Measuring Hot-Spot Interaction Length in Single-Strip SNSPD

Margaret Polyakova, Evgeniia Sheveleva, Alexander Semenov, and Gregory Goltsman

Abstract—**Superconducting nanowire single photon detectors (SNSPD) functionality is based on the local suppression of the superconducting order parameter upon photon absorption, causing a change in resistance which can be detected as a DC voltage pulse. Finding the size and the profile of the superconducting order parameter suppression area (the so-called "hot-spot") experimentally is a challenging task. Here, we report the results of a quantum detector tomography on micron-length SNSPDs. The high internal detection efficiency of our SNSPDs allowed us to extract single and double photon efficiencies from the count rate vs radiation power dependence and extract hot-spot interaction length. We investigated a series of SNSPD samples made of NbN films with different sheet resistance and a MoSi film, with various widths of the stripe. The experimental results confirmed that regardless of the material or the film resistance, the hot-spot interaction length coincides with the strip width which is a promising feature for making a 2-photon counter with high fidelity.**

Index Terms—**Double-photon detection efficiency, hot spot interaction length, quantum detector tomography, superconducting nanowire single photon detector.**

I. Introduction

Modern development of quantum technologies formed a request for photon detectors which are capable of measuring the number of photons in the optical pulse with high fidelity. Even though it is enough to distinguish between zero, one, two and more than two photons [1] for most applications, such demand itself is quite challenging. One of the best candidates for telecom wavelength is superconducting nanowire single photon detector (SNSPD) which demonstrates close-to unity detection efficiency (DE) in this range together with an extremely low false (dark) count rate. Additionally, they potentially have a very high operation rate, and a low timing jitter. Their capability of measuring the number of photons is related to the fact that each absorbed photon creates a hot spot (HS), and the number of HSs in the strip of an SNSPD can in principle be measured by observing characteristics of its response pulse.

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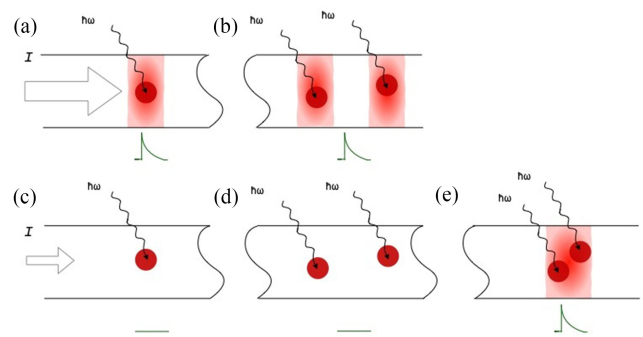

Fig. 1. Different kinds of photo-counts in SNSPD. At large bias current, a single absorbed photon produces a resistive region and a voltage response (a), and the same holds for two absorbed photons (b). At smaller bias current, separated HS are unable to produce a resistive region (c, (d), but two HSs at the distance smaller than s are able to do so (e).

For SNSPDs, it is useful to distinguish between the two-photon and the so-called "double-spot" counts, i.e. counts produced by the two interacting hot-spots. This is due to the reason that in all practical SNSPDs the area of the strip is much larger than the area where energy of the absorbed photon is distributed, i.e. the area of the HS. The most probable case of a two-photon counting event is one when the two photons are absorbed at distant points of the strip and the two HSs interact with the bias current independently. This case is sketched at Fig. 1(b). From the viewpoint of the detection mechanism, such counts are very similar to the single-photon counts (Fig. 1(a)). In particular, they have the same dependence of DE on the bias current. We suggest calling them double-photon but "single-spot" counts. Nevertheless, they can be distinguished from the single-photon counts by their shorter time of the rising part of the voltage pulse, which is explained by greater resistance of two resistive domains and was demonstrated in the experiment [2].

