Determining the timing jitter of superconducting nanowire single-photon detectors using a CW laser

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ABSTRACT

We investigated the timing jitter of superconducting nanowire single-photon detectors (SNSPDs) and found a strong dependence on the detector response. By varying the material stack, we observed changes in pulse shape which are attributed to capacitive behaviour affecting the pulse heights, rise times and consequently timing jitter. Moreover, we developed a technique to predict the timing jitter of a single device within certain limits by capturing only a single detector pulse, eliminating the need for detailed jitter measurement using a pulsed laser.

1. INTRODUCTION

Recent years have seen major advances in photon based quantum technologies\textsuperscript{1} such as deep space optical communication (DSOC),\textsuperscript{2,3} quantum key distribution (QKD),\textsuperscript{4,5} quantum computation\textsuperscript{6} or state teleportation.\textsuperscript{7} For such applications, components such as single-photon emitters (e.g. quantum dots,\textsuperscript{8} NV centres in diamond\textsuperscript{9} or 2D materials\textsuperscript{10}), spin-photon interfaces\textsuperscript{11,12} or single-photon detectors are needed. In terms of detectors, superconducting nanowire single-photon detectors (SNSPDs)\textsuperscript{13–16} have prevailed over other options such as single-photon avalanche photodiodes (SPADs)\textsuperscript{17} or transition edge sensors (TES).\textsuperscript{18} Besides near unity quantum efficiency,\textsuperscript{19} one of their outstanding performance features is the timing jitter describing the temporal resolution.\textsuperscript{20} It was shown to be as low as 2.6 ps for a short (5 µm long) and thin (80 nm wide) superconducting nanowire at λ = 775 nm. For a meandering nanowire covering an area of 10x10 µm\textsuperscript{2}, values of 28 ps have been reported.\textsuperscript{22} Amongst others, it is composed of contributions from the amplifiers, hotspot formation, electrical and thermal noise as well as detector geometry.\textsuperscript{22} It is a crucial parameter for various applications such as the characterization of single-photon emitters,\textsuperscript{23} single-photon QKD\textsuperscript{24} or pulse-position modulation,\textsuperscript{25} where information is encoded in so-called time bins. The smaller the timing jitter the more time bins fit within a certain amount of time. Therefore, it is of utmost interest to develop an understanding of the various influences on timing jitter, how to improve it, and how to speed up the characterization process.

2. EXPERIMENTAL

All measurements were carried out with a Janis cryogenic probestation at 4.5 K. The NbTiN detectors are typically 8 nm thick, have a nanowire width of 100 nm and an areal fill factor of 33% covering an area of 10x10 µm\textsuperscript{2}. For the efficiency measurements a CW laser (780 nm) was used to illuminate the detectors. In Fig. 1(a) a typical detector response is shown. It consists of a fast rising edge and an exponential decay following \( \tau_{\text{fall}} = \frac{L_k}{Z_{\text{load}}} \),\textsuperscript{26} where \( Z_{\text{load}} \) is the load impedance (typically 50 Ω) and \( L_k = \frac{\hbar R_{\text{device}}}{2 \pi T_c} \),\textsuperscript{27} the kinetic inductance. Here \( R_{\text{device}} \) describes the device resistance and \( T_c \) corresponds to the switching temperature of the superconductor. For the timing measurements a pulsed laser (pulse width < 3 ps, at 850 nm) was used. The laser signal is divided between a fast photodiode (UPD-15-IR2-FC, start signal) and the detector unit consisting of the detector and two room temperature amplifiers (53.5 dB, stop signal). Both channels are connected to the sampling scope (MSO64) to perform a delay measurement. In Fig. 1(b), the normalized occurrences of the delay measurement are plotted as a function of time. The corresponding FWHM represents the devices timing jitter (28.6 ps).
Figure 1. Detector response upon photon absorption. (a) Typical voltage pulse showing a fast rising edge and exponential decay. The rise time is defined as the time between 1/e and 90% of the maximum pulse height. (b) Timing jitter measurement using a pulsed laser.

