths from 700 nm to 1000 nm in steps of 50 nm, \( I_b \) was scanned from 6.8 \( \mu \)A to 11.4 \( \mu \)A. All curves are normalized to 106 cps at \( I_b = 10.2 \mu \)A to simplify the fitting procedure. The original data (solid squares) and the normalized data (circles) of one test curve taken at arbitrary laser intensity are shown. The recalibrated test data can be clearly assigned to the 1000 nm calibration curve.

with \( j \) being different wavelengths:\(^1\):

\[
\text{sum}(j) = \sum (x_i - \text{cal}_i(j))^2 / \text{cal}_i(j)
\]  

(5.2)

By finding the minimum value of \( \text{sum}(j) \), the actual wavelength of the test curve could be determined. We have tested our fitting procedure on 14 test curves. For each wavelength (i.e., 700 nm, 750 nm,...), two test curves were measured at different laser intensities. All except one test curve could be assigned to the correct wavelength. In figure 5.7, the normalized \( \text{sum}(j) \) with respect to its minimum value is shown for all test curves (the test data shown in figure 5.6

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\(^1\)We assume that the measurements are independent, so sum\((j)\) has a \( \chi^2 \) distribution.
Figure 5.7: Wavelength assignment for all 14 test curves. For each test curve \( \text{sum}(j) \) with respect to all calibration curves is calculated. The normalized squared difference for each test curve is plotted versus the calibration curves. The minimum value indicates the assigned wavelength. For all curves, except one, there is a clear minimum value of \( \text{sum}(j) \) and the photon wavelength can be assigned with high certainty. The dotted line represents a relative difference of 5, which is used as threshold for an unambiguous assignment.

are represented by red circles). For all expect one curve, a relative difference higher than 5 (cf. figure 5.7 dotted line) is obtained and the wavelength could be assigned with high certainty. Problems arise if for two calibration curves the relative squared difference is almost similar, as in the case of one 1000 nm test curve (cf. figure 5.6, red squares). The measurement must be free of any external disturbances, such as bias current fluctuation or drift, or laser fluctuations on a time scale \(< 1 \text{ s}\), which could not be completely compensated in our experiments. In particular, the value taken at 4.5 V bias voltage which is used for recalibration is very sensitive to any disturbance. Therefore for an unambiguous photon energy assignment a threshold value for the difference between the relative squared differences should be defined. We have chosen e.g. a relative difference of factor
5.2 Resolving the wavelength using a statistical method

which is represented as a dotted line in figure 5.7. We stress, that this latter condition is satisfied for all test curves except one. If the above threshold is not reached then simply the measurement of the test curve has to be repeated until the criterion is fulfilled. The energy information about the incident photons is obtained statistically, i.e., we have to measure the photon-count rate for at least two different bias current settings. That requires a stable light source over the time needed for performing the bias scan, which is 1-2 min in our case when using 4 different bias current settings. By reducing the number of points and the amount of averaging, this acquisition time can be lowered, however, at the cost of accuracy.

Detector instabilities, which cause slightly different count rates for exactly the same experimental conditions are, probably, the main reason for the observed 50-nm wavelength resolution limit of our method. When taking calibration curves with smaller wavelength step size, the error bars of the calibration curves start to overlap. By using a more uniform SSPD with higher DE and a better-shielded readout system, our energy resolution should be substantially improved.

Light source with two different wavelengths

We have also investigated the possibility to determine the wavelengths contributions of a light source emitting simultaneously photons with two different wavelengths. For that, we equipped our setup with a single-mode fiber optic coupler (Thorlabs, 10202A-50-FC) and used the pump laser of our system (Coherent, Verdi: 530 nm) as the source of one (green) wavelength radiation, while the Ti:sapphire laser at a wavelength of 900 nm was the second source of photons.

Figure 5.8 presents the photon-count rates obtained for the three different cases: (a) only the green (530 nm) laser was connected to the single-mode fiber of the SSPD, (b) only the IR wavelength beam of the Ti:sapphire laser was used, and, finally, (c) both beams were coupled in at the same time and fed to the SSPD. Additionally, figure 5.8 shows the calculated sum (open circles) of the curves (a) and (b). At low values of \( I_b \), the counts rate curve when photons of both wavelengths are incident on the SSPD is dominated by the contribution of the green laser. That is due to the fact that the QE is much higher for green photons as compared to IR photons. As a consequence, the low \( I_b/I_c \) regime can be used for determining the wavelength of the high-energy photons as well as their flux number. We note that in general, the photon-count curve (c) follows almost perfectly the open-symbols curve, obtained by adding together the

\[ \chi^2 = 2.2 \] for 7 degrees of freedom, the relative difference corresponds to a cumulative probability of 86%. To have a 95% confidence with respect to the calibration, \( \chi^2 = 2.2 \) should be used.
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Figure 5.8: Wavelength assignment for a light source composed of two different wavelengths. The count rate of only the pump laser (a), only the Ti:sapphire laser (b) and of both lasers simultaneously (c) are shown together with the calculated sum of (a) and (b) (open circles). In the lower bias current range the slope of curve (c) is identical to the high-energy contribution of the green laser, whereas in the high bias current range, the curve (c) resembles the calculated sum.

curves corresponding to the (a) and (b) cases. Thus, the careful analysis of the measured photon-count curves (e.g., in separated $I_b/I_c$ windows) and their direct comparison with the pre-recorded calibration curves can allow accurate energy determination not only in case of monochromatic incident photons, but also in case of the incident flux consisting of photons of different energies.

5.2.4 Conclusions

We have demonstrated that besides their photon-counting abilities, SSPDs can also be used in photon-energy resolved experiments, by developing a novel statistical method for obtaining accurate information about the energy of the photons. We used the fact that the DE of SSPDs depends on energy of the absorbed photons. With our statistical method we could obtain an energy resolution of 50 nm. We expect that the energy resolution can be improved by implementing devices with higher fiber-coupling factors and higher intrinsic QEs. The presented photon energy-resolution concept should result in development of very compact,
single-photon spectroscopy setups and further lead in their implementation in, e.g., determination of the emission wavelength of quantum dots or ultraweak astronomical bodies.
Chapter 5. Polarization and wavelength dependence
Chapter 6

NbSi SSPDs

The quantum efficiency of NbN and NbTiN superconducting single photon detectors drops with decreasing photon energy. A lower gap material would enable single photon detection deeper in the infrared. We have fabricated a NbSi detector and compare its characteristics with a NbTiN device. NbSi ($T_C \approx 2$ K) has a smaller superconducting bandgap than NbTiN (and NbN) ($T_C \approx 15$ K). We measure the detection efficiency for a wavelength range from 1100 to 1900 nm. In this range the NbSi detector shows a tenfold increase in relative efficiency with respect to the NbTiN detector.

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6.1 Introduction

Superconducting single photon detectors (SSPDs) made from a NbN or NbTiN nanowire are sensitive to single photons\cite{16, 48}. These detectors show a low dark count rate, low timing jitter (60 ps)\cite{47} and short dead time (10 ns)\cite{16}. SSPDs are already used in various experiments ranging from quantum key distribution\cite{49} and entanglement experiments\cite{72} to time of flight measurements\cite{75}, characterization of optical quantum dots\cite{50} and near-field sensing of surface plasmon polaritons\cite{53}. The detector usually consists of a long ($\sim 500$ $\mu$m) superconducting nanowire, with a width of $\sim 100$ nm, and a thickness $\sim 5$ nm. The operation principle is based on the transition from the superconducting state to the normal state of a segment of the nanowire after absorption of a single photon. Their efficiency is moderate (up to 30\%) in the visible part of the spectrum and drops considerably for wavelengths above 1 $\mu$m. Efficient single photon detectors in the infrared ($\lambda > 1 \mu m$) will enable quantum optics experiments with single photon sources emitting in the infrared (i.e. low gap semiconductor or carbon nanotube quantum dots) and study of intra band transitions. One approach to increasing the efficiency in the infrared is the use of optical cavities\cite{29, 47}. In this way the absorption probability is increased (up to 80\%), but this approach is not helpful when the photon energy is insufficient to induce a detection event. In order to have detectors as sensitive in the near infrared as in the visible part of the spectrum we have fabricated SSPDs of amorphous NbSi. We compare NbTiN and NbSi by measuring the quantum efficiency as a function of wavelength.

6.2 Theory

There is no complete theory for the microscopic detection principle of photons with SSPDs. However it is generally believed that the energy of a photon $E_{ph} = h \cdot \nu \approx 1$ eV causes breaking of Cooper pairs, with a superconducting bandgap energy of $E_g \sim k \cdot T_c \approx 5$ meV (for NbTiN). The increased number of quasi particles leads to a finite resistance in a section of the nanowire, inducing a detection event. With decreasing photon energy, fewer Cooper pairs are broken and the quantum efficiency of the SSPD drops. A lower $E_g$ yields a higher $E_{ph}/E_g$ ratio and more Cooper pairs per photon are broken, leading to a higher quantum efficiency. SSPDs made of NbSi have a critical temperature of $\sim 2$ K, meaning that the superconducting gap is approximately ten times lower than NbTiN (and NbN), with $T_c \sim 15$ K\cite{76}. In addition, NbSi has a high resistivity, necessary to make efficient SSPDs\cite{77}.
6.3 Fabrication

Fabrication of NbSi SSPDs is comparable to the fabrication of NbTiN SSPDs [48]. First a 10 nm layer Nb$_{0.48}$Si$_{0.52}$ is co-sputtered from a Nb (DC) and a Si (RF) target on oxidized silicon. The sheet resistance is typically 262 $\Omega$/square. A film of this thickness and composition has a critical temperature of approximately 2 K. Nb/AuPd contacts are lithographed using liftoff and the NbSi wire is etched with reactive ion etching in a gas mixture of SF$_6$ and He. The wire is 160 nm wide and 90 $\mu$m long. A scanning electron microscope picture of a device similar to the ones used in the experiment is shown in figure 6.1a. The NbTiN nanowire has a width of 100 nm and a length of 500 $\mu$m.
Chapter 6. Wavelength dependence

Figure 6.2: (a) Count rates and QE for the NbTiN (circles) and NbSi (squares) detector. The solid lines through the QE measurements are exponential fits. (b) NbSi count rate as a function of NbTiN count rate for $\lambda=1400$ nm and $\lambda=1800$ nm. The slope in the exponential plot is $0.95(0.27)$ and $0.91(0.16)$ respectively, close to linear.
6.4 Setup

In order to perform the experiment a NbSi detector and a NbTiN detector are cooled down in a $^3$He cryostat, equipped with a multimode optical fiber. The measurement temperature is 300 mK. To directly compare the sensitivity of NbSi with NbTiN we place the two detectors besides each other, and an optical fiber is mounted above the detectors such that the spot simultaneously illuminates both detectors with approximately the same intensity (see figure 6.1a). A supercontinuum white light source filtered by a monochromator is used as the excitation light source. A long pass filter at 1100 nm blocks second orders produced by the monochromator. The output of the monochromator is calibrated with a spectrometer and a full width half maximum of the line width of ≤1.6 nm is measured. We confirm that no second order was present. The SSPDs are biased with DC current and the output pulses are amplified (gain +30 dB) and read out with a pulse counter or an oscilloscope. The critical current of the NbSi SSPD was 2.2 $\mu$A ($0.9I_c$), implying a critical current density of $1.4 \times 10^5$ A/cm$^2$ ($0.63I_c$). The quantum efficiency under illumination with 1700 nm light is shown in figure 6.1b. As expected, the quantum efficiency exponentially increases with current. A typical photon detection pulse is shown in the inset of figure 6.1b. The pulse length (1 ns) is limited by the bandwidth of our amplifiers (0.01-1 GHz). Given the relatively low kinetic inductance of our device (~50 nH), the reset time of the device is shorter than 1 ns. The absorption efficiency is determined by the optical constants of the material, in particular the complex index of refraction ($k$)[65]. We have measured the optical constants of NbSi and NbTiN with an ellipsometer. This is shown in figure 6.1c, and it can be seen that the complex index of refraction of NbSi is comparable to NbTiN, which means that the absorption efficiency will be similar.

6.5 Results

In figure 6.2a the count rates for the NbTiN detector and the NbSi detector are shown as a function of wavelength, the detectors were current biased at 10 $\mu$A and 1.4 $\mu$A, respectively. We observe that latching occurs for higher bias current for the NbSi detector. We attribute this latching to the low kinetic inductance of the device, preventing the detector from cooling down and returning to the superconducting state, as the current in the device increases too fast.[25] Increasing the length of the wire will increase the kinetic inductance, which allows biasing the detector closer to the critical current and increases the active area. We measure a dark count rate of less than 1 count per second for both detectors. For
each point the integration time was 30 seconds. By measuring the power we also calculated the quantum efficiency for the wavelengths 1100 nm to 1700 nm. From the plot in figure 6.2a we can see that the quantum efficiency drops exponentially with increasing wavelength for both detectors. Using \( \ln(QE) = -k \cdot \lambda + A \), with \( A \) a scaling factor, a linear fit gives a slope of \( k_{NbSi} = 2.67(0.30) \cdot 10^{-3}\text{nm}^{-1} \) for NbSi and \( k_{NbTiN} = 7.70(0.29) \cdot 10^{-3}\text{nm}^{-1} \) for NbTiN. This shows that the degradation in efficiency with increasing wavelength is three times slower for NbSi compared to NbTiN. We note that the absolute efficiency of the NbSi detector can be improved by optimizing the geometry of the device.

We have also measured the count rate as a function of power. This is shown in figure 6.2b for a wavelength of 1400 nm and 1800 nm. We plot the NbSi count rate as a function of the NbTiN count rate and fit the data linearly in log-log scale. It has been shown that SSPDs made of NbTiN are single photon detectors for (near) infrared wavelengths [50]. We confirmed in a separate measurement that the count rate as a function of power of the NbTiN SSPD at \( \lambda = 1400 \) nm is linear, a clear indication of single photon detection. The slopes of the fit in figure 6.2b correspond to 0.95(0.27) and 0.91(0.16), which indicates a linear power dependence. We conclude that the NbSi SSPD is also a single photon detector.

Figure 6.3 shows the enhancement in sensitivity for longer wavelengths by plotting the ratio of the count rates as shown in figure 6.2a of NbSi and NbTiN. As the ratio increases for longer wavelength it clearly shows the relative improvement of NbSi over NbTiN. The enhancement is more than tenfold at a wavelength
6.6 Conclusion

In conclusion, we have fabricated and tested NbSi SSPDs. These detectors have a smaller superconducting bandgap compared to NbTiN detectors, making them more sensitive for infrared wavelengths. We have compared the relative sensitivity with NbTiN detectors for different wavelengths and observed an enhancement by an order of magnitude over a wavelength range from 1100 nm to 1900 nm. By improving the geometry of the NbSi detector and fiber coupling them[47] a high system detection efficiency for single photons at infrared wavelengths can be achieved.
Chapter 6. Wavelength dependence
Chapter 7

Readout techniques

7.1 A superconducting single photon detector array

Superconducting nanowire detectors have opened new possibilities in sensitive imaging. Targeting such applications requires integration of an array of fast and efficient detectors with reasonable readout complexity. We report experimental results of two multiplexing methods (series and parallel) and their combination for multi-pixel single photon detection. The first method offers simultaneous readout of all pixels resulting in higher count rates, whereas the second provides efficient implementation for larger arrays. A larger number of detectors was implemented within a matrix by combining both types of arrays inheriting all the advantages. In all cases the readout circuitry complexity was significantly decreased.