In contrast, the two photons absorbed closely enough produce two hot spots which act on the distribution of the bias current jointly, hence the detection current is decreased compared to the case of a single-spot count, – see the sketch at Fig. 1(e). We suggest calling these detection events "double-spot" counts. The distance at which joint action of the HS on the distribution of bias current becomes important, is called the HS interaction length, s [3]. It demarcates between the single-spot and the double-spot two-photon counts. Contrary to the single-spot double-photon counts, double-spot counts are related with the appearance of just

TABLE I
THE LIST OF THE STUDIED SAMPLES AND THEIR MAIN PROPERTIES

material	w (nm)	L (μm)	R_s $(\Omega/\square)$	T_C (K)	I_{dep} (μA)
NbN	104	1	1283	6.3	8.74
NbN	168	1	1283	6.3	14.12
NbN	160	1	1283	6.3	13.45
NbN	256	1	1283	6.3	21.52
NbN	126	2	630	8	32.26
NbN	80	1	630	8	20.48
NbN	120	1	630	8	30.73
NbN	120	2	630	8	30.73
MoSi	150	5	590	3.6	11.36
MoSi	120	5	590	3.6	9.09
MoSi	120	2	590	3.6	9.09
NbN	234	1	1308	6	17.72
NbN	130	1	1308	6	9.84

one resistive domain and hence cannot be distinguished from the single-photon counts by rising time of voltage pulse.

Both single- and double-spot double-photon counts can be used to realize detectors of Fock states of light. The approach of [2] suits naturally for large areas of a detector, when the probability of the double-spot counts is negligible compared to the probability of the double-photon but single-spot counts, and a large kinetic inductance of the long strip results in long voltage pulse ans allows to distinguish the difference in duration between single- and double-photon counts. At the same time, the large kinetic inductance limits the timing performance of such detectors, limiting the count rate by tens of MHz and the geometrically driven jitter parameter by tens of ps. The approach of using double-spot counts requires the strip shorter than the HS interaction length, which makes optical matching more difficult but removes the limitation on the operation rate by the kinetic inductance, allowing for very fast detection with the time set by the lifetime of the HS.

Double-spot counts in SNSPD were first reported in 2002 in [4], where they were used to prove the photo-counting nature of the response. Quantitative measurements of double-spot DE, η_2, were performed in [3], [5]–[7]. However, none of these works found a solid saturation of η_2 with the increase of the bias current I, which is a sign of near-unity intrinsic efficiency of double-spot counts (each couple of close enough spots produces a photo-count) and allows to extract s. This was due to either too small contribution of double-spot counts, related to the use of a meander-shaped SNSPD with total length of hundreds of microns [5], or due to a constriction-like design of the samples which did not allow to observe the saturation even for the single-photon counts [3], [6]. In [7], we proposed a protocol based on a use of micron-scale length SNSPDs with saturated single-spot iDE at large I, containing a self-consistent calibration of the number of absorbed photons and allowing for quantitative measurements of η_2 and s. We applied it to analyze the data obtained on waveguide-integrated SNSPDs, and found signatures of the expected saturation of η_2, but a consistent study required specially designed samples and measurements. In [8], [9], we made two steps in this direction, demonstrating the saturation for the first time with NbN samples and then confirming the universality of the observation with MoSi samples.

In this paper, we present the study with a representative number of samples optimally designed for the measurements of double-photon counts and with varying parameters. Our aim is to study single- and double-spot DE, η_1 and η_2, vs. bias current I and determine HS interaction length s. To investigate the effect of the film parameters on the HS interaction length, we used the samples with the working element made of three different films: i) NbN film with the sheet resistance typical for commercial SNSPDs; ii) thinner and more resistive NbN films with the sheet resistance up to 2 $k\Omega$; iii) MoSi films. We obtain quantitative data for η_2 and s and study prospects of double-spot counting in SNSPD for detection of pairs of photons with high fidelity.

II. Experiment

Study of the HS interaction length requires an SNSPD with near unity internal DE (IDE) [7], which is easier to achieve in relatively short strips without turns. Further, the need to have a noticeable probability of double-spot events compared to single-spot ones suggests using strips which are as short as possible. But to avoid the contribution of photo-counts in taper parts of the detector (which hampers interpretation of the results obtained with single square detectors [3], [6]), we designed the samples in such way that they contain a sensitive superconducting strip of the length of several microns, at least one order of magnitude larger than its width.