Table 1. Timing jitter of the measurement setup characterized by mimicking the detector signal using an AWG

| Pulse height (V) | Jitter (ps) | PH (V) | J (ps) | PH (V) | J (ps) |
|------------------|------------|--------|--------|--------|--------|
| 0.1              | 61.1       | 0.35   | 19.0   | 0.6    | 10.8   |
| 0.15             | 41.9       | 0.4    | 16.4   | 0.65   | 10.2   |
| 0.2              | 31.6       | 0.45   | 14.4   | 0.7    | 9.6    |
| 0.25             | 26.4       | 0.5    | 12.6   | 0.75   | 9.5    |
| 0.3              | 22.0       | 0.55   | 11.6   | 0.8    | 9.4    |

To characterise the timing jitter of the setup, an AWG was used that mimics the detector signal before it gets attenuated and amplified again (table 1). The error is assumed to be less than 3 ps. Note that the timing jitter can be calculated using $t_{\text{tot}} = \sqrt{\sum t_i^2}$ for the different contributions. The data reveals that the jitter of the setup is significantly lower than the measured values ensuring that it did not influence the presented results significantly.

3. RESULTS

To investigate the dependence of the pulse shape on the timing jitter, samples with different stacks were fabricated. While most detectors were produced on a full-chip sized gold mirror (10 nm Ti / 50 nm Au) with varying SiO$_2$ layer thicknesses to form a bottom cavity, detectors were furthermore fabricated on small (100 µm diameter) gold mirrors (hereafter: Au*) and Si/SiO$_2$ wafers.

Fig. 2(a) shows the efficiency of the aforementioned samples as a function of the silicon dioxide thickness measured at a wavelength of 780 nm. In agreement with FDTD simulations, the data set reveals a maximum

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efficiency around 80 % for 105 nm SiO$_2$ (1st maximum) and 390 nm SiO$_2$ (2nd maximum) on a full-chip sized (FCS) gold mirror as a bottom cavity only. While similar results can be achieved for small gold mirrors with 105 nm SiO$_2$, the efficiencies for the data points in between are significantly lower. In Fig. 2(b) the timing jitter is shown as a function of the applied bias current for different NbTiN thicknesses on a FCS gold mirror with 105 nm SiO$_2$. The jitter decreases with an increased current converging against 65 ps. The inset shows the same data in comparison to detectors on wafer in the range up to 12 µA. Here, a significantly improved jitter can be observed for the detectors on wafer reaching values of 37 ps. The comparison indicates a strong influence of the gold mirror underneath.

**Influence of the material stack**

To analyze the influence of the material stack, detector pulses for 105 nm, 260 nm, 390 nm SiO$_2$ on a FCS gold mirror and 105 nm SiO$_2$ on the small gold mirror only below the detector are shown in Fig. 3(a).

The pulses show an increased steepness (from bottom to top) resulting not only in a shorter rise time but also in higher pulses. Note that the pulse for the 105 nm SiO$_2$ on a small gold mirror shows a significantly steeper rising edge compared to the same SiO$_2$ thickness on a FCS film. Moreover, for a FCS film a general trend of faster rise times for thicker SiO$_2$ layers can be observed. In Fig. 3(b) we present the corresponding pulse height as a function of the material stack used at a fixed bias current of 16 µA. It increases with an increased SiO$_2$ thickness until it reaches the same pulse height as both the detector on the small gold mirror (inset Fig. 3(b)) and on wafer. To conclude, for thicker SiO$_2$ thicknesses (or small gold mirrors) the rise time becomes faster and the pulse height larger.

![Figure 3](image_url)

**Figure 3.** Comparison of the detector response for different material stacks at an applied bias current of 16 µA. (a) Normalized voltage pulses shown for 105 nm, 260 nm, 390 nm SiO$_2$ on a FCS gold mirror and 105 nm SiO$_2$ on a small gold mirror. The reference lines mark the start and end position of the rising edge for the 100 µm mirror. (b) Mean pulse height. Inset: microscope image of the detector on both types of gold mirrors.