7.1.1 Introduction

Array implementations of SSPDs have been proposed [78, 79] with the potentials of increasing count rates and providing spatial information. Higher count rates can be obtained because while one detector is in its recovery phase, the others can still detect. Imaging is also possible if one distinguishes pulses from different detectors. Extending the arrays into a large matrix could provide a fast and high resolution imaging sensor suitable for applications like medical optical tomography [44] where both temporal and spatial information must be obtained. However, no scalable implementation of SSPD matrices has yet been reported. One important challenge is the readout circuitry complexity which grows linearly with increasing pixel number using current readout techniques. In this letter we

This section is based on I. Esmaeil Zadeh, S. Dorenbos, and V. Zwiller, A superconducting single photon detector array, submitted for publication
Figure 7.1: (a) Schematic of a serial array of detectors. Detectors, $D_i$, are connected by transmission lines. (b) Oscilloscope trace of a detection event measured at each output (red and blue curves). The 9.14 ns time delay corresponds to the length of the transmission line between the two detectors. Inset represents the experiment where the opposite detector is illuminated with a transmission line time delay of 17 ns. (c) Time resolution measurements with different transmission line lengths. Inset shows the signal delay vs additional transmission line length, the slope corresponds to the signal velocity in our transmission line. The time uncertainty sets a limit on the length of transmission lines.
7.1 A superconducting single photon detector array demonstrate two alternative ways for implementation of arrays of SSPDs with a reduced number of interfaces and amplifiers. The first approach is based on serial arrangement of SSPDs, providing higher saturation count rate, and the second method is a parallel implementation with better scalability. Both methods have minimum number of interfaces which do not increase when scaling up the array. Finally, a combination of both methods for implementing a larger SSPD matrix, while maintaining the same low readout complexity is presented.

7.1.2 Serial array

Isolated detectors were interconnected with aluminum bonding wires forming arrays of SSPDs and coax cables were used as transmission lines for series structures. The schematic of a serial array is depicted in figure 7.1a, each detector is modeled as an inductor with a series resistance in parallel with a switch. In series architecture n detectors are connected via n - 1 transmission lines. Using these transmission lines the switched detector(s) can be identified by comparing the time delay between detection pulses at both ends of the cascade. Figure 7.1b shows an oscilloscope trace for such a measurement where two series SSPDs are connected through a 9.14 ns transmission line. The connections are made using a coaxial cable. The inset of figure 7.1b represents the measurement corresponding to the case where the opposite detector is illuminated and the transmission line delay is 17 ns. It is clear that using this arrangement, higher photon count rates as well as additional spatial information can be obtained compared to a conventional single SSPD. However, due to the timing jitter there is a lower bound on the length of transmission lines and hence the length of the whole series. Figure 7.1c represents the measurement results for different delay lines. As shown in the figure, there is about 540 ps FWHM uncertainty in the measurements. This uncertainty can be reduced by averaging over multiple detection events. Yet another limit on the number of pixels in series architecture is set by the signal to noise ratio (SNR) which is affected by the reflection and attenuation in transmission lines. SNR can be relaxed by integration of transmission lines and adding matching circuits. The inset of figure 7.1c shows the linear dependence of time delay on transmission line length.

7.1.3 Parallel array

An alternative for array implementation of the detectors is to operate them in parallel. The working principle of this array is based on sequentially activating the detectors. This is achieved by means of a dedicated resistor for each SSPD
and a variable voltage source. The branch with lowest resistance receives the highest share of bias current. The bias current is then increased to activate the next detector leaving the previous one in the resistive mode. The schematic of such a structure is shown in Fig. 2a. Switching between detectors can be done immediately after detection of a photon if one aims at increasing the count rate or after integrating over a number of counts, more useful in the case of imaging. In this way the sources of pulses in the array are spatially distinguished and the maximum count rate is enhanced.

Figure 7.2b shows an I-V curve for an array consisting of three detectors in parallel. As indicated by small circles in the figure, three transition regions (cumulative critical currents) are clearly distinguished. Biasing the array with each of these critical currents will efficiently activate one of the detectors in the array at a time. Measured photon detection pulses corresponding to the array are represented in figure 7.2c. Clearly, the pulse widths are different. This difference is mostly due to different time constants, $\tau = L/R$, because of different series resistance for each SSPD. In our case $R_1 = 0$ and $R_2$ and $R_3$ are both a few hundred ohms but different. It has been shown [24] that a series resistance can speed up the recovery time of SSPDs operation. However, at some point it will cause the SSPD to quench because a stable equilibrium between Joule heating and heat dissipation in the substrate is established, preventing the detector from switching back into superconducting mode. It should be noted that increasing the bias current above the critical current of an active SSPD latches the SSPD into normal mode provided that enough current passes through the switched detector to maintain the Joule heating needed for quenching the SSPD. The shunt resistance is used for balancing the current distribution. The parallel array enables higher count rates as well as spatial information. Moreover, unlike previous works [78, 80] each detector can be operated very close to its critical current, so the efficiency is not affected and high detection efficiency for each pixel can be obtained. Finally, there is no contribution to dark counts from inactive SSPDs as they are biased far from their critical currents.

### 7.1.4 Combination of parallel and serial array

The serial and parallel implementation can be combined to form yet a larger matrix of SSPDs. The schematic of such a matrix is shown in Fig. 3a. In this structure each line is activated by setting the bias to the corresponding critical current in that line (parallel mode), also the output pulses coming from each pixel in a line can be distinguished by comparing the time delay between detection events at the two readout nodes (series mode). The experimental results for a
7.1 A superconducting single photon detector array

Figure 7.2: (a) Schematic for the parallel detector array. Each detector has its dedicated resistance $R_i$. (b) I-V curve for an array of three detectors (c) Detection pulses for each of three pixels.
Figure 7.3: (a) Combination of the serial and parallel approach, enabling very large numbers of detectors to be readout with only two interfaces. (b) detection pulses at 18 $\mu$A and (c) 32 $\mu$A biasing currents.
2x2 array is presented in figure 7.3b and figure 7.3c. The first two detectors in the line with lower resistance were activated by setting the bias current to 18 $\mu$A and the second line was enabled by switching the bias to 32 $\mu$A. It should be noted that for biasing currents above 18 $\mu$A up to a few $\mu$A below 32 $\mu$A, detection events are unlikely to happen. This is because both detectors in the first line are latched to normal mode and no detector in the second line is sufficiently biased. Detection pulses in figure 7.3b and figure 7.3c again have different widths due to different series resistances. As our array consists of isolated detectors connected by bonding wires and transmission lines (coax cables), reflection and attenuation occur. However, integration of these detectors will improve SNR and reduce the reflection. The transmission lines can be approximated using lumped element circuits or be replaced by simple phase shifters. In our case, detection pulses and reflections are distinguishable by considering the time delay in transmission lines and setting a threshold voltage for the counter. This is because detection pulses are usually larger in amplitude compared to reflection.

7.1.5 Conclusions and outlook

In conclusion we have shown new methods for implementation of multi-pixel SSPD. The new proposed approaches may work at higher count rates, provide spatial information and maintain the same complexity for readout interfaces as is the case for a single or at most two SSPDs. Further study is needed but initial results for arrays based on our methods, confirm the potentials of SSPD arrays for imaging. As the only limit on the length of transmission lines in series structures is set by uncertainty in the time delay between pulses, reducing the timing jitter makes using shorter transmission lines possible. The ultimate case is measuring the pulses at two ends of a single detector.
7.2 Capacitive readout and gating of superconducting single photon detectors

7.2.1 Introduction
We propose and develop a readout scheme for superconducting single-photon detectors based on a capacitive integrating circuit. This relaxes the need for large bandwidth amplification but results in lower time resolution. By gating the detector, the time resolution can be regained. Additionally, gating allows filtering of scattered light in time and reduces dark counts even further, leading to a boost in quantum efficiency. A gate pulse is generated on detection of a photon created by a spontaneous parametric down-conversion source, heralding the presence of a second photon. These two schemes could find applications within array detection systems and quantum cryptography.

7.2.2 Capacitor readout
Traditional SSPD operation involves counting voltage pulses triggered by single photon detection events. This requires large amplification with large bandwidth and pulse counting electronics. We replaced the high-frequency amplification stage by a capacitor functioning as an integrating element to simplify the operation. This would also allow for easy detector multiplexing, similar to CCD operation. We demonstrate experimentally that the readout voltage is still quantized and can therefore be used for photon counting.

Simulation
Prior to the experiment, a simulation of the capacitor voltage readout was performed. The electronic model used in the simulation (Micro-cap 9), is shown schematically in Figure 7.4a. The SSPD was modeled as a current controlled (CC) switch in parallel with a 6 kΩ resistor. The system is biased with a DC current $I_{DC}$ ($V_b$ over a 100 kΩ resistor) and a pulsed current $I_P$ ($V_p$ over a 250 kΩ resistor) to simulate the effect of an incoming photon. The sum of these currents is monitored by $I_{sense}$ and used to control the CC switch. The switch operates in hysteresis mode around 10 μA, which means that it opens when the current reaches 12 μA and closes when it drops below 8 μA. Since the critical current $I_C$ for our detector was measured to be just below 10 μA, the DC bias component

This section is based on Hatim Azzouz, Reinier W. Heeres, Sander N. Dorenbos, Raymond N. Schouten, Valery Zwiller
Figure 7.4: (a) Simulation diagram. (b) The bias voltage \(V_b\), voltage pulses driving the laser diode \(V_l\), average of five capacitor voltage readout measurements \(V_{Cap}\) and simulation results \(V_{sim}\). The bias voltage is scaled up by a factor of 10. The bias gating window is 120 ns wide.

was set to 7.5 μA and the pulsed component to 5 μA. The pulse width was 0.3 ns and the repetition rate was 16 MHz, giving events separated by 62.5 ns. At the start of the simulation the current is small and the CC switch is therefore closed, representing the SSPD in the superconducting state. The pulsed source increases the current to above the threshold of 12 μA and causes the CC switch to open. The current then flows through the 6 kΩ resistor representing the hotspot resistance. When the current decreases to 7.5 μA, the CC switch closes again, corresponding to restoration of the superconducting state. The model values are based on measurements and literature. The hotspot resistance \(R_{SSPD}\) was estimated to be around 6 kΩ in [24]. The SSPD kinetic inductance \(L_k\), which limits the detector count rate, is determined from the recovery time \(\tau_{LR} = \frac{L_k}{50 \Omega} \) [26]. The measured value of \(\tau_{LR}\) is \(\sim 8\) ns, implying a kinetic inductance of 400 nH. A capacitor of 1 nF, which constitutes the main element in this scheme, was introduced in the circuit. This gives an RC-time \(\tau_{RC} = (50 \Omega + R_d)C\) seconds, where 50 Ω corresponds to the termination resistance to match the coaxial line impedance and \(R_d\) is the discharge resistor, which allows to control the time constant. The readout voltage was probed at the node labeled 'readout'.
Experiment

The measurements were performed in a liquid helium bath cryostat at 4.2 K. A 633 nm pulsed laser diode was used for optical excitation and was focused onto the detector by a coupling lens (NA 0.25, f=11 mm). The SSPD was mounted on a circuit board and connected electrically in a way similar to Figure 7.4a. However, the DC bias line was replaced with a second coaxial cable and a 500 Ω resistor in series close to the detector to allow gating. The resistor converts the applied voltage pulses into a pulsed bias current. The output signal was connected to the capacitor at room temperature, after which it was amplified and measured on an oscilloscope. Assuming a pulse length of $t \sim 2$ ns, we expect the capacitor readout voltage prior to amplification to be in the order of tens of microvolts ($V = \frac{It}{C}$, where $I \sim 10 \mu A$).

Figure 7.4b shows both experimental and simulation results obtained for the capacitor readout. Within the window of 120 ns that the detector was biased with $\sim 10 \mu A$, two laser pulses were applied to the SSPD with a repetition rate of 16 MHz. The average capacitor voltage readout of five events recorded by the oscilloscope shows the expected integrating behaviour and contains two distinct peaks separated by around 60 ns, corresponding to two detection events. The delay between the laser pulses and detected events was set by the length of the coaxial cables and the optical fiber. The simulated curve $V_{sim}$ is in good agreement with the measured capacitor readout $V_{Cap}$. In this case it is possible to distinguish between 1 and 2 detection events based on the readout amplitude. However, it would be hard to measure the difference between more events because the RC time constant is too short. This can be solved by increasing the value of the discharge resistor $R_d$.

7.2.3 Gating of SSPD

The advantage offered by capacitive readout, i.e. the fact that the number of detected photons can be stored for a while and measured with low bandwidth, has a drawback: time information is lost. However, by applying fast gate pulses to the device, some of this information can be retrieved. Gating can also increase the signal to noise ratio by enabling the application of a larger current (and hence a higher detection efficiency) during a short time when a photon is expected, without suffering from large dark noise when no photon is expected. Figure 7.5a shows the setup used for gating our detector. Here, a single mode fiber was pigtailed to the SSPD providing optical illumination with a coupling efficiency of around 1%. The pigtailed detector was mounted on a dip-stick and immersed in
liquid helium. It was electrically connected similarly to the schematic in Figure 7.4a, but instead of sending the output signal to the capacitor it was amplified directly by $\sim 54$ dB over a bandwidth of $\sim 1$ GHz and sent to an oscilloscope. A constant DC bias current of $\sim 4 \, \mu A$, about 80% of the critical current, was applied.

Figure 7.5: (a) Experimental setup for gating. The electrical readout is represented by the driver box. (b) Gating and measured signals. The APD detection pulse (APD) was reshaped by the electronics box into a 50 ns inverted gate pulse (Gate). A regular detection event without gating the SSPD (Regular) and an event occurring when a gate pulse is applied (Gated).

The optical illumination in the schematic of Figure 7.5a was provided by a spontaneous parametric down-conversion (SPDC) source. A continuous wave 532 nm pump laser drove a collinear SPDC process in a 2 cm long KTP crystal cut for degenerate type-II phase-matching. After the crystal, a polarizing beam-splitter separated the generated photon pairs, and the individual correlated 1064 nm photons were collected in single-mode fibers. One of these fibers was connected to an Avalanche Photodiode (APD). A detection event of this detector heralds a photon in the other fiber, which was connected to the pigtailed SSPD. The APD signal was converted to a proper gating pulse with a pulse stretcher to create a 50 ns wide TTL signal, a 80 dB attenuator, and a low pass filter ($\sim 13$ ns rise time). The filter is important to decrease the direct cross-talk of the gating pulse to the AC-coupled high-frequency pulse detection electronics. The pulse was then applied across a 500 $\Omega$ resistor to add it to the DC bias current. The processing of the APD signal caused a delay of $\sim 10$ ns. This gating pulse provided only a fraction ($\sim 20\%$) of the required bias current. The main DC component
was provided by the driver ($I_{APD} \ll I_{Bias}, I_{APD} + I_{Bias} = I_{TotalBias}$). However, $I_{Bias}$ could be kept smaller than usual, resulting in no dark counts when the detector was not gated on. The involved signals, APD pulse, gate pulse, regular detection event, and gated detection event, are shown in Figure 7.5b.

![Figure 7.5b](image.png)

**Figure 7.5b:** The involved signals: APD pulse, gate pulse, regular detection event, and gated detection event.

To measure the correlation between photons detected by the SSPD and the APD, both output signals were sent to a time correlated single photon counter module (PicoHarp 300, resolution set to 256 ps). Figure 7.6a shows the measurement where the heralded photons were delayed by adding pieces of 1 m optical fiber patches at a time. Figure 7.6b shows the results when the gate pulse was delayed by adding 1 m coax line at a time. The sharp peak in both cases clearly indicates a correlated signal, and shows that a heralded photon was detected within the gating window. The envelope of the $\sim 50$ ns wide curve, where detection events occur, is caused by both background light and dark counts. It gives an indication of the shape of the gating pulse applied to the SSPD.

