Dark counts double switching rates in NbTiN Superconducting Nanowire Single Photon Detectors

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Abstract. In this work we present a study of the dark counts rate in a NbTiN Superconducting Nanowire Single Photon Detectors (SNSPD). We measure the distribution of the time intervals elapsed between two consecutive dark pulses at the fixed temperature of 4.2K. Due to the stochastic nature of the dark counts, the distribution is expected to have a Poisson shape but what we observe is a combination of two Poisson-like processes. A further analysis of the distributions dependence on the bias current highlights that the weight of the two process is not constant. In the scenario presented by Ejrnaes et al. [1], this result can confirm that, in this temperature regime, dark counts are generated mainly by multiple consecutive fluctuation events and the contribution to the dark counts rate coming from single fluctuations increases in the high bias current region.

1. Introduction
The interest in the use of SNSPD as single photon detectors increased in the last years due to their high performances, as high detection efficiency [2], low timing jitter [3] and low dark counts rate (DCR)[4]. The detector consists of a long and thin superconducting strip with a meander type geometry. In the operating conditions, the meander works at a temperature that is lower than $T_C$ and is biased with a current close to the critical value; when a photon is absorbed, a normal region across the strip, called hot spot, is generated. The hot spot forces the supercurrent to flow in a restricted volume where it overcomes the critical current value, producing a normal belt across all the strip width. The cooling process restores the superconducting state with a time constant $\tau$ of the order of 30ps [5].

As a consequence of the normal belt, the detector generates a voltage pulse that decays in time exponentially with the time constant of the detector-readout circuit [5][6]. By counting the pulses it is possible to count the single photons. That heating model cannot completely explain the formation of a dark count, a pulse spontaneously generated by the detector in absence of photons. As explained in [7] the
DCR exponentially increases with the bias current and the dark count generation mechanism, even if poorly understood, can be ascribed to the transit of flux vortices across the current-carrying superconducting nanowire. Others models for the intrinsic fluctuations have been put forward: quantum phase-slips, single vortex crossings and vortex-antivortex pair nucleation \[8\][9]. According with these models, the intrinsic fluctuations produce a small normal region that generates a pulse similarly as what happens in the case of photon absorption. Furthermore, in 1D \[10\] and 2D \[1\] cases, it has been measured that the single thermal fluctuations just mentioned can produce a dark count just in a restricted temperature regime and, when a crossover temperature is passed, multiple fluctuations are required in order to lead the device into the normal state.

To gain more insight in the dark counts dynamics, we measured the distribution of time intervals between two consecutive dark counts at the fixed temperature of 4.2K. This distribution is expected to be Poisson-like, as the dark count is a stochastic phenomenon. However, we observed that the distribution is the combination of two process occurring with different rates. These two rates have different dependence on the bias current. We fitted the two rates and just one of them exhibits the expected exponential increase with current while the other rate slowly decreases with current. This result could support one of the results presented in \[1\], that is that in NbTiN SNSPD, in the high bias current regime a single fluctuation can produce a dark count while, at lower currents, multiple fluctuations are required.

2. Experiment

We measured a NbTiN meandered SNSPD, 5nm thick and 80nm wide. The film was deposited on a double-side polished thermally oxide silicon substrate by reactive DC-magnetron sputtering at room temperature in a Ar and N\(_2\) atmosphere. We fabricated the meander geometry using reactive-ion etching (RIE) and electron beam lithography (EBL). The meander is shaped as a circle with a diameter of 15 \(\mu\)m. The fabrication details can be found in \[11\].

The detector package was cooled inside a liquid helium dewar at 4.2K. The sample was shunted with a 50\(\Omega\) resistance in parallel and connected through a coaxial cable to a bias tee, two amplifiers and an oscilloscope.

Through the acquisition program we measured the time intervals passed between two different dark pulses at fixed bias currents; we took as time reference the instant in which the pulse amplitude reaches its half on the rising edge, that leasts about 50ps. The pulse fall time is of 120ns and its amplitude after amplification is 200mV.

3. Analysis

We calculated the inter-pulse histogram, the statistic distribution of the measured time intervals. The shape of that distribution is expected to be Poissonian due to the stochastic nature of the observed phenomenon. In the case of a Poissonian inter-pulse histogram, the integral in time of the distribution provides the mean time interval elapsed between two consecutive dark counts and its inverse corresponds to the DCR. As one can see in Fig.[1], the data exponentially decay but with two different rates.