![Figure 4](image_url)

**Figure 4.** Influence of the distance and size of the buried gold mirror relative to the (10 nm Ti / 50 nm Au) contact pad at a bias current of 16 µA. (a) Rise time and timing jitter for the different material stacks used. (b) Calculated rise time consisting of a capacitance, bias current and kinetic inductance component.
To quantify these findings, we plot the rise time and timing jitter for the different samples at a fixed bias of 16 \( \mu \text{A} \) in Fig. 4(a). Here, the timing jitter follows the same trend as the rise time. While for 105 nm SiO\(_2\) on a FCS film a timing jitter of only 80 ps was measured, we achieved around 30 ps for the same SiO\(_2\) thickness on a small mirror. Again, the detectors on 390 nm SiO\(_2\)/Au, a small gold mirror and the detectors directly fabricated on the wafer behave similar confirming the results in Fig. 3. In Fig. 4(b) we calculate the expected rise time at a bias level of 16 \( \mu \text{A} \), consisting of a kinetic inductance, bias current and capacitive component. The fraction of the kinetic inductance \((\tau_{\text{rise}} = \alpha \cdot L_k/R_n)\) depends on the scaling factor \(\alpha = 0.9 - 1/e\), which relates to the limited rising edge from \(1/e\) to 90\%, the kinetic inductance, and the resistance of the normal-conducting region upon photon absorption. To determine the latter to be 0.56 k\(\Omega\) with \(V_\text{SSPD} = R_n/\text{device}\), we calculated the average hotspot size \(V_{\text{HS}}\) derived the SSPD volume \(V_{\text{SSPD}}\) from the present geometry, and considered the measured device resistance \(R_{\text{device}}\). For an average kinetic inductance of \(L_k = 194 \text{nH}\), we finally calculated the resulting rise time contribution. The second component is related to the bias current. Here, the corresponding rise time decays with \(\tau_{\text{rise}} \propto \sqrt{1/I_{\text{Bias}}}\) (cp. Fig. 5(a)) but stays constant at a fixed bias. To derive it, we considered detectors on a small mirror with a known kinetic inductance component. The third parameter is a capacitive component forming between the FCS (small) gold mirror and the gold contact pads. For each type of mirror we assume a plate capacitor \(C_{\text{tot}} = C_{\text{Sig}} + C_{\text{load}} = \frac{d_{\text{SiO2}}}{\epsilon_0} (\frac{1}{\epsilon_{\text{SiO2}}} + \frac{1}{\epsilon_{\text{SiO2}}})\) considering separately both contributing areas signal \((A_{\text{Sig}})\) and ground \((A_{\text{Gnd}})\), with \(d_{\text{SiO2}}\) as the thickness of the silicon dioxide layer, \(\epsilon_0\) as the vacuum permittivity and \(\epsilon_R\) as the relative permittivity of silicon dioxide. Subsequently, we calculate the cutoff frequency \(f_{\text{cutoff}} = \frac{1}{2\pi C_{\text{tot}} R_{\text{load}}}\) and get the capacitive component of the rise time \(\tau_C = \frac{1}{f_{\text{cutoff}}}\). The difference in \(\tau_C\) (orange dashed vs. green line) shown in Fig. 4(b) is due to the different areas contributing to the capacitance. Thus, by choosing the small gold mirror, the rise time and therefore timing jitter can be improved significantly following \(\tau_{\text{tot}} = \sqrt{\tau_{\text{Lk}}^2 + \tau_{\text{bias}}^2 + \tau_C^2}\).

**Current dependence of rise time, jitter and pulse height**

The typical detectors dependence of the rise time, timing jitter and pulse height on the bias current is shown in Fig. 5(a). The data set reveals a linear increase for the pulse height, an exponential decay in the timing jitter (compare Fig. 2(b)) and a slow exponential decay of the rise time.

![Figure 5](image-url)

**Figure 5.** Current dependence of different pulse parameters. (a) Current dependence of the pulse height (top), the timing jitter (middle) and the rise time (bottom) of the detector on a gold mirror with a diameter of 100 \(\mu\text{m}\). (b) Ratio of rise time and timing jitter as a function of applied current for all material combinations used.