![Figure 7.6a](image.png)

![Figure 7.6b](image.png)

**Figure 7.6:** Gated operation of the SSPD. (a) Detection events as a function of optical delay of the heralded photon. The reference shows detection events for a 7 m fiber optical delay without gating. (b) Detection events as a function of gate pulse delay. When the heralded photon falls outside the gate window (lowest trace) there are no correlated detection events.

To measure the correlation between photons detected by the SSPD and the APD, both output signals were sent to a time correlated single photon counter module (PicoHarp 300, resolution set to 256 ps). Figure 7.6a shows the measurement where the heralded photons were delayed by adding pieces of 1 m optical fiber patches at a time. Figure 7.6b shows the results when the gate pulse was delayed by adding 1 m coax line at a time. The sharp peak in both cases clearly indicates a correlated signal, and shows that a heralded photon was detected within the gating window. The envelope of the $\sim 50$ ns wide curve, where detection events occur, is caused by both background light and dark counts. It gives an indication of the shape of the gating pulse applied to the SSPD.

### 7.2.4 Conclusion

In conclusion, we have demonstrated the implementation of a capacitor-based voltage readout, allowing us to resolve the number of incoming photons within the RC-time of the capacitor. This was simulated using a circuit model with two photon pulses and confirmed by measurements. For an SSPD array, multiplexing will be possible by sequentially reading out the capacitors corresponding to individual pixels. This allows all photons to be detected and their position to be determined, resulting in a single-photon imaging detector with low noise that
is sensitive over a broad wavelength range. Furthermore, we have shown that it is possible to gate an SSPD to provide some of the time-information that is lost when using capacitive readout. This also gives the opportunity to increase the detection efficiency in small time windows when photons are expected without suffering from dark counts outside this window. Further study is needed to confirm the detection efficiency and dark count rate during the gate pulse.
Chapter 7. Readout techniques

7.3 HEMT based readout

7.3.1 Introduction

Reference [85] first proposed that, in principle, if we place an amplifier with a high load impedance next to the SSPD, such that $R_L > R_{hs}$, it should be possible to read out the true amplitude of the voltage pulses, and in turn $R_{hs}$, such that $V_{pulse} \approx G \cdot (I_b - I_{ret}) \cdot R_{hs}$. Such an approach should enable us to distinguish the difference between the dark and photon counts, by looking at pulse amplitudes directly, and even achieve the spectral and photon-number resolution.

In this work, we present a new readout technique, which utilizes a high-electron-mobility transistor (HEMT) directly, in-situ, integrated with the SSPD, in order to achieve output pulse amplitude resolution. Because HEMT input impedance is nearly infinite, we have also implemented $R_L = 500 \Omega$ in parallel with our SSPD.

7.3.2 Setup

A schematic of the HEMT-based readout circuit is shown in figure 7.7. The SSPD is mounted (wire-bonded) on the same printed circuit board as the HEMT and $R_L$, and the entire circuit is placed inside a liquid-helium cryostat. The HEMT acts as an infinite-impedance element to separate the 50 Ω output transmission line from the SSPD. Because the HEMT input impedance is very high, we also utilize a 500 Ω load (or shunt) resistor in parallel with the detector and the HEMT, as is shown in figure 7.7. The output electrical connections were achieved through a 50 Ω coaxial cable and a 0.08- to 26-GHz-bandwidth custom-made bias-tee. Such an integrated arrangement allowed us to DC bias both the SSPD and HEMT, using $R_{bias} = 150 k\Omega$, mounted on the board together with the rest of the components, and, simultaneously, read out the AC photoresponse voltage signal. By applying the detector transient response to the gate of the HEMT, we can read out the drain voltage, which should, for $R_L >> R_{hs}$, be proportional to the hotspot resistance and equal to $V_{out}$. The $V_{out}$ signal, constituting either the photon- or dark-count event, is read out using a 0.01- to 8.5-GHz-bandwidth amplifier and a 6-GHz single-shot oscilloscope. As a photon source, we use a tunable Ti:sapphire modelocked laser or a NIR laser diode, heavily attenuated and fiber coupled to our SSPD. For dark-count measurements, the detector was

This section is based on Jennifer Kitaygorsky, Sander Dorenbos, Elisabeth Reiger, Raymond Schouten, Val Zwiller, and Roman Sobolewski, IEEE Transactions on Superconductivity 19, 346 (2009)
blocked from all incoming radiation, i.e., shielded inside the cryostat by a metallic enclosure. To understand the electrical photoresponse of our SSPDs and decide on the operating parameters of the readout circuit, we have performed extensive circuit simulations using the SSPD equivalent circuit shown in figure 7.7 and a commercial PSpice program. The PSpice simulations revealed that values higher than $R_L = 270\,\Omega$ lead to an underdamped circuit, due to a small parasitic capacitance coming from a circuit board, as well as other components, estimated to be around 2 to 3 pF, and, eventually, to latching. Thus, we choose the value of $R_L$ to be 500 Ω as a trade-off for having the highest $R_L$ possible with a limited amount of underdamping and no latching, even though we realized that this value was going to be lower than the $R_{hs}$ formed in our SSPD and estimated to be 1.2 kΩ. Thus, the $V_{out}$ signals we are presenting in this work are actually proportional to a parallel connection of $R_L$ and $R_{hs}$, limiting our ability to fully, quantitatively distinguish between the different types of the SSPD counting events. Thus, our experimental observations are mainly qualitative.

![Figure 7.7: Circuit schematics implementing HEMT amplifier and 500 Ω load resistor $R_L$. The 10 nF capacitor sets the maximum ac gain and a 200Ω resistor sets the dc current for the HEMT; $R_{bias}$ and $R_D$ are the biasing and pull-up resistors, respectively.](image)

**7.3.3 Dark-count versus photon-count events**

Figure 7.8 presents histograms that compare pulse-amplitude distributions of the dark- (gray) and photon-count (black) events. The photon counts were collected for a very weak illumination (i.e., average number of absorbed photons per pulse $n << 1$) from a Ti:sapphire laser operating at $\lambda = 700$ nm. The amplitude histograms were very accurately fit with Gaussian distributions (solid lines). We can clearly see that the HEMT readout allows us to easily distinguish between
the dark and photon counts, as the average voltage $V_{\text{ave}}^{\text{dark}}$ of the dark-count pulses is substantially larger than in the case of photon pulses. Correspondingly, the full-width-at-half-maximum (FWHM) distribution of the Gaussian fit for dark-count events is twice as narrow as the photon-count-pulse FWHM. The latter is also illustrated in figure 7.9, which presents the FWHMs of the dark- and photon-pulse amplitude distributions at different $I_b$s. We note that the dark-count FWHM (open squares) is independent of $I_b$, while for photon counts in the $n << 1$ regime (closed circles), as $I_b$ approaches $I_c$, the FWHM starts to drop around $I_b = 0.83I_c$. In this range, the dark counts simply start to dominate over the photon counts and, eventually, both FWHMs overlap at $I_b > 0.9I_c$. The latter behavior agrees very well with our earlier observation of the dependence of photon- and dark-count rates on $I_b/I_c$, as shown in the inset in figure 7.9.

![Figure 7.8: Pulse-amplitude histograms of dark counts (red) and photon counts at $\lambda = 700$ nm in the single-photon regime (black). Measurements were performed at 4.2 K and at $I_L = 0.8I_c$. The SSPD output voltage amplitudes are divided by the amplifier gain.](image)

The behavior shown in figures 7.8 and 7.9 can be explained as follows: because the fabrication of SSPDs is not perfect, we know that there must be a variation in width and, likely (due to, e.g., substrate imperfections and/or local defects), in thickness of our NbN stripes [20]. We also know that the experimental $I_c$ is determined by the narrowest and thinnest section(s) of the stripe. The dark counts are most likely to be generated in these particular sections because, as we have demonstrated before [31, 86], they are due to either phase-slip centers or vortex-antivortex pair unbinding in our NbN stripes, depending on the stripe
geometry and properties. As the dark counts originate at the weakest constriction sites of the SSPD meander, the Joule heating resulting from the events produces a normal region that is going to have only slight variations in resistance and an averaged value expected to be the largest (narrowest constriction). On the contrary, hotspot-driven photon-count events can be triggered, in principle, at any place along the length and the width of the meander, naturally leading to variations in collected voltage pulses and resulting in the overall broadening of the pulse-amplitude distribution with somewhat lower mean peak value. The latter effect will be amplified by any fluctuations in the meander width, as they translate to fluctuations of final hotspot resistance. In summary, in case of an SSPD with a perfect NbN meander (no constrictions), we expect a large number of photon counts and large QE [20], with almost negligible dark counts.

\[ \text{Figure 7.9}: \] Amplitude distribution width (FWHM of Gaussian fits) for dark counts (open squares) and photon counts such that \( n << 1 \) (closed circles). The inset shows the counting rate as a function of bias current for dark counts (open squares) and photon counts with \( n << 1 \) (closed circles).

7.3.4 Conclusions

We have implemented a HEMT-based, high-load readout setup that allowed us to resolve the amplitude variations of the SSPD output transients, when the device was either illuminated with photons of different energies or completely isolated and generated the dark counts only. Using the HEMT setup, despite its
limitation (namely, that we could not fulfill the condition $R_L > R_{hs}$) we could, nevertheless, with the good contrast, qualitatively distinguish the signals coming from either photon counts or dark counts, confirming that the physical origins of both events are different.
Part 2
Chapter 8

Position controlled nanowires for infrared single photon emission

We report the experimental demonstration of single-photon and cascaded photon pair emission in the infrared, originating from a single InAsP quantum dot embedded in a standing InP nanowire. A regular array of nanowires was fabricated by epitaxial growth on an electron-beam patterned substrate. Photoluminescence spectra taken on single quantum dots show narrow emission lines around 1.2 μm. Superconducting single photon detectors enable us to measure the second order correlation function as well as cross correlations. Clear antibunching is observed \( g^{(2)}(0) = 0.12 \). Furthermore we have identified a biexciton-exciton cascade and two excitonic charge states.

---

8.1 Introduction

Semiconductor quantum dot (QD) structures are attractive candidates for solid-state single photon and/or entangled-photon pair generation.[11, 87, 88, 89, 90, 91] Nanowire quantum dots (NW-QDs) are promising candidates for such sources due to the controllability of doping, shape, and material freedom.[92, 93, 12, 94] Furthermore, due to the high light extraction efficiency [95] and straightforward electrical contacting, nanowires present advantages over self assembled dots. In addition, fine structure splitting, present in self assembled dots, is predicted to be absent in NW-QDs, which makes NW-QDs ideal for the creation of entangled photon pairs. [96] While single photon emission from a NW-QD was shown recently at a wavelength <1000 nm [97, 98], a single photon NW-QD emitter at telecommunication wavelengths and a detailed study to its emission lines has not been reported. In this letter we report on the fabrication and characterization of a regular array of InAsP QD embedded in an InP nanowire and characterization of the QD photoluminescence. InAsP is an attractive material due to its band gap, which can be tuned to telecommunication wavelengths by changing its composition. We demonstrate controlled positioning of the nanowires by growing them in a regular array. Control of the position allows further advancement towards practical devices and control of the density, which is necessary for uniform properties. We show that a NW-QD indeed is a source of single photons by measuring non-classical antibunching in second-order photon correlation experiments, proving sub-Poissonian light statistics. Furthermore we perform cross correlation experiments to identify biexcitonic and excitonic transitions.

8.2 Nanowires

Arrays of InAsP QDs embedded in InP NWs were synthesized by selective area metal organic vapor phase epitaxy (SA-MOVPE [99]). A metal catalyst is usually used (i.e. Au) to grow NW structures, however with SA-MOVPE a catalyst is not needed, preventing diffusion of the metal into the NW. A (111) InP wafer was covered by 30 nm of SiO$_2$. By electron beam lithography and wet-etching, 40 to 60 nm diameter openings were created to form nanowire nucleation-sites. At a growth rate of 3 nm/s, first a 1 μm long segment of InP was grown by adding trimethylindium (TMI) and tertiarybutylphosphine (TBP) to the MOVPE reactor at 640 °C. Subsequently the temperature was lowered to 580 °C and arsine (AsH$_3$) was added to the reactor (V/III ratio 340, partial pressure TBP:AsH$_3$ 3:1) to grow a 8 to 10 nm layer of InAsP to form the QDs. To cover the QDs with an InP shell, InP growth was first performed at 580 °C. To finalize the nanowire,
8.2 Nanowires

Figure 8.1: (a) Scanning electron microscope image of the regular array of nanowires. (b) Schematic of the nanowire, consisting of two 1 μm long InP segments and a 10 nm InAsP section forming the quantum dot. (c) Spectrum of the nanowire quantum dot. The origin of the $X^0$ line and the $XX^0$ line follows from the power dependence. (d) Power dependence of the spectrum, revealing exciton and biexciton behaviour. The solid lines are exponential fits. (e) Time resolved measurement of the $X^0$ line. The solid line is a fit with a mono-exponential decay, which gives a lifetime of 2 ns.

A second 1 μm segment of InP was grown at 640 °C. A scanning electron microscope image of the array is shown in figure 8.1a. A schematic of an individual nanowire is shown in figure 8.1b.

NW-QD photoluminescence (PL) spectroscopy was performed by micro-PL measurements. The sample was cooled to 5 K in a He flow cryostat. An excitation laser beam directed along the NW growth direction was focused on the sample surface by an aspheric lens (NA=0.5). The NW-QD emission collected by the same aspheric lens was dispersed by a double grating spectrometer (f = 1.0 m) and was detected with a liquid-nitrogen-cooled InGaAs photodiode array. The typical exposure time was 1 s to obtain a spectrum with a high signal-to-noise ratio. The excitation source was a pulsed-Ti:sapphire laser at a wavelength of 800 nm with a repetition rate of 76 MHz. A typical spectrum is shown in figure 8.1c. At an excitation intensity of 150 W/cm$^2$, we identify an intense peak
centered at 1211.30 nm (1.02328 eV) with a linewidth of 46 μeV FWHM. As expected, the fine structure splitting normally induced by QD lateral anisotropy and associated exchange interaction [100, 101] was not observed in polarization dependent measurements, within our setup resolution of less than 5 μeV. Because the laser intensity dependence (figure 8.1d) is linear, we assign this peak to a single exciton. We name this transition X₀ in the following. Determination of the actual charge state is beyond the scope of this chapter. With increasing excitation power, the PL intensity of X₀ saturates at an excitation power of 393 W/cm². An additional line, labeled XX₀, appears at a power of 19 W/cm² with its PL intensity increasing super-linearly as shown in figure 8.1d. The origin of XX₀ was therefore assigned to the biexciton of the InAsP QD. This was confirmed by cross correlations, as will be shown later. The radiative lifetime of the X₀ transition was measured by time-resolved PL measurements using a streak camera and a pulsed laser, see figure 8.1e. A mono-exponential fit reveals a lifetime of 2 ns. The long lifetime indicates absence of fast non radiative processes, revealing the high quality of NW-QDs.