As shown in the inset of Fig.[1], we first measured the dark count rates as a function of the bias current; then we fixed the current value and measured the inter-pulse histogram for each bias current value. In Fig.[1] we show the inter-pulse histogram for \(I_b = 9.26\mu A\). From the slope of the distribution, one can see that for short time intervals the rate is higher and we observe a peak in the curve \(\Gamma(t)\); for longer time intervals the rate is lower. For this reason we wrote \(\Gamma(t)\) as the combination of two Poisson distributions with different weights

\[
\Gamma = Ke^{-\Gamma t} = \alpha(I_b)\Gamma_1e^{-\Gamma_1 t} + [1 - \alpha(I_b)]\Gamma_2e^{-\Gamma_2 t}, \quad \alpha(I_b) \in [0, 1] \tag{1}
\]
Figure 1. Inter-pulse histogram at $I_b = 9.26 \mu A$. Inset: Dark Count Rates as function of the bias current.

Figure 2. Fit of the inter-pulse histogram measured at $I_b = 9.26 \mu A$ (logarithmic scale).

We fitted the inter-pulse histogram (IPH) with the function (1) and the result is shown in Fig. 2. The two rates $\Gamma_1$ and the weight $\alpha$ are fit parameters.

We repeated the same analysis for other current values and we obtained the rates shown in Fig.[3]. The rate $\Gamma_1$ represents the contribution coming from the first branch of the IPH, while $\Gamma_2$ comes from the long tail. In Fig.[4] one can see that the weight of each $\Gamma_i$ depends exponentially on the bias current. We observe from Fig. [3] that the value of $\Gamma_1$ is two orders of magnitude higher than $\Gamma_2$ for $I_b/I_c \approx 0.95$ while they become similar at bias current close to the critical current.

In [1][12] authors observe that in 2-D superconducting nanowires the dark counts generation is due to different process, according with the working temperature. In details, they identify three temperatures regimes:

(i) $0K < T < T_Q$: in this regime DCR does not depend on the temperature;
(ii) $T_Q < T < T_M$: in this regime the DCR increases with the temperature and each thermal fluctuation occurring in the device is energetic enough to produce the switching. In this region the DCR corresponds to the thermal fluctuations’ rate;
(iii) $T > T_M$ : in this regime the DCR drops down faster than what expected when the bias current decreases. In this regime each thermal fluctuation has not enough energy to generate a dark count but the overlap of multiple fluctuations is needed; in this regime the DCR depends on the number of fluctuations needed to produce the switching [1].

In [1] they also observe that in the third temperature regime the number of fluctuations needed to produce a dark count decreases as the bias current increases. For that reason, also in the third temperature regime, it is possible to produce a dark count with a single fluctuation if the current is sufficiently high. This means that, at higher bias current, the DCR depends both on single and multiple fluctuation rate, while at low bias current the dark counts are generated mainly by the overlap of multiple fluctuations.

What we observe from Fig. [3] is that around $I_B/I_C = 0.95$, the rate $\Gamma_1$ is higher than $\Gamma_2$ but, as the current increases, the contributions of each rate to DCR become similar.

In this scenario, it is reasonable to make the hypothesis that $\Gamma_1$ is related to multiple fluctuation switching process and $\Gamma_2$ is the single fluctuation rate.

Anyway, what we observe in Fig. [3] might also be the sign of the presence of two different process occurring in the strip and both of them produce a dark count, with different dependence on the bias current. At the moment, we have no data to support one hypothesis or the other.

4. Conclusions

The results presented in this work clearly show that, at 4.2K, the dark counts in NbTiN meandered nanowire are produced by two process. These two process occur at two different rates and behave differently when the bias current changes. The specific dependence of the two measured rates on the bias current could confirm what observed in [1] in which authors claim that at 4.2K dark counts are produced both by single and multiple fluctuations, according with the bias current value. On the other hand, we cannot exclude that what we observe is the combination of two completely different process.

To confirm the first hypothesis, the same measurement should be done at different temperatures because, in the single fluctuation temperature regime ([1][12]), the rate $\Gamma_1$ and the change in the slope observed in Fig. [1] would disappear if they are due to multiple fluctuations events.

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