Considering the latter two, we present the relation between timing jitter and rise time as a function of the applied bias current in Fig. 5(b). Here, all data points of the different material stacks follow the same trend. This is even more noteworthy as the rise time in Fig. 4(a) differs strongly for the different samples. It can be concluded that the relation between timing jitter and rise time is stable for a fixed bias current (within a current dependent limit) regardless of the material combination used. Also, it allows to approximate the jitter for a given bias current and rise time.

**Dependence between timing jitter and slew rate**

To investigate the fundamental relations between pulse shape and timing jitter even further, we look at the dependence of the timing jitter relative to the slew rate (ratio between pulse height and rise time) in Fig. 6.
The reduced slew rate (top x-axis) refers to the initial pulse height without amplification (53.5 dB) keeping it comparable to other measurement setups. For an increased slew rate we observe a decreased timing jitter in agreement with D.Zhu. It decreases rapidly from 280 ps to 80 ps for a slew rate from 100 V/µs to 600 V/µs. Subsequently, the decrease slows down until it reaches a timing jitter around 25 ps for a slew rate of 3200 V/µs. Again, these findings are independent of the material stack used. The clear dependence of the timing jitter on the slew rate allows to deduce the timing jitter only by measuring the slew rate. Thus, by measuring a single pulse (e.g. pulse height and rise time) it is possible to predict the timing jitter within a slew rate dependent tolerance. In particular this means that the timing jitter characterization can be conducted only using a CW laser with matching wavelength. The inset shows a more detailed view of selected points at a bias current of 12 µA and 16 µA. For an increased bias current, the slew rate becomes higher and the timing jitter lower. Note that only the slew rate itself is strongly dependent on the material stack used. This fits well with the results in Fig. 3 and 4(a), where a decreased rise time was always accompanied by an increased pulse height resulting in a higher slew rate.

4. CONCLUSIONS

We investigated the relation between the SNSPD timing jitter and the detector response at a wavelength of 850 nm measured at 4.5 K. The detectors were fabricated on a full-chip sized gold mirror (10 nm Ti / 50 nm Au) with varying SiO₂ layer thicknesses, on small (100 µm diameter) gold mirrors and Si/SiO₂ wafers. Besides a strong dependence on the bias current (Fig. 2(b)), we observed a dependence of the timing jitter on the material stack underneath the SNSPD (inset: Fig. 2(b)). In particular, the entire pulse shape changes (Fig. 3(a)) resulting in different pulse heights (Fig. 3(b)), rise times and timing jitters (Fig. 4(a)). Note that the origin of this is a capacitive behavior between the FCS gold mirror and the gold contact pads (Fig. 4(b)). Thus, the rise time increased and the pulse height decreased. However, by fabricating the detector on a small gold mirror (100 µm diameter) underneath the detector (and not the entire Ti/Au contact pad) we were able to restore the timing jitter as found on bulk Si/SiO₂ substrates. Hence, to combine a good efficiency with a good timing jitter either a small gold mirror or a thick SiO₂ layer (> 300 nm) can be used. The second major finding is the dependence of the timing jitter on the rise time (Fig. 5(b)). In particular, we were able to extend these findings to the dependence of the timing jitter on the slew rate (Fig. 6). We found a general trend independent of the stack of material used that enables to predict the timing jitter for a given detector pulse slew rate. Thus, by measuring the entire pulse shape this technique allows it to speed up the timing jitter characterization process as there is no direct measurement needed. It eliminates the need to use a pulsed laser, reduces drastically the time needed for such a study and paves the way for industrially scalable timing jitter characterisation.

Author Contributions

R.F. designed study, analyzed data and drafted manuscript. R.F., L.Z., C.S. and S.S. fabricated samples. R.F. and C.S. performed the experiments. F.F. contributed simulations. J.F. and K.M. led the research projects. All authors discussed results and revised the manuscript.
Conflicts of interest

There are no conflicts to declare.

Acknowledgements

We gratefully acknowledge the German Federal Ministry of Education and Research via the funding program Photonics Research Germany (contract number 13N14846), via the funding program quantum technologies - from basic research to market (contract numbers 16K1SQ033, 13N15855, 13N15982 and 13N15760), and via the projects Q.com (contract number 16K1S0110) and MARQUAND (contract number BN105022), as well as the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany’s Excellence Strategy – EXC-2111 – 390814868.

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