8.3 Correlation measurements

Single photon emission was demonstrated by a Hanbury Brown-Twiss (HBT) experiment. A schematic of the setup is shown in figure 8.2a. The NW-QD is optically excited with a He-Ne source at 633 nm and a spectrum similar to figure 8.1c is observed. The emission is filtered with a long pass filter (1100 nm) and sent to a 50:50 beamsplitter. After each beamsplitter output the emission is filtered with a 0.5 nm wide band pass filter to select the X₀ line and sent to a superconducting single photon detector (SSPD). At the wavelength of interest SSPDs are a logical choice for correlation experiments [102]. The detectors were operated at 4.2 K, the following settings for the current and associated dark count rates are used for the two detectors: for detector 1, at 85 % of I_c (I_c = 3.8 μA) a dark count rate of 70 counts per second is observed, together with 4 % efficiency at a wavelength of 1.3 μm. For detector 2 I_c = 5.2 μA and it was operated at 82% of I_c, where it showed 40 dark counts per second and an efficiency of 3%. Count rates ranging from 5 kHz to 15 kHz were observed for an excitation power intensity of 1.5 kW/cm².

The second order correlation function of the output of the two detectors was measured by feeding the output signals of the detectors to the start and stop input of a time to amplitude converter. A histogram of the coincidence counts was recorded with timebins of 200 ps and is shown in figure 8.2b. The correlation
8.3 Correlation measurements

Figure 8.2: (a) Setup for measuring auto and cross correlations. The emission is filtered with a long pass filter (LPF, 1100 nm) and a 0.5 nm broad band pass filter (BPF). A wavelength tuneable, fibre coupled, 50:50 beam splitter (BS) is employed. The filtered emission is sent to the SSPDs, which are connected to a time to amplitude converter (TAC). A schematic of the SSPD operation is added, showing the current supply ($I_{bias}$) and a SEM picture of the device, consisting of a 100 nm wide, 500 μm long wire, meandering in an area of 10x10 μm. The output of the SSPD is amplified with a 50 dB amplification stage. (b) Normalized histogram of the autocorrelation measurement of the X, excitation wavelength is 633 nm and the timebins are 200 ps. The solid line is a fit, indicating a dip of the correlation function of $g^{(2)}(0) = 0.12$.

Counts are normalized. A dip at zero time delay can be seen, indicating the emission of non-classical light. The data is fitted through a second-order correlation function $g^{(2)}(\tau) = 1 - a \cdot e^{-|\tau|/t}$, $a$ accounts for background light (produced by the source), $t = t_l + t_p$, where $t_l$ is the lifetime of the NW-QD and $t_p$ is the inverse pumping rate. The function at zero delay gives $g^{(2)}(0) \leq 0.2$, far below the threshold of 0.5, i.e. unambiguously proving that the NW-QD is a single photon emitter. To correct the data for the background light, the data is fitted with $g_b^{(2)}(\tau) = 1 + \rho^2(g^{(2)}(|\tau|) - 1)$, with $\rho = S/(S+B)$ related to the signal to noise ratio.[103] Here a value of $g_b^{(2)}(0) \leq 0.12$ is obtained with $\rho = 0.97$. From the mono-exponential decay of the fit the time constant of this measurement can be extracted, which is $t = 1.51$ ns. Measurements with different $t_p$ would allow to extract $t_l$, which can be compared to the streak camera measurement.

To show that the exciton and biexciton were correctly identified through the laser intensity dependence (figure 8.1c), a cross correlation experiment was per-
Figure 8.3: Cross correlation function of the XX<sub>0</sub> (start) and X<sub>0</sub> (stop). Excitation wavelength is 920 nm. This configuration leads to a peak for positive times \( g^{(2)}(0.4)=1.5 \), where the probability of emitting a photon (X<sub>0</sub>) is enhanced. For negative times the probability is decreased resulting in a dip: \( g^{(2)}(-0.2)=0.65 \). The biexciton-exciton cascade is modeled as a 3 level system (see inset). The solid line is a fit according to this model. The fit gives a lifetime for the exciton \( t_X = 1.24 \) ns and for the biexciton \( t_{XX} = 0.34 \) ns.

formed. If the biexciton and exciton originate from the same charge state they will recombine in a cascade. In the inset of figure 8.3a a schematic of the biexciton-exciton cascade is shown. Upon excitation with rate \( r_{01} \) and \( r_{12} \), the dot is filled with two electron-hole pairs (XX<sub>0</sub>), neglecting resident charges. At a rate \( r_{21} \) one electron-hole pair recombines, leaving the X<sub>0</sub> behind, which subsequently recombines at a rate \( r_{10} \). The excitation laser was switched to a continuous wave Ti:Sapph laser, tuned at 920 nm, below the band gap of InP, which reduces background counts. At output port 1 of the BS of the HBT setup the biexciton was selected, while the exciton was selected at output port 2, with the use of band pass filters. The selected emissions were each sent to an individual SSPD. The output signals of the SSPDs were connected such that the biexciton served as the start and the exciton as the stop of the time to amplitude converter. Again the second order correlation function is measured and shown in figure 8.3a. The difference with figure 8.2b can be immediately seen as the function is not symmetric around a time delay of 0 ns. As has been shown before [91], this is the signature of cascaded emission. For positive time the peak indicates an enhanced probability of emitting X<sub>0</sub> after emission of XX<sub>0</sub>. For negative times, the dip represents a decrease in probability of the emission of the next XX<sub>0</sub> after the emission of X<sub>0</sub>, because the system has to be re-excited. The cascade is modeled as a 3 level system (see figure 8.3a inset), which implies the cross-correlations
can be fitted to two decay paths with their own typical time-constants. From the fitting we conclude that the dip reaches \( g^{(2)}(-0.2) = 0.65 \) and the peak has a value of \( g^{(2)}(0.4) = 1.5 \). The exponential decay obtained from the fit leads to a lifetime of 0.34 ns for the biexciton and 1.24 ns for the exciton. Again, the function does not reach 0 at \( \tau = 0 \), attributed to stray background light. It has been confirmed that the exciton as well as the biexciton show antibunching under these conditions (not shown).

### 8.4 Conclusions

To conclude, we have shown that SSPDs enable efficient correlation measurements on single nanowire QDs emitting at 1210 nm. Arrays of NW-QDs with very good properties can be fabricated without the use of catalysts and can form arrays of non classical light emitters in the infrared. Due to the specific properties of nanowires, an electrically controlled source \[104\] of single photons and temporally correlated photon pairs is now within reach.

### 8.5 Derivation cross correlations fit

The cross-correlation curves at different intensities can be fitted in terms of the solutions of a linear system of differential equations that correspond to a three-level model (inset of figure 8.3)

\[
\begin{align*}
\frac{dn_G}{dt} &= -\frac{n_G}{\tau_e} + \frac{n_X}{\tau_X} \\
\frac{dn_X}{dt} &= \frac{n_G}{\tau_e} - \left( \frac{1}{\tau_e} + \frac{1}{\tau_X} \right) n_X + \frac{n_{XX}}{\tau_{XX}} \\
\frac{dn_{XX}}{dt} &= \frac{n_X}{\tau_e} - \frac{n_{XX}}{\tau_{XX}}
\end{align*}
\]

where \( n_a \) is the probability that the system is in level \( a \) (with \( G \) being the ground level) \( \tau_X \) and \( \tau_{XX} \) are the lifetimes of the exciton and biexciton levels, while \( \tau_e \) is the characteristic time for the excitation process which is inversely proportional to the incident intensity. The solution is of the form

\[
n = 1 \cdot S + c_2 \cdot e^{-\lambda_X} S + c_3 \cdot e^{-\lambda_{XX}} \cdot S
\]

with \( \lambda_k \) and \( S \) the eigenvalues and eigenvectors of the matrix in 8.1. The cross correlation measurement performed in this chapter (figure 8.3) is actually two measurements: (1) the probability of occupation of the exciton level (\( n_X \))
after detection of a biexciton, (2) the probability of occupation of the biexciton level after detection of an exciton. For positive times the first measurement is seen and the curve is fitted with the solution for $n_X$. For negative times the second measurement is represented and the curve is fitted for $n_{XX}$. From the data sets the lifetimes can be calculated.
Chapter 9

Quantum nature of light measured with a single detector

The introduction of light quanta by Einstein in 1905 triggered strong efforts aimed at directly demonstrating the quantum properties of light, without involving matter quantization. It however took more than seven decades for the quantum granularity of light to be observed in the fluorescence of single atoms.[4] A single atom emits photons one at a time, this is typically proven with a Hanbury-Brown-Twiss setup [5] where incoming light is split by a beam splitter and sent to two detectors resulting in anticorrelation of detected events. In a purely classical interpretation of this effect, photons are regarded as indivisible particles. However, this interpretation evokes the false impression that a beam splitter is necessary to prove non-classicality of light. Here we demonstrate single photon statistics measurements from a quantum emitter with only one detector. The superconducting nanowire detector we fabricated has a dead time shorter[16] than the coherence time of a colour center in diamond.[13] No beam splitter is employed, yet anticorrelations are observed, enforcing a quantum mechanical interpretation. Our work can significantly simplify a widely used photon-correlation technique with applications ranging from single-molecule detection[9] to quantum information processing.[105]

This chapter is based on Gesine A. Steudle, Stefan Schietinger, David Höckel, Sander N. Dorenbos, Valery Zwiller, and Oliver Benson, submitted for publication
9.1 Introduction

A photon is a single excitation of a mode of the electromagnetic field. The probability $P(n)$ to find exactly $n$ excitations in the mode distinguishes different states of light. Figures 9.1a and 9.1b show a schematic representation of a coherent state where $P(n)$ is a Poissonian distribution together with a number (or Fock) state with exactly 1 photon per mode, respectively. In the case of a single-photon state ($n=1$) detection of a single excitation projects the measured mode to the vacuum state, i.e. the probability to detect another photon in the very same mode is zero. Since the temporal mode profile is associated with a characteristic coherence time $\tau_c$, coincidence events within the time interval $\tau_c$ are absent, antibunching is observed. On the contrary, for a coherent state the probability to detect a second photon within the same mode is unchanged. Antibunching is thus not only a consequence of photons being indivisible particles but requires a specific quantum statistical distribution of discrete excitations. The latter requirement is overlooked in a simple classical explanation of antibunching in a Hanbury Brown and Twiss (HBT) experiment (figure 9.1c). There a photon is regarded as a classical indivisible particle and necessarily has to decide which path to take when impinging on a beam splitter. Such an interpretation is too naïve [106] and even led to paradoxical conclusions, such as Wheeler’s delayed choice paradox.[107]

9.2 Single photon sources

Today, many different sources have been realized that generate antibunched light such as single-photon sources based on single atoms[108, 109], ions[110], molecules[111, 112], colour centres[113], or semiconductor quantum dots[114]. Another approach utilizes quantum correlations between photon pairs to herald the presence of a single excitation in a specific mode.[115] Photon statistics is typically measured in the above mentioned HBT setup. However, the only reason to use a beam splitter and two detectors is to circumvent the detector’s dead time $\tau_d$. For example, commercial avalanche photodiodes (APDs) have dead times of 50 ns - 100 ns or longer, preventing the detection of coincidence events within the coherence time of typical single-photon sources which is on the order of a few nanoseconds. Although more recent experiments could generate single photons with coherence times up to several microseconds[116, 117, 118] HBT setups are still used.

Recently, measurements of photon statistics with single detection devices based on a gated Geiger mode InGaAs APD [119] or a modified streak camera
9.3 Experimental setup

In our approach we determine the statistical properties of a photon stream from a single emitter by detecting the arrival times of individual photons with a single detector (Fig. 9.1d). For this, the detector’s dead time $\tau_d$ has to be shorter than the characteristic correlation time. In the case of weak excitation this correlation time is the Fourier-limited coherence time $\tau_c$ of the photons corresponding to the lifetime $\tau_{life}$ of the excited state, so we require $\tau_d < \tau_{life}$. In our experiment we use a nitrogen-vacancy (N-V) centre in diamond[13] as a single-photon source in single-photon counting mode[120, 121] were reported. Non-classical dynamic features were observed in the light from semiconductor microlasers. However, it was so far not possible to detect non-classical properties of light from a single quantum emitter because of poor detection efficiency.[122]

**Figure 9.1:** Schematics of quantum states of light and experimental configurations for their statistical analysis. Cartoon of a coherent state (a) and a single-photon Fock state (b). Spatial-temporal modes (indicated by blue lines) of a specific coherence time are populated by discrete excitations. For a coherent state this image corresponds to a snapshot, since the number of excitations per mode $n$ can only be predicted with a certain probability $P(n)$. In a single photon Fock state there is exactly one excitation per mode. A detection event projects the mode to the vacuum state. (c) Schematics of a standard Hanbury-Brown and Twiss setup, where the light is split on a beam splitter allowing to measure intensity correlations within time intervals shorter than the individual detector dead times. (d) Direct statistical analysis of light by detecting single photon arrival times with a single detector.
together with a superconducting single-photon detector (SSPD). N-V centres in diamond where a nitrogen atom replaces a carbon atom with an adjacent vacancy in the diamond lattice are the subject of intense research due to their exceptional role as single-photon sources at room temperature. The optical transition in a N-V centre occurs between two spin-triplet states. At least one additional singlet state introduces an off-state. The fluorescence spectrum of a N-V centre is broadened by higher phonon lines, but has a pronounced zero phonon line peak at 638 nm. At room temperature, single-photon emission with count rates up to $10^6 \text{s}^{-1}$ can be observed.[123] The lifetime of the excited state in N-V centres in diamond nanoparticles is around 30 ns, which is long compared to other single-photon sources.[124] As a single-photon detector we utilized a fibre-coupled SSPD[16] (see Methods). It consists of a NbN meandering nanowire coupled to a single-mode fibre (Fig. 9.2a). Its dead time $\tau_d$ is limited by its kinetic inductance[26], here $\tau_d < 5$ ns. Yet, this value is clearly shorter than the N-V centres lifetime.

Antibunching is quantified by measuring the second-order auto-correlation function of the electric field, given by

$$g^{(2)}(\tau) = \frac{\langle E(t)\dagger E(t+\tau)\rangle}{\langle E(t)\dagger E(t) \rangle^{\frac{1}{2}}} = \frac{\langle :I(t)I(t+\tau):\rangle}{\langle I(t)\rangle^{2}}$$

(9.1)

where $E\dagger$ and $E$ are the field operators and $: :$ denotes normal ordering. For uncorrelated light, e.g. laser light, with a Poissonian photon number distribution, $g^{(2)}(\tau) = 1$ for all $\tau$. However, for a number state $|n\rangle$, at $\tau=0$ it drops to $g^{(2)}(0) = 1 - 1/n < 1$. Fig. 9.2b shows the experimental setup for measuring the $g^{(2)}$-function. Fluorescence was coupled into a single-mode fibre, and detection was done in two configurations. Configuration 1 is the single detector setup, i.e. the light was sent via the optical fibre directly to the SSPD. In configuration 2, the HBT setup, light was coupled for comparison into a standard free space HBT setup consisting of a beam splitter and two APDs. In configuration 1, the amplified electrical pulses from the SSPD were fed to an oscilloscope with 1 GHz bandwidth. The oscilloscope was programmed to save a pulse trace whenever a trigger level of 200 mV was exceeded twice with a time difference of between 5 ns and 200 ns (see Fig. 9.2c). For measuring the $g^{(2)}$-function, 30,000 traces were recorded and analysed. In configuration 2, the time intervals between signals from the two APDs were recorded with a time interval counter.
Figure 9.2: (a) Scheme of the fibre-coupled detector chip. (b) A single N-V centre in a diamond nanocrystal is excited with a 532 nm cw laser. Its emission is collected via a confocal optical microscope, coupled to a single mode (sm) optical fibre, and detected in two configurations: 1. a single fibre-coupled SSPD and 2. a standard free beam Hanbury-Brown-Twiss (HBT) setup containing a beam splitter (BS) and two avalanche photodiodes (APDs). Correlations are analyzed by a fast 1 GHz oscilloscope or by a time interval counter. (c) Typical voltage trace with two detection events recorded with the oscilloscope. Only double events with a time difference of between 5 ns and 200 ns were collected. With the trigger level at 0.2 V (dashed line) the spurious reflections (see text) were not detected.

9.4 Results

We first performed two test experiments with classical light. Light from an attenuated laser was coupled into only one of the APDs and the detector clicks were fed into the oscilloscope. The measured $g^{(2)}$-function (Fig. 9.3a) shows an absence of coincidence counts at time intervals shorter than 30 ns. This is due to the dead time of the APD preventing detection of coincidence events within a 30 ns time interval. It is interesting to note the similarity of this classical suppression of coincidences compared to antibunching where the suppression is due to the quantum mechanical projection of a quantum state. For correlation times between 30 ns and 50 ns a bunching feature is observed due to the APDs afterpulsing. The afterpulsing probability according to the manufacturer is 0.5%. Here this is relevant since at our photon count rates of around 300,000 s$^{-1}$ the
probability for a second photon to arrive within a time window between 30 ns and 200 ns after a first one is 5%, i.e. one out of eleven events when a second pulse is detected is due to afterpulsing. These events account for the bunching observed in Fig. 9.3a. In a second test we coupled attenuated laser light into the SSPD and again measured the \( g^{(2)} \)-function (Fig. 9.3b). Obviously, there are no correlations between incoming photons and, more important, no suppression of coincidence events at short time intervals. Furthermore, no afterpulsing is observed.

Figure 9.3: Correlation measurements with classical light (a) Measured \( g^{(2)} \)-function of light from an attenuated laser beam sent to a single commercial APD and analysed via the fast oscilloscope by evaluating traces when a second detector event occurs within a time window of 5 ns - 200 ns after a first one. The dashed line indicates the dead time of the APD. The bunching observed between correlation times of 30 ns and 50 ns is due to afterpulsing. For a rate of 300,000 s\(^{-1}\) and an afterpulsing probability of 0.5% one out of eleven events is an afterpulsing event and contributes to the area above the solid line \( (g^{(2)}(\tau) = 1) \). (b) Same measurement, but with a SSPD with a dead time below 5 ns. Since only time differences larger than 5 ns were recorded no dead time effect was resolved. The absence of any correlation indicates a Poissonian photon number distribution. The black line is a linear fit.

Finally, a nanodiamond sample was prepared (see Methods), and a single N-V- centre was located using an inverted microscope as described elsewhere.\[125\] The 532 nm continuous wave excitation light was filtered out before coupling the emission into a single-mode optical fibre. We measured the \( g^{(2)} \)-function in the two different configurations of Fig. 9.2b, the single-detector setup (configuration 1), and the standard HBT setup (configuration 2), respectively. The experimental results are shown in Fig. 9.4. Blue dots correspond to the \( g^{(2)} \)-function measured with the single SSPD detector. It has a pronounced antibunching dip which fits well to a three-level rate equation model (solid black line). Red dots correspond to the standard HBT measurement. Obviously, both measurements reveal the
quantum nature of the photon stream in the same manner proving that a statistical analysis of a stream of single photons can very well be performed with a single detector only.

**Figure 9.4:** Measurement of the $g^{(2)}$-function in the single detector configuration 1 of Fig. 9.2b (blue dots) and the standard HBT configuration, configuration 2 of Fig. 9.2b (red dots), respectively. The black line is a fit to a three-level rate equation model. An additional bunching is observed due to occasional population of a metastable singlet state.

### 9.5 Conclusions

In conclusion, our results highlight the fact that there is no need to introduce a beam splitter dividing photons and two detectors for demonstrating the quantum nature of light. On the contrary, our fast detectors have such short dead times that statistical analysis of the detection events yields identical results. Fast detection of single-photon states is highly attractive to study more complex non-classical photon states, such as superpositions of different modes in the temporal rather than in the spectral\[126\] or spatial\[127\] domain. Antibunching from sources with shorter coherence times can be measured by further reducing the detector’s dead time which is here limited by its kinetic inductance. For example shortening the wire or using a parallel meander geometry are possible routes.\[79\]
Finally, even beyond fundamental considerations such detectors are useful for applications in fluorescence correlation spectroscopy[9] in order to simplify the experimental apparatus.

9.6 Methods

**Superconducting Detection System** We use a fibre-coupled superconducting single-photon detector consisting of a 100 nm wide and 5 nm thick NbN meandering wire. The meander structure is fabricated on a sapphire crystal and covers an area of 10 μm x 10 μm. The detector was coupled to an optical fibre. For that purpose the sapphire was thinned to a thickness of 100 μm and its back side was polished. The end facet of a single-mode fibre was aligned on the detector area and glued directly on the back side of the sapphire crystal. The pulses from the detector are amplified by 76 dB with two 2 GHz bandwidth amplifiers and fed to an oscilloscope with 1 GHz bandwidth. Fig. 9.2c shows a typical response curve recorded with the oscilloscope for two photons absorbed within a time window of 200 ns. There was always a small reflection of the pulse observed after 14 ns which we attribute to impedance mismatch. The dark count rate of the detector was < 50 s$^{-1}$ and its overall efficiency at 630 nm was around 10 %. The temporal resolution of the whole detection system (detector and correlation electronics) was measured by applying femtosecond optical pulses from a titanium-sapphire laser. The voltage pulses of the SSPD and the trigger signal from the laser were connected to a time interval counter with 4 ps resolution. We found a time resolution of our system of 100 ps.

**Sample preparation** An aqueous suspension of nanodiamonds (diluted approx. 1:50 from the original batch (Microdiamant AG MSY 0-0.05)) is spin-coated onto a glass coverslip. Among the nanodiamonds, only around 1 % contains a single N-V center, deduced from combined optical and atomic force microscopy measurements. Typical heights between 20 and 35 nm are found while the lateral extension is up to twice this values.
Surface plasmon polaritons (plasmons) have the potential to interface electronic and optical devices. They could prove extremely useful for integrated quantum information processing. Here we demonstrate on-chip electrical detection of single plasmons propagating along gold waveguides. The plasmons are excited using the single-photon emission of an optically emitting quantum dot. After propagating for several micrometers, the plasmons are coupled to a superconducting detector in the near-field. Correlation measurements prove that single plasmons are being detected.

This chapter is based on Reinier W. Heeres, Sander N. Dorenbos, Benny Koene, Glenn S. Solomon, Leo P. Kouwenhoven, and Valery Zwiller, Nanoletters 10, 661 (2010)
10.1 Introduction

The term plasmons refers to light confined to a metal/dielectric interface, with appealing characteristics of shortened wavelengths and enhanced field strengths [128]. Plasmons are also easily guided on-chip over distances of many micrometers. Most interest has been in the classical, many-photon regime where plasmons are generated by light and after traveling along the metal surface, re-emitted as photons into free space. A few experiments with respect to quantum properties have been performed. First, it was shown that the plasmon-mediated enhanced light transmission through arrays of holes in a metal surface conserves the photon’s polarization properties, including quantum superpositions [129]. Similar work showed that energy-time entanglement is also preserved [130]. Second, it was shown that coupling single emitters to silver nanowires in the near-field allows excitation of single plasmons [131, 132]. All these schemes relied on conversion of the plasmon to a free photon and subsequent far-field detection with traditional single photon detectors. Alternatively, on-chip electrical detection has been demonstrated using organic photodiodes [133], gallium arsenide structures [134] and germanium wires [135]. However, none of these techniques has provided single plasmon sensitivity. By coupling a plasmon waveguide to a superconducting single-photon detector (SSPD), we demonstrate on-chip electrical detection of single plasmons. Next to single-photon sensitivity [16], this on-chip, near-field detection has the potential for high detection efficiency, large bandwidth, and low timing jitter.

10.2 Device and setup

Our SSPDs consist of a meandering NbN wire (100 $\mu$m long, 100 nm wide, 5 nm thin). The critical temperature $T_c$ below which the wire becomes superconducting is approximately 9 K. When applying a bias current close to the critical current, absorption of a single photon is sufficient to create a local region in the normal, resistive state. This short-lived resistive state is detected as a voltage pulse at the terminals of the wire. The excess energy is dissipated within a fraction of a nanosecond, after which the superconducting state can be restored. The detection rate is limited by the kinetic inductance of the superconducting wire[26], which in our current detectors gives a maximum count rate of 100 MHz. As we show here, this detection mechanism can also efficiently measure individual plasmons. We fabricate plasmon waveguides from polycrystalline gold strips, which are electrically insulated from the NbN by a thin dielectric (Figure 10.4, Supporting Information). Gratings at both ends serve to couple incoming free-
space photons to plasmons confined to the bottom gold/dielectric interface[136]. These plasmons propagate to the detector where they are absorbed and detected (Figure 10.1b). Measurements are performed in a cryostat at 4 K with the sample mounted on an XYZ translation stage. A laser is focused through a cold microscope objective, and a countrate XY-map is measured as a function of laser-spot position.

**Figure 10.1:** (a) A scanning electron microscopy image showing the superconducting detector (cyan) and two gold waveguides (yellow) with coupling gratings. (b) Representation of the low-temperature setup. The sample is XY-scanned through the laser focus. Illumination of the grating excites plasmons at the substrate/gold interface. After propagating along the waveguide, absorption in the SSPD gives a voltage pulse, V. (c) SSPD pulse counts versus laser-spot position. (d) 2D XY-scan. The blue and red lines (WG1 and WG2) indicate where the line-cuts in (c) are taken.

### 10.3 Results

We find a large detector response when the laser directly illuminates the SSPD (three peaks at $X \approx 11 \mu m$ in parts c and d of figure 10.1). The detector response is very low with the laser spot on the substrate or gold strip, except at the grating regions. These detector peaks (consistently shifted for waveguides 1 and 2, figure 10.1c) show that light converted to plasmons is detected electrically on-chip. To substantiate the electrical detection of plasmons, we have performed
several checks. First, we measured one waveguide with an intentional 1 \( \mu m \) gap between grating and detector (figure 10.4 in Supporting Information), resulting in a strong suppression of the detector signal. Second, we rotated the incoming light polarization and retrieve a proper polarization-dependent detector signal (figure 10.5 in Supporting Information). We further measured wavelength dependence and find a vanishing signal at 650 nm due to losses in the gold film and a rapidly increasing detector response for longer wavelengths. Finally we measured the plasmon decay length in our gold strips and find a 1/e-decay of 10 \( \mu m \) for 810 nm light. All these checks are in qualitative agreement with simulations using Lumerical FDTD software. We have fabricated several waveguides with varying grating-detector distances and shapes (e.g., a bend, Figure S1 in Supporting Information).

**Figure 10.2:** (a) Microscope image of a plasmon Y-splitter device. The SSPDs (cyan) are colorized. (b, c) Signal of the left (b) and right (c) detector when scanning a laser spot (980 nm) across the device in (a). Just one detector produces a signal when illuminating the left or right detector. Both detectors produce a signal when illuminating the grating on the bottom left, indicating that plasmons couple to both arms of the Y-splitter. The white contours of the waveguide are a guide to the eye. Note that the color scales are different due to different dark-count levels in the left and right detectors.

We also designed more complex structures to illustrate the flexibility of our fabrication method, one of which is a Y-splitter (figure 10.2a). Again the experiment consists of scanning a laser beam across the sample. In this case, the count rates of the left (figure 10.2b) and the right (figure 10.2c) detectors are monitored simultaneously. Next to the individual detectors, which are visible in just one of the signals, the grating in the bottom left is visible in both images. This indicates that plasmons excited at the grating are propagating in both arms of the Y structure. This device could be used as an integrated plasmon Hanbury Brown and Twiss interferometer. The splitter is designed to be symmetric and therefore balanced. However, because the efficiency of the individual de-
tectors is determined by their intrinsic sensitivity (e.g., microscopic properties) and the applied bias current, it is not possible to measure the absolute splitting ratio in this configuration. Our current plasmon waveguides are all multimode, but in the future they can be downsized to single-mode structures implementing interference-based devices such as Mach-Zehnder interferometers [137] and coincidence-based quantum logic gates [138] using plasmons.

Figure 10.3: (a) Schematic representation of the measurement setup. Quantum dots and SSPD are cooled to 4 K in two separate cryostats, which are coupled free-space. BS1 and BS2 are both beamsplitters transmitting 10% and reflecting 90% of the incoming beam. The microscope objectives M1 and M2 are 60x, 0.85 NA and 100x, 0.90 NA, respectively. (b) Spectrum of a single SK quantum dot and a scanning electronic microscopy image of the distributed Bragg reflector (inset). (c) Time-correlation measurement with 10% of the quantum dot emission going to an APD and 90% sent directly to the SSPD. The integration time is 33 min, fitted normalized depth 0.46, and lifetime 655 ps. (d) Counts of the SSPD (same device design as Figure 1a) as a function of focus position of the emission from the quantum dot in (b). The dashed circles indicate the positions where the correlation measurements in (c) and (e) are taken. (e) Time-correlation measurement with 90% of the light sent to the grating on the bottom right. The dip at t = 0 ns confirms that the photon statistics are maintained after photons are converted into plasmons. The integration time is 8 h, fitted normalized depth 0.50, and lifetime 708 ps.
10.4 Detection of single plasmons

SSPDs are well characterized and proven to have single photon sensitivity [16]. The power dependence (figure 10.6 in Supplementary) already strongly suggests single plasmon sensitivity, since it is linear even in the regime where the average number of incoming photons within the detector dead time (10 ns) is much smaller than 1. However, to unambiguously prove single plasmon sensitivity requires a single photon source for plasmon excitation in addition to a time-correlation measurement [131]. We performed this measurement by cooling Stranski-Krastanov (SK) quantum dots (QDs) in a second cryostat. This sample contains QDs at the center of a distributed Bragg reflector microcavity (Figure 10.3b, inset) to enhance the brightness[139]. The emission of one of these QDs is collected and sent through a narrow bandpass filter. The filtered spectrum is shown in figure 10.3b. Ten percent of this emission is collected in an optical fiber and sent to an avalanche photodiode (APD). The other 90% is coupled through free-space to the setup containing the SSPD with waveguides (figure 10.3a). To confirm that we are looking at a single-photon source, we first position the incoming beam directly at the SSPD. The correlation measurement between detection events from the APD and the SSPD is shown in figure 10.3c. An antibunching dip with a fitted depth close to 0.5 is clearly visible. The fact that the dip does not go below the theoretical limit of 0.5 for a single emitter is likely to be due to background emission from the substrate and nonperfect filtering, especially since the two main peaks in the spectrum only constitute 60% of the total counts. The next step is to perform another XY-scan using the single photons from the QD (figure 10.3d). This scan clearly confirms that single plasmons can be excited by illuminating the gratings with single photons. After focusing the emission of the single-photon source on the lower-right grating, another correlation measurement is performed between the APD and the SSPD. The SSPD now detects plasmons that have propagated about 7.5 μm along the waveguide after coupling in through the grating. The resulting data clearly show that the quantum statistics of the original photons are maintained and that single plasmons are being detected. This is the first time that single plasmons are observed on-chip in the near-field and opens up a wide range of possibilities in quantum plasmonics. By placing a single emitter on-chip using nanomanipulation[140], the integration could even be taken one step further, resulting in a complete optical circuit with efficient coupling of a single-photon source[141, 142] to a waveguide and a detector on a monolithic device. Detecting single plasmons on-chip makes our waveguide detector scheme very promising for ultrafast detection with low dark-count rates. The time resolution of <70 ps that can be achieved with an SSPD today is comparable
to the best APDs. However, contrary to those detectors the SSPDs also provide good sensitivity in the near infrared range, up to several micrometers in wavelength. Combined with the flexibility for fabricating various complex waveguide structures, this results in many potential applications as sensors or interconnects and for quantum information processing.

10.5 Supplementary

10.5.1 Sample fabrication

The SSPDs are fabricated on a sapphire substrate with a thin layer (∼5 nm) of NbN. After evaporating Nb/AuPd contacts using an e-beam lift-off step, the meandering detector lines are defined using reactive ion etching with an HSQ e-beam mask. A layer of 20 nm SiO$_2$ is sputtered to electrically isolate the waveguides from the detectors. A conducting layer is required for the next e-beam step to avoid charging of the isolating sapphire substrate. Therefore a triple layer of photo-resist (Shipley S1813, 400 nm), tungsten (7 nm) and PMMA 950k (100 nm) is used. After writing the waveguide structures, the chip is developed and dry etched (SF6 for tungsten, O2 for photo-resist). Finally, a 125 nm thick layer of gold is evaporated and lifted-off in acetone. A similar fabrication method was reported earlier (see [136]).

10.5.2 Measurement Setup

The SSPD sample is placed on an Attocube XYZ positioner stage in a dipstick at liquid helium temperature. A Leitz microscope objective (100x, 0.90 NA) is positioned close to the sample and a laser and white-light imaging system is coupled through free-space. The laser source is either a 785 nm or 980 nm diode or a tunable Ti:sapphire laser (Spectra-Physics 3900) from 750 to 1000 nm. The SSPD is current-biased close to the critical current $I_c = 12 \mu$A using a homemade bias-T. Pulses are counted using a Stanford Research 400 pulse counter after being amplified by a Miteq JS2-01000200-10-10A low-noise amplifier. Our current devices support count-rates up to 100 MHz. Rates beyond 1 GHz are feasible by reducing the kinetic inductance, using shorter superconducting wires. After calibrating the forward and backward step sizes of the positioners, the 2D scans are taken by stepping and recording detector counts at each location. For the time-correlation measurements, an amplifier and pulse inverter are added in series, after which the pulses are registered using a Picoquant Picoharp 300 correlator.
10.5.3 Quantum Dots

The quantum dot (QD) sample is made by molecular-beam epitaxy and contains a dilute ensemble of selfassembled InAs/GaAs QDs grown at the central antinode of a planar optical microcavity. The QD density is less than $1 \mu m^{-2}$. The microcavity consists of two distributed Bragg reflectors (DBR) surrounding a full-wave GaAs spacer. The DBR region consists of alternating, quarter-wave thick pairs AlAs and GaAs (15.5 lower and 10 upper). The sample was placed in a liquid He bath cryostat with a 4.2K base temperature. At this temperature discrete emission from the QD ensemble spans a wavelength range of approximately 880 to 990 nm. The cavity mode of interest is located at 915 nm. Discrete single QD emission is coupled to a 60x, 0.85 NA microscope objective (laser spot size 1 $\mu m$) and then to free-space optics. A 10 nm band-pass filter (center wavelength: 920 nm, used at an angle to filter at shorter wavelengths) was used to spectrally select the emission of the QD. The excitation was a standard 532 nm continuous wave diode pumped solid state laser, with approximately 15 $\mu W$ of power on the sample.

10.5.4 Fitting Details

The time correlation data should be fitted with a function of the form $A(1 - e^{(|t-t_0|/\tau)})$. However, because the time-response of the system is finite, the exponential is first convolved with a Gaussian $Be^{(-t^2/\tau^2)}$, where $B$ is a normalization constant setting the integral of the Gaussian to 1. The parameter $\tau$ is also fitted for, giving the values 305 ps and 345 ps for the fits in figure 10.3c and 10.3e respectively. This is in good agreement with the expected time-response of the system containing the APD (Perkin Elmer), SSPD and time-correlator (Picoquant Picoharp 300). The APD generates most of the jitter.
Figure 10.4: (a, b) Optical microscope images of two other waveguide structures that have been fabricated, illustrating the flexibility of our approach. (c) XY-scan of the interrupted waveguide in a. The measurement shows a large reduction of plasmon detection from the isolated grating on the right (dashed circle, right) compared to the grating on the left (dashed circle, left), in qualitative agreement with FDTD simulations using Lumerical. Note that the 1 μm gap next to the grating on the right is clearly visible in the scan, indicating that it is also an efficient way to excite plasmons.

Figure 10.5: SSPD count-rate as a function of the polarization of the laser beam (980 nm), which is varied by rotating a λ / 2 wave-plate. 90 degrees corresponds to polarization along the waveguide and SSPD meander. The contrast (amplitude / average) is 0.66.
Figure 10.6: Power dependence of the SSPD count-rate as a function of the incident power (785 nm) on the grating closest to the SSPD for different bias currents. $I_c = 12 \mu A$ is the critical current, at which the detector switches to the normal state. For smaller bias currents, the slope is clearly different from 1. Close to the critical current $I_c$ the fitted line corresponds to an exponent of about 1, indicating a linear dependence. This is a requirement for a process detecting single plasmons. The fact that the curve is linear even at powers where the average number of photons within the dead-time of the detector ($\sim 10$ ns) is much smaller than one strongly suggests that single plasmons are detected [16]. The maximum calculated quantum efficiency based on these curves is $2.7 \cdot 10^{-3}$ for the complete photon - plasmon - detection event process.
Chapter 11

Particle detection

11.1 A high efficiency superconducting nanowire single electron detector

We report the detection of single electrons using a Nb$_{0.7}$Ti$_{0.3}$N superconducting wire deposited on an oxidized silicon substrate. While it is known that this device is sensitive to single photons, we show that it also detects single electrons with keV energy emitted from the cathode of a scanning electron microscope with an efficiency approaching unity. The electron and photon detection efficiency map of the same device are in good agreement. We also observe detection events outside the active area of the device, which we attribute to sensitivity to backscattered electrons.

11.1.1 Introduction

The versatility of superconducting nanowires as single particle detectors relies on their sensitivity to the minute amount of energy required to locally induce a resistive transition. From this point of view, the latest achievements involving the detection of organic molecules [143] and photons in the infrared range [40] all derive from early experiments with $\alpha$-particles in the MeV range [144]. In order to go beyond the optical resolution limit, the scanning electron microscope (SEM) working at low temperature [145], proved useful. This technique enabled the visualization of the real size of the hot spot caused by a detection process [146]. However, the best achieved resolution is limited by thermal diffusion to about 1 $\mu$m and single electron detection has not been demonstrated. In this

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Figure 11.1: Average number of counted peaks per bias current pulse $n_d$ as a function of the number of incoming electrons $n_i = I_b \times t_d/e$ ($E_e = 10$ keV, $I/I_c = 0.85$). A linear fit (solid line) gives a detection efficiency $\eta = 0.91(0.01)$. (Inset) A typical experimental signal at the output of the detection chain. One pulse corresponds to the detection of one electron.

In this letter, we show single electron detection using a superconducting nanowire. It offers a high spatial and timing resolution and we compare the electron detection efficiency map with a photon detection efficiency map, measured on the same sample.

11.1.2 Device and measurement setup

The fabrication process of our superconducting nanowire has been described before [48]. It is etched from a 6 nm thick layer of Nb$_{0.7}$Ti$_{0.3}$N and has a width of 100 nm. The wire is folded into a meander structure, with a separation of 100 nm between adjacent detecting branches (see figure 11.1a). It covers a $10 \times 10$ μm$^2$ surface. One end of the wire is grounded whereas the other end is connected to a cryogenic coaxial cable used to inject a current through the structure. We measure a DC critical current $I_c = 10$ μA at 4.2 K and $I_c = 5.2$ μA at 8 K. Our experimental setup consists of a cryogenic scanning electron microscope [147].
The detector is mounted on a cold translation stage at $T=8$ K under the electronic beam of an SEM. The current $I_b$ is controlled and can be measured with a picoammeter (measurement uncertainty 10 %). The energy of the incident electrons $E_e$ can be varied between 5 and 30 keV.

To block low frequency $1/f$ noise we use a DC-block, through which we can only bias the wire with pulses of current amplitude $I$ and duration $t_d = 800$ ns (see inset of Fig. 1). Each pulse is reflected by the circuit. When the current is on, the detection of an electron triggers a short pulse at the output of the system (duration of a few ns, see inset of Fig. 1). The change in baseline is caused by the limited bandwidth (0.1 to 1000 MHz) of the amplification of the output pulses, but does not affect the bias current of the SSED. We count the average number of detection pulses and compare it to the average incoming number of electrons $n_i = I_b \times t_d / e$ in order to infer the absolute detection efficiency $\eta$. We can adjust the current $I_b$ down to a few pA, and obtain single electrons separated by approximately 100 ns. We have measured the number of detection events $n_d$ versus incoming electrons $n_i$ (figure 11.1). The linearity of this plot shows that we detect single electrons. A complete map of $\eta$ is obtained by scanning the electron beam over the sample with a full control of the step size and dwell time.

### 11.1.3 Results

To compare the relative performances of our superconducting nanowire detector for single electrons and single photons, we present in figure 11.2a a two-dimensional plot of the photon detection efficiency for our sample, obtained by scanning a laser spot (1 $\mu$m diameter) over the detector with an intensity, low enough to be in the single photon regime. A detailed description of the setup is given in Ref. [148]. It shows spatial variations over the active area that could originate from structural and/or chemical inhomogeneities of the layer. This reference image can be compared to figure 11.2b which shows the detection efficiency for electrons of energy 30 keV and a bias current $I/I_c=0.35$. We observe that the electron detection efficiency is more homogeneous than in the case of photon detection. There exists however a clear correlation between the two measurements, with the maxima and minima located at the same position for both images. It demonstrates that the detection process is affected in the same way for both particles. It shows also that SEM measurements could be used to characterize the performances of superconducting nanowires for photon detection. With increasing bias current, the electron detection efficiency saturates and becomes homogeneous over the whole detector active area as illustrated by fig. 11.2c ($I/I_c=0.85$, $E_e=20$ keV). We note that we have also been able to produce elec-
Figure 11.2: 2D plots of the detection efficiency. (a), for single photons ($\lambda=532$ nm, $I/I_c=0.8$). The white area corresponds to missing data (b), for single electrons (bias current $I/I_c=0.35$, electron energy $E_e=30$ keV). (c), same map as (b) with $I/I_c=0.85$ and $E_e=20$ keV. (d) Zoom of figure c for a $1 \times 1 \mu m^2$ area. A square shown in (c) indicates the relative scale and orientation of (d).
tron detection efficiency maps with NbN wires of 500 and 1000 nm widths [147]. However, the present NbTiN detector covers a larger area and offers a better efficiency with fewer inhomogeneities.

In both figures 11.2b-c, one observes sharper details than in fig. 11.2a. This is expected as electron microscopy has a much better spatial resolution than optical microscopy. In order to evaluate our resolution, we present in figure 11.2d a $1 \times 1 \ \mu m^2$ image of the detection efficiency taken in the conditions of fig. 11.2c. The plot directions make an angle of 60° with respect to the wire direction. It reveals the inner structure of the detector via a small modulation of the detection efficiency (0.05 modulation, compared to an average efficiency of 0.85). The period of the modulation corresponds to the pitch of the meander structure. In order to estimate over which typical distance a single nanowire can detect, we fit a cross-section of figure 11.2d with a set of gaussians centered on the wire centers. It gives a characteristic width of 220 nm (FWHM), of the same order as the wire size and inter-wire separation. This makes it very difficult to deconvolute the intrinsic resolution of our instrument from the detector profile. Nevertheless it allows us to claim that it is of the order of 100 nm. We also observed that for electron energies $E_e \leq 10$ keV, the resolution is degraded (to about 850 nm FWHM) and one can no longer distinguish individual wires. We attribute this loss of performance to charging effects on the substrate which degrade the SEM resolution.

Figure 11.3a summarizes our results for $\eta$ as a function of $I/I_c$ and $E_e$. For $E_e \geq 10$ keV, $\eta$ increases with $I/I_c$ until it reaches a plateau for values larger than 0.4. Moreover, the plateau value decreases with increasing electron energy. Our results suggest that the characteristic size of the normal region created by the electron as it impinges on the detector does not depend much on $E_e$. This fact is in good agreement with previous studies that showed that the mean electron energy loss $\Delta E_e$ is of the order or 100 eV for the impinging electron energy range we have explored [150]. Moreover, one has $\Delta E_e = S \times \lambda_{in}$, where $\lambda_{in}$ is the inelastic mean free path of the electron and $S$ is the stopping power of the material, which is well described by the Bethe formula [151] or empirical variations of the latter [152, 150]. To a first approximation $S = f(E_e)/E_e$ and $\lambda_{in} = g(E_e) \times E_e$ where $f$ and $g$ are slowly varying functions. As a consequence, the first inelastic collision in the detector happens deeper for high energy electrons and is less likely to trigger a transition of the nanowire, explaining the decrease of $\eta$ with increasing $E_e$. The low efficiency at $E_e = 5$ keV (60%) is not consistent with this model. We think it arises from charging effects at the detector surface that are also responsible for the degradation of the resolution of the 2D-plots at this energy.
Figure 11.3: (a) Electron detection efficiency for different values of bias current and electron energy. The beam position is fixed and close to the center of the active area. (b) Cross-section of the detection efficiency map of fig. 11.2c (log scale). The fall of detectivity at the edge of the active area is fitted by a double gaussian (dotted blue lines: individual gaussians, solid red line: sum) with characteristic lengths $l_1 = 330$ nm and $l_2 = 1450$ nm respectively. (c) Plot of $l_2$ as a function of the electron energy $E_e$. At high energy ($\geq 10$ kV), it is in good agreement with Monte-Carlo simulations of the mean radius of exit for backscattered electrons [149].
Evidence of the detection of backscattered electrons is provided by the cross-section of the efficiency map of fig. 11.2c, presented in figure 11.3b. We observe shoulders for the detection efficiency signal at the border of the detector, proving that it is still possible to detect electrons impinging at distances larger than the SEM resolution. A double gaussian fit at the edge for different cross-sections, both horizontal and vertical, gives two average characteristic lengths $l_1 = 330(40)$ nm and $l_2 = 1760(230)$ nm, with a ratio in amplitude around 80:20. We attribute the first length to the intrinsic resolution of our apparatus. It is convoluted here with the finite step size of the SEM beam for this experiment (200 nm). We attribute the second length scale to the detection of backscattered electrons. This distance is consistent with Monte-Carlo simulations of the electron trajectories that predict a mean distance between the entry and exit points of $l_{MC} = 1320$ nm. This distance depends strongly on the energy of the incident electron. We present in figure 11.3c a comparison of $l_2$ and $l_{MC}$ for different values of $E_e$. At low energy, the distance $l_{MC}$ is of the order of or lower than the apparatus resolution degraded to 500 nm. We only observe a single gaussian. At larger energies, above 10 keV, the agreement between experiment and simulation is very good.

11.1.4 Conclusions

In conclusion, we have operated a fast and efficient single electron counter using a superconducting nanowire. We show an efficiency close to unity. Its low noise, short dead time and high timing accuracy makes this device interesting in situations where a cryogenic environment is available. Optimizing further these devices for the specific purpose of electron detection can certainly improve future performances. For example, a thin conducting layer on top of the nanowire can reduce the charging effect and improve the efficiency for low energy electrons ($\leq 5$ keV). For high energy electrons, increasing the superconducting layer thickness will improve the performances. Fabricating the devices over a thin membrane would avoid backscattering. Arrays of such devices, could provide an imaging system for electrons with a time resolution below 60 ps [47] and a pixel size below 10 $\mu$m. Those figures could significantly improve the technologies presently used for example in ultrafast electron microscopy [153].
Chapter 12

Conclusions, future directions and applications

As mentioned in the introduction, the following requirements for a (single) photon detector are important:

1. Efficient over a large wavelength range, independent of polarization
2. Low noise
3. Short dead time
4. Low timing jitter
5. Photon number resolution
6. Large array

In this section I will summarize the current status as described in part 1 of this thesis and what can be done to improve this.

(1) We have fabricated NbTiN on an oxidized silicon substrate. It shows a peak efficiency of 34 % at a wavelength $\lambda = 1200$ and in this thesis sensitivity over a large wavelength range, from $\lambda = 700$ nm to $\lambda = 1700$, is presented. We have also measured single photon sensitivity at shorter wavelengths (with light emitting diodes, at $\lambda=285$, 365 and 405 nm). This is illustrated in figure 12.1. Steps have been taken to increase the efficiency further. The most limiting factor is the absorption efficiency, calculations have shown that NbTiN on DBRs have twice the absorption efficiency with respect to NbTiN on oxidized silicon. However the first devices showed low efficiencies, below 1%. Constrictions in the wire have been identified as the source for the low efficiency. Improving the smoothness of the dielectric layers would probably solve the issue of constrictions and higher efficiencies are expected. The intrinsic efficiency of NbTiN is clearly
Figure 12.1: UV sensitivity of SSPDs. It is measured using light emitting diodes at the given wavelength. The dark count rate during this measurement was $\sim 500$ cps. As the illumination was free space a precise efficiency is hard to calculate, but is close to an expected value of 10%. A linear fit clearly demonstrates single photon efficiency.

dropping for wavelengths larger than 1000 nm. We have used another material (NbSi) to improve this effect. We expect larger hot spots in a NbSi nanowire than those in NbTiN, because the superconducting gap energy is smaller, and thus more Cooper pairs are broken when a photon is absorbed. We report a relative increase in efficiency for longer wavelengths, optimizing the geometry is needed to fully make use of this approach. As photons can be used to transfer information, which is often encoded in the polarization state of light[15], so it is inconvenient if the detection process is polarization dependent. We have shown that a spiral geometry removes the polarization dependence of SSPDs. We have also taken steps to improve the technique of fiber coupling. A fiber coupled device greatly improves the user friendliness, opening a wide range of applications (see next section).

(2) SSPDs made of NbTiN on oxidized silicon show a very low intrinsic dark count rate, especially when it is cooled down to temperatures below 4 K. In the literature sources of this intrinsic dark count rate have been identified. Further investigation is needed to use this knowledge to decrease the intrinsic dark count rate.

(3) We have shown that the dead time of SSPDs is approximately 10 ns. It is dependent on the kinetic inductance of the wire and the impedance in the circuit.
Following [26] we have confirmed by fabricating shorter wires that decreasing the kinetic inductance shortens the dead time. When the dead time is decreased further it will at some point be limited by thermal time scales (cooling time \( \sim 100 \) ps). It is however expected that before this limit is reached by reducing the electrical dead time (kinetic inductance, impedance of the readout circuit) the resistive spot after absorption will become stable and the device will latch [24]. Until this issue is resolved dead time of SSPDs will be limited to a few ns.

(4) During this thesis work we took steps to decrease the timing jitter related to components in our setup. We have taken the timing jitter down to 60 ps.

(5) We have tried to resolve photon number by increasing the input impedance of the amplifier as suggested in Ref. [85]. We measured the voltage pulse height as a function of the number of photons absorbed in the device. We did not find a convincing correlation between the pulse height and photon number. Recent literature [77] suggests that with this method it is not possible to resolve the photon number because if two hotspots are formed simultaneously at different locations along the nanowire, the total energy dissipated in both hotspots will result in a combined resistance of the two hotspots that is approximately equal to the resistance of an individual hotspot.

(6) We have shown a preliminary proof of principle to extend a single pixel detector to a multi pixel device without the need for a complete readout circuit per pixel. Connecting different pixels in serial and parallel offers two approaches which could preserve high count rates, provide spatial information and maintain the same complexity for readout interfaces as is the case for a single or at most two SSPDs. The experimental results for arrays based on our methods, confirm the potentials of SSPD arrays for imaging. As the only limit on the length of transmission lines in series structures is set by uncertainty in the time delay between pulses, reducing the timing jitter will enable shorter transmission lines, with the ultimate limit of no transmission line. Another approach is capacitive readout, which also relaxes the need for large bandwidth amplification.

Implementation in different experiments (part 2 of this thesis) has shown that SSPDs are indeed useful devices for research laboratories. In table 12.1 a comparison to other single photon detectors is made. It can be seen that for applications in the (near) infrared, superconducting detectors are the best option, because the InGaAs APD has a low efficiency, high dark count rate and a long deadtime. Comparing TES with an SSPD it is noted that although the TES has a high efficiency, SSPDs are easier in use, and have much better timing properties. In the visible range of the spectrum the Si APD has a higher efficiency, however, SSPDs can still be preferred when timing properties are important for the application.
<table>
<thead>
<tr>
<th>Detector</th>
<th>Operating wavelength</th>
<th>Operating T</th>
<th>QE</th>
<th>DCR</th>
<th>Deadtime</th>
<th>Timing jitter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si APD</td>
<td>400-1100 nm</td>
<td>Room</td>
<td>90%</td>
<td>$1 \times 10^3$</td>
<td>100 ns</td>
<td>500 ps</td>
</tr>
<tr>
<td></td>
<td>800-1700 nm</td>
<td>Room</td>
<td>10%</td>
<td>$1 \times 10^5$</td>
<td>100 ns</td>
<td>500 ps</td>
</tr>
<tr>
<td>InGaAs APD</td>
<td>300 nm- 10 μm</td>
<td>100-300 mK</td>
<td>99%</td>
<td>$1 \times 10^5$</td>
<td>100 ns - 10 μs</td>
<td>100 ns</td>
</tr>
<tr>
<td>TES</td>
<td>300 nm- 10 μm</td>
<td>4 K</td>
<td>30%</td>
<td>$1 \times 10^2$</td>
<td>10 ns</td>
<td>60 ps</td>
</tr>
<tr>
<td>SSPD</td>
<td>300 nm- 10 μm</td>
<td>4 K</td>
<td>30%</td>
<td>$1 \times 10^2$</td>
<td>10 ns</td>
<td>60 ps</td>
</tr>
</tbody>
</table>

**Table 12.1:** Detector comparison.
12.1 Applications

**Quantum cryptography**

Cryptography is already used since ancient times to transfer messages in a secure way from a sender (conventionally called 'Alice') to a receiver ('Bob') without anyone else ('Eve') to read the message. One of the first examples is the use of transposition ciphers, which rearrange the order of letters in a message. Of course one needs a key to de-rearrange the order or decipher the message. It is shown that for total security, a key as long as the text is needed for encryption. Therefore, a common used method to generate a key is based on the factorization of two numbers, leading to a public key and a private key (i.e. the RSA algorithm). To break the key, computer power which grows exponentially with the length of the key, is needed, so it is relatively easy to get the required security. However, things changed with technology proposals based on quantum mechanics. In principle, a quantum computer can use Shor's algorithm to factorize numbers, and the amount of quantum computer power required only grows linearly with the length of the key. In addition, the idea of quantum cryptography is introduced, a method which allows Alice and Bob to determine whether the channel is eavesdropped. One needs a channel through which quantum information can be sent. Quantum information for transport over long distances is most conveniently coded in single photons, so single photon sources and single photon detectors are required. In theory this method is 100% reliable, but sets requirements on the technology which can (and for some will) not be reached. For example, a channel without loss will not exist: this requires error correction, giving Eve the opportunity to stay hidden. In depth reviews of quantum cryptography can be found in [15, 154, 155]. Here I will describe what requirements can be set for single photon detectors. The non perfectness of single photon detectors lie in limited efficiency, dark counts and dead time.

These limitations impose bounds on the secret key rate. Limited efficiency causes losses and the rate cannot scale with the distance better than the transmittivity of the line and on the achievable distance where losses are so large that the signal is lost in spurious events, the 'dark counts'. The dead time also limits the rate. A bound on the dark count rate can be derived as follows: the detection rates must be written as

\[ R_n = R_{n,p} + R_{n,d} \]  \hspace{1cm} (12.1)

where \( R_{n,p} \) is the contribution of detections and \( R_{n,d} \) is the dark count rate. There are two differently contributing error mechanisms. The errors on the line are introduced only on the photon contribution, while the dark counts always
give an error rate of approximately $1/2$. If the error rate per bit exceeds $1/4$, there is no way to create a secure key. With such an allowed error rate simple intercept-measure-resend attack causes Bob and Eve to share (approximately) half of Alice’s bits and to know nothing about the other half; hence, Bob does not possess information that is unavailable to Eve, and no secret key can be distilled. From 12.1 it follows that

$$R_{n,p} > R_{n,pd}$$

and with non perfect transmission efficiency this constraint becomes: $N_{cr} > 2N_{dc}/\eta$ with $N_{cr}$ the measured count rate, $N_{dc}$ the dark count rate per detector and $\eta$ the efficiency.

Furthermore, double clicks in detection devices, resulting from dark counts, cannot be simply ignored, as this would open up a security loophole. A simple attack exploiting this loophole goes as follows: Eve intercepts the photon, measures the polarization state and resends a pulse containing a large number of photons in the detected polarization. If Bob measures in the same basis as Eve, he will receive a single detector click, about which Eve has full information. If Bob measures in a different basis, he will almost always receive double clicks, which he discards. Therefore Eve has perfect information about all signals retained by Eve, allowing her to break the QKD scheme.

In summary, the higher the efficiency and the lower the dark count rate, the better security over larger distance can be obtained. In 2007 a quantum key distribution experiment with a 42 dB channel loss using SSPDs was performed, succeeding in a record distance of 200 km.

**Loophole free Bell experiment**

The Bell inequality experiment[156] is at the heart of quantum mechanics. This experiment was performed for the first time with photons emitted from a laser by Aspect et al. [157]. However, so far all reported Bell experiments suffer from so-called ”loopholes”, imperfectnesses in the experiments, which could be used to explain the results with a local realistic theory.

The two main loopholes are: locality loophole and detection loophole. The locality loophole occurs when the distance between the local measurements is too small to prevent communication between one observers measurement choice and the result of the other observers measurement. In other words the detectors should be separated in space more than light can travel within the measurement time. A promising candidate for closing the locality loophole are optical photons, where good polarization analyzers exist and spacelike separation can be achieved.
In fact, the locality loophole has been closed by Weihs et al. [158]. However, thus far, all Bell experiments with photons suffer from the detection loophole [159]. The imperfect efficiency of photodetectors makes the results of all these experiments compatible with local realistic models. It turns out that the efficiency needed for ruling out a local realistic explanation is dependent on the dark count rate: for \(\sim 1\%\) dark counts, the efficiency needed is 83\% and for a very low dark count rate 69\%. [160] Massive particles (i.e. ions) are much easier to detect, efficiencies can be close to 100\%, so in this system the detection loophole has been closed [161], however they are extremely difficult to separate, so in this experiment the requirements for the locality loophole are not met. Given the low dark count rate and short dead time of SSPDs, they are a good candidate to use in a loophole free Bell experiment, provided that an (overall) efficiency will be reached of 69\%.

Quantum computation

In 2001 a paper published by Knill, Laflamme, Milburn showed that quantum computation was possible with single photons as quantum bits and linear optical elements, such as polarizers, waveplates [6]. Quantum computing with linear quantum optics, has the advantage that the proposed quantum bits (the photon) are potentially free from decoherence: The quantum information stored in a photon tends to stay there. This same fact introduces the difficulty that photons do not naturally interact with each other, and in order to apply two-qubit quantum gates such interactions are essential. Cross-Kerr nonlinearities can be used to induce a single-photon controlled-NOT operation. However, naturally occurring nonlinearities are many orders of magnitude smaller than what is needed for the purpose of quantum computation.

An alternative way to induce an effective interaction between photons is to make projective measurements with photo-detectors. Knill, Laflamme, and Milburn constructed a protocol in which probabilistic two-photon gates are teleported into a quantum circuit with high probability. Subsequent error correction in the quantum circuit is used to bring the error rate down to fault-tolerant levels. Initially, the KLM protocol was designed as a proof that linear optics and projective measurements allow for scalable quantum computing in principle. However, new experiments in quantum optics, demonstrating the operation of high-fidelity probabilistic two-photon gates, followed. As pointed out in [105] two photon gates based on projective measurements are probabilistic, meaning that a percentage of the operations fail, which could lead to an exponential need for resources. However the KLM gate provided a success rate which could be made higher than
50%, so the resources time can be scaled linearly with the number of gates. The only element which was needed, and to date is unavailable, is a high efficiency photon number resolving detector. Photon number resolving is needed because the exact number of photons in a mode has to be known. This also means that the efficiency has to be high because otherwise the number of photons detected is less than the actual number. In the original paper efficiencies close to 100% are needed for the implementation, with error correction this requirement has become less severe.

Medical imaging

Medical imaging refers to observation of (parts of) the human body. Nowadays techniques are Röntgen photographs, CT scans and magnetic resonance imaging (MRI). These techniques all have their disadavantages and imaging based on (visible) light would be more convenient. Although the human body is absorptive and scattering, it is slightly transparent. For example fast bursts of optical energy (laser pulses) are either randomly scattered (losing their coherence) or absorbed as they travel through a media, however, across short distances, a few photons keep their coherence and pass through in straight lines without being scattered. These coherent photons are commonly referred to as ballistic photons. As SSPDs are sensitive to low light levels, they are a potential candidate for this application. Imaging techniques cannot rely on a single pixel detector, although the object can be scanned by scanning the laser, faster operation and a higher resolution is achieved with a detector array. In this thesis steps have been taken towards an array of superconducting single photon detectors. This has to be developed further to fabricate a real device.
12.1 Applications
Bibliography


Superconducting single photon detectors

Superconducting single photon detectors (SSPDs) are sensitive, fast and low noise single photon detectors. They consist of a long superconducting wire and the operation principle is based on the formation of a normal state after absorption of a single photon. The work in this thesis has been focused on: (1) Improving the properties of SSPDs (2) Implementation in experiments.

In 2001 researchers at the Moscow State Pedagogical University showed that a (part of a) strip of superconducting material turns into the normal state after absorption of light. By running current through the wire they could extract voltage pulses. They showed that the frequency of voltage pulses scales linearly with the intensity of the light absorbed a clear signature of single photon detection. They also showed that the dead time, the time it takes before a second photon can be detected, is low compared to existing single photon detectors (i.e. InAs Avalanche Photodiodes). This promising proof of principle was the starting point of this thesis. The aim of this work was to improve the properties such that the SSPD is competitive with existing technologies and to demonstrate that the detector indeed meets requirements for implementation in experiments.

The key requirement for implementation in experiments is a high system detection efficiency. System detection efficiency (SDE) means the chance that a photon is detected after entering the system of a detector (usually an optical fiber), i.e. the SDE consists of the coupling efficiency between the optical fiber and the active area of the SSPD, the chance of absorption and the intrinsic efficiency. At the time the work of this thesis started, the SDE was low (<1%), because the active area was too small and coupling to a fiber was not demonstrated. In addition, the absorption efficiency could be improved and also for longer wavelengths the intrinsic efficiency dropped severely. Furthermore, in optical experiments information is often coded in the polarization state of the photon. The absorption efficiency in a long meandering wire is polarization dependent, which is inconvenient for this type of experiments.

In this thesis we have shown that it is possible to fabricate SSPDs made of
Summary

NbTiN on a silicon substrate (chapter 3), with an active area of 12x12 μm. The large active area enabled coupling to an optical fiber. We have demonstrated two techniques: (1) mechanical coupling (chapter 4, 8 and 9), (2) coupling by an optical fiber sleeve, enabled by the silicon substrate (chapter 3). In addition we have demonstrated that a silicon dioxide/silicon interface acts as a reflector, improving the absorption efficiency and we have taken steps to improve the absorption efficiency towards unity by fabricating the SSPD on a distributed Bragg reflector (chapter 4). The geometry of a straight wire has been adjusted such that the absorption efficiency has become polarization independent (chapter 5). We have also fabricated an SSPD from a low superconducting gap material, to increase the intrinsic efficiency in the infrared (chapter 6).

During the course of this thesis, work has also been performed on the read out of SSPDs. This has been motivated by the fact that the SSPD has to be read out by large bandwidth amplifiers. Scaling a single SSPD to an array requires a different read-out approach. We report (chapter 7.1) experimental results of two multiplexing methods (series and parallel) and their combination for multi-pixel single photon detection. The first method offers simultaneous readout of all pixels resulting in higher count rates, whereas the second provides efficient implementation for larger arrays. A larger number of detectors was implemented within a matrix by combining both types of arrays inheriting all the advantages. In all cases the readout circuitry complexity was significantly decreased. Another approach to scale to large arrays is to couple the SSPD to a capacitor, equivalent to the well known CCD chips (chapter 7.2). A capacitor keeps the created voltage for a longer time, relaxing the need for a high bandwidth amplifier. By gating the detector, the reduced timing resolution can be regained. Additionally, gating allows filtering of scattered light in time. For the sake of directly measuring the resistance of the hotspot the SSPD was read out with a high-electron-mobility transistor (HEMT) (chapter 7.3). If the input impedance of the amplifier is higher than the resistance of the hotspot (R_{hs}), the pulse amplitude is proportional to R_{hs}. We utilize an in-situ HEMT to increase the input impedance and are able to distinguish between photon and dark counts, however no clear correlation between photon number and output pulse amplitude has been found.

In the second part of this thesis experiments with SSPDs are described. A typical quantum optics experiment is antibunching of photons emitted from a single photon emitter. It is also the ultimate proof that SSPDs are single photon detectors. This experiment is described in chapter 8. As single photon emitters a single InAsP quantum dot embedded in a standing InP nanowire is used. A regular array of nanowires was fabricated by epitaxial growth on an electron-beam patterned substrate. Photoluminescence spectra taken on single quantum
dots show narrow emission lines around $1.2 \, \mu m$. SSPDs enable us to measure the second order correlation function as well as cross correlations. Clear antibunching is observed ($g^{(2)}(0) = 0.12$). Furthermore we have identified a biexciton-exciton cascade and two excitonic charge states.

The antibunching as described in chapter 8 is typically demonstrated with a Hanbury-Brown-Twiss setup where incoming light is split by a beam splitter and sent to two detectors resulting in anticorrelation of detected events. In a purely classical interpretation of this effect, photons are regarded as indivisible particles. However, this interpretation evokes the false impression that a beam splitter is necessary to prove non-classicality of light. In chapter 9 we demonstrate single photon statistics measurements from a quantum emitter with only one detector. The SSPD has a dead time shorter than the coherence time of a colour center in diamond. No beam splitter is employed, yet anticorrelations are observed, enforcing a quantum mechanical interpretation.

Another implementation of SSPDs consists of the detection of single surface plasmon polaritons (chapter 10). Surface plasmon polaritons (plasmons) have the potential to interface electronic and optical devices. They can prove extremely useful for integrated quantum information processing. Here we demonstrate on-chip electrical detection of single plasmons propagating along gold waveguides. The plasmons are excited using the single-photon emission of an optically emitting quantum dot. After propagating for several micrometers, the plasmons are coupled to a superconducting detector in the near-field. Correlation measurements prove that single plasmons are being detected.

Finally (chapter 11) we have shown that SSPDs also detect single electrons with keV energy emitted from the cathode of a scanning electron microscope with an efficiency approaching unity. The electron and photon detection efficiency map of the same device are in good agreement. We also observe detection events outside the active area of the device, which we attribute to sensitivity to backscattered electrons.
Samenvatting

Supergeleidende enkele photon detectoren

Supergeleidende enkele foton detectoren (SSPDs) zijn gevoelige, snelle, enkele foton detectoren met weinig ruis. Ze bestaan uit een lange supergeleidende draad en de werking is gebaseerd op de formatie van een normale toestand na het absorberen van een enkel foton. Het werk in dit proefschrift focust zich op (1) Verbeteren van de detectoren (2) Implemetatie in experimenten.

In 2001 onderzoekers aan de Moscow State Pedagogical University lieten zien dat (een deel van) een strip supergeleidend materiaal verandert in de normale toestand na het absorberen van licht. Door het sturen van stroom door de draden konden ze voltage pulsen verkrijgen. Ze lieten zien dat de frequentie van de voltage pulsen lineair schaalt met de intensiteit van het licht, een duidelijk signaal voor enkele foton detectie. Ze lieten ook zien dat de dode tijd, de tijd nodig voordat een tweede foton kan worden gedetecteerd, is kort vergeleken met bestaande enkele photon detectoren (d.w.z. InAs Avalanche Photodiodes). Dit veelbelovende proof of principle experiment was het startpunt voor dit proefschrift. Het doel van het werk was het verbeteren van de SSPDs zodanig dat ze kunnen worden gementeerde in experimenten.

De belangrijkste voorwaarde voor implementatie in experimenten is een hoge systeem detectie efficintie (SDE), de kans dat een foton wordt gedetecteerd na het binnenkomen van het detectie systeem (meestal via een optische fiber). De SDE bestaat uit de koppelingsefficintie tussen de optische fiber en het gevoelige deel van de SSPD, de kans op absorptie en de intrinsieke detectie efficintie. Aan het begin van dit proefschrift de SDE was laag, omdat het gevoelige deel te klein was, en koppeling met een optische fiber was nog niet gedemonstreerd. Verder kon de absorptie efficintie worden verbeterd en ook de intrinsieke efficintie voor lange golflengtes was laag. Verder, in optische experimenten informatie is vaak gecodeerd in de polarisatie van het foton. De absorptie efficintie in a lange meanderende draad is polarisatie afhankelijk, wat onhandig is voor dit type experimenten.

In dit proefschrift hebben we laten zien dat het mogelijk is om SSPDs te
fabriceren van NbTiN op een silicium substraat (hoofdstuk 3) met een gevoelig oppervlak van 12x12 μm. Het grote gevoelige oppervlak maakt koppeling met een optische fiber mogelijk. We hebben twee technieken laten zien: (1) mechanische koppeling (hoofdstuk 4,8 en 9), (2) koppeling door een optische fiber sleeve, mogelijk gemaakt door het silicium substraat (hoofdstuk 3). Verder hebben we laten zien dat het silicium dioxide/silicium oppervlak zich gedraagt als een spiegel, wat de absorptie efficiëntie verbetert en we geprobeerd om de absorptie efficiëntie verder te verhogen door de SSPD te fabriceren op een distributed Bragg reflector (hoofdstuk 4). De geometrie van een rechte draad is zodanig aangepast dat de absorptie efficiëntie polarisatie onafhankelijk is geworden. (hoofdstuk 5) We hebben ook een SSPD gefabriceerd met een lage supergeleidende gap, om de efficiëntie voor langere golflengtes te verhogen. (hoofdstuk 6)

We hebben ook gewerkt aan verschillende uitlees schema’s voor SSPDs. Dit is gemotiveerd door het feit dat de SSPDs uit moeten worden gelezen door versterkers met een grote bandbreedte. Het opschalen van een enkele SSPD naar een matrix van SSPDs vereist een andere uitlees benadering. We rapporteren (hoofdstuk 7.1) experimentele resultaten voor twee multiplex methodes (serie en parallel) en de combinatie voor multi-pixel SSPDs. De eerste methode geeft gelijktijdige uitlezing van alle pixels, resulterend in hogere tel frequenties en de tweede methode geeft efficiënte implementatie voor grote matrices. Een aantal detectoren zijn gemoduleerd in een matrix door het combineren van beide methodes, wat de voordelen van beide oplevert. In alle gevallen was de complexiteit van het uitlees circuit verminderd. Een ander benadering voor het opschalen naar grote matrices is het koppelen van een detector aan een condensator, equivalent aan CCD chips (hoofdstuk 7.2). De condensator houdt het gecreerde voltage langer vast, waardoor het uitlezen van meerdere detectoren makkelijker wordt. Door het gaten van de detector de gereduceerde tijdsresolutie kan worden teruggekregen. Voor het meten van de hoogte van de voltage puls een high electron mobility transistor (HEMT) is gemoduleerd. (hoofdstuk 7.3) Als de load weerstand groter is dan de weerstand van de detector na foton absorptie hangt de hoogte van de puls af van deze weerstand. Een HEMT is gebruikt om de load weerstand te verhogen en we kunnen dark detecties van foton detecties onderscheiden, maar er is geen correlatie gevonden tussen pulse hoogte en het aantal fotonen.

In het tweede deel van het proefschrift experimenten met SSPDs zijn beschreven. Een typisch quantum optics experiment is antibunching van fotonen uitgezonden door een enkele foton emitter. Het is ook het ultieme bewijs dat SSPDs enkele foton detectoren zijn. Als enkel foton emitter wordt een InAsP quantum dot in een InP nanodraad gebruikt. Een matrix van nanodraden is gefabriceerd door epitaxiale groei op een door electron-beam beschreven substraat. Photoluminis-
Centrale spectra genomen op een enkele quantum dot laten smalle emissie lijnen zijn rond 1.2 μm. SSPDs maken het mogelijk correlatie functies te meten. Duidelijke antibunching is geobserveerd \( g^{(2)}(0) = 0.12 \). Verder hebben we een biexciton-exciton cascade en twee exciton toestanden gedifferentieerd.

De antibunching beschreven in hoofdstuk 8 wordt altijd gedemonstreerd met een Hanbury-Brown-Twiss setup waar inkomend licht wordt gesplitst door een beam splitter en naar twee foton detectoren verzonden, resulterend in een anticorrelerelatie tussen detecties. In een puur klassieke interpretatie van dit effect worden fotonen beschouwd als ondeelbare deeltjes. Echter, deze interpretatie geeft de verkeerde impressie dat een beam splitter nodig is voor het bewijzen dat licht niet klassiek is. In hoofdstuk 9 laten we een enkele photon statistiek meting zien van een enkel foton emitter met slechts een detector. De SSPD heeft een dode tijd korter dan de coherentie tijd van een NV centrum in diamant. Geen beam splitter is gebruikt, toch worden anticorrelaties geobserveerd, wat een kwantumelementeering interpretatie geeft.

Een andere implementatie van SSPDs bestaat uit het detecteren van enkele surface plasmon polaritons (SPPs). SPPs zouden de interface kunnen zijn tussen elektronische en optische toepassingen. Hier demonstreren we on-chip detectie van enkele SPPs in een SPP-geleider van goud. De SPPs worden gexciteerd door enkele fotonen. Na het propageren over enkele micrometers worden ze gedetecteerd door een SSPD in het nabije veld. Correlatie metingen bewijzen dat enkele SPPs worden gedetecteerd. (hoofdstuk 10)

In hoofdstuk 11 hebben we laten zien dat SSPDs ook enkele elektronen kunnen detecteren, die keV energie hebben en worden uitgezonden door de kathode van een scanning electron microscoop. De detectie efficiëntie is vrijwel 100%. De elektron en foton detectie efficiëntie uitlezing van dezelfde detector zijn in goede overeenstemming. We observeren detecties buiten het actieve gedeelte van de detector, wat we wijten aan de detectie van teruggekaatste elektronen.
Curriculum Vitae

Sander Nugraha Dorenbos


Graduate research under supervision of dr. Elisabeth Reiger, dr. V. Zwiller and prof. dr. ir. L.P. Kouwenhoven.
Subject: "Fabrication and characterization of superconducting detectors for single photon counting"

2007-2011 Ph.D research at Delft University of Technology
under supervision of dr. V. Zwiller
and prof.dr.ir. L.P. Kouwenhoven
Subject: "Superconducting single photon detectors"
23. *Efficiently fiber coupled superconducting single photon detectors*
   S.N. Dorenbos, R.W. Heeres, E.F.C. Driessen and V. Zwiller
   Submitted

22. *Fast path and polarisation manipulation of telecom wavelength single photons in lithium niobate waveguide devices*
   Submitted

21. *A Superconducting Nanowire Particle Detector*
   H. Azzouz, S.N. Dorenbos, D. De Vries, E. Bermudez-Urena, T. Zijlstra, V. Zwiller
   Submitted

20. *A superconducting single photon detector array*
   I. Esmaeil Zadeh, S.N. Dorenbos, and V. Zwiller
   Submitted

19. *Capacitive readout and gating of superconducting single photon detectors*
   H. Azzouz, R.W. Heeres, S.N. Dorenbos, R.N. Schouten, and V. Zwiller
   Submitted

18. *Generation and characterization of high-purity, pulsed squeezed light at telecom wavelengths from pp-KTP for quantum information applications*
   Submitted
17. **Analysing Non-Classical Photon Statistics of a Single Quantum Emitter with a Single Superconducting Detector**

G.A. Steudle, S. Schietinger, D. Höckel, S.N. Dorenbos, V. Zwiller, and O. Benson
Submitted

16. **Correlated photon-pair generation in a periodically poled MgO doped stoichiometric lithium tantalate reverse proton exchanged waveguide**


15. **A low bandgap superconducting single photon detector for infrared sensitivity**


14. **Characterization of high-purity, pulsed squeezed light at telecom wavelengths from pp-KTP for quantum information applications**

Proceedings of Quantum Electronics and Laser Science Conference, Optical Society of America, QWA7 (2011)

13. **Read-out of superconducting single photon detectors**

S. N. Dorenbos, V. Zwiller and R.N. Schouten
Dutch patent **2003572** (2011)

12. **Characteristics of correlated photon-pair generation from a chalcogenide As$_2$S$_3$ rib waveguide**

11. A high efficiency superconducting nanowire single electron detector

10. Position controlled nanowires for infrared single photon emission

9. Enhanced telecom wavelength sensitivity in NbTiN superconducting nanowire single-photon detectors fabricated on oxidized silicon substrates

8. Linewidth narrowing and Purcell enhancement in photonic crystal cavities on an Er-doped silicon nitride platform
Y. Gong, M. Makarova, S. Yerci, R. Li, M.J., Stevens, B. Baek, S.W. Nam, R.H. Hadfield, S.N. Dorenbos, V. Zwiller, L. Dal Negro and J. Vuckovic
Optics Express 18, 2601 (2010)

7. On-Chip Single Plasmon Detection
R.W. Heeres, S.N. Dorenbos, B. Koene, G.S. Solomon, L.P. Kouwenhoven, V. Zwiller
Nanoletters 10, 661 (2010)

6. HEMT-Based Readout Technique for Dark- and Photon-Count Studies in NbN Superconducting Single-Photon Detectors
J. Kitaygorsky, S.N. Dorenbos, E.M. Reiger, R. Schouten, V. Zwiller, and Roman Sobolewski

5. Impedance model for the polarization-dependent optical absorption of superconducting single-photon detectors
1. Fiber-coupled NbN superconducting single-photon detectors for quantum correlation measurements

2. Spectroscopy With Nanostructured Superconducting Single Photon Detectors
IEEE Journal Of Selected Topics In Quantum Electronics 13, 934 (2007)

3. Low noise superconducting single photon detectors on silicon
S.N. Dorenbos, E.M. Reiger, U. Perinetti, V. Zwiller, T. Zijlstra, T.M. Klapwijk

4. Superconducting single photon detectors with minimized polarization dependence