Each batch of NbN SNSPD samples was fabricated on the Si/SiO_2 wafer using DC magnetron sputtering for NbN deposition and patterned as a narrow superconducting bridge by e-beam lithography. To avoid latching, to provide more precise and easier connection to the single-mode optical fiber, and additionally to protect the strip from burning due to static electricity while mounting, we embedded the sensitive strip into a kinetic-inductance meander structure filling the area of 10 μm by 10 μm which is biased to the large golden contact pads formed by photolithography. We produced the samples with the variable strip width (w) of 56 to 300 nm and 1 to 3 μm length, the meander line width was fixed to be 350 nm. For our study, we chose the series of NbN samples with the sheet resistance values at room temperature of 630, 1283 and 1308 $\Omega/\square$ and MoSi samples with the sheet resistance of 590 $\Omega/\square$ (see Table I). SEM image of a typical sample is presented on Fig. 2.

We performed the detector tomography, following the protocol we proposed before [7]. To generate optical pulses, we used a pulsed laser operating at 1550 nm with tunable repetition rate (set to 10 MHz in our experiment), followed by a tunable optical attenuator. The power passing through the attenuator was measured by a power meter and was corresponding to 0.1 – 10^5 photons per pulse. First, we investigated single-photon DE, searching for saturation at high bias current, and, assuming $IDE = 1$ there, determined the coupling efficiency and calibrated the attenuation in terms of the mean number of photons absorbed in SNSPD per pulse, M. Then we recorded set of dependencies of count probability per pulse on M, $P(M)$, for a range of bias currents, and fitted them with the expression $P(M) = \eta_1 M + (\eta_2 - \eta_1^2 + a_2^{bias})M^2/2$ to extract the double-spot efficiency η_2 vs. I. Here, the term $(-\eta_1 M^2/2)$

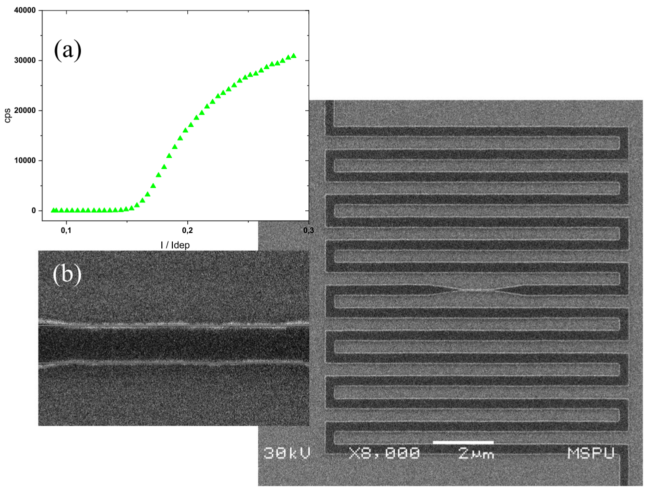

Fig. 2. A SEM image of the experimental SNSPD structure - a thin NbN strip of 130 nm width as a sensitive element (inset *b*) and a 350 nm wide meander line. Inset *a* images a typical count rate vs current dependence, showing a solid saturation at large bias current.

represents the lack of counts due to single-spot double-photon events [7]. We also checked for the systematic error due to AC biasing (the term a_2^{bias}), following the procedure described in [7], and discarded the data corrupted by this error. As an additional check, for several samples we showed that the $P(M)$ is independent of the repetition rate, which is a direct proof of absence of the AC biasing contribution [7]. Finally, for the samples where saturation of $\eta_2(I)$ at large I was found (η_2^{sat}), we calculated the HS interaction length, s, as $s = L\eta_2^{sat}$, with L the length of the strip. A typical $L\eta_2(I)$ with solid saturation with the increase of the bias current is plotted at Fig. 3(a). As the main result, we found that for all studied samples, the HS interaction length value is close to the width of the strip. That is expected for the case when size of HS doesn't reach the width of the strip. The trend formed by all studied samples is presented in the Fig. 3(b).

III. Discussion

The observed closeness of the HS interaction length to the width of the strip has a simple explanation in terms of "hot spot - vortex model," which tells that HS or HSs quench formation of the resistive state by redistribution of the bias current [10], [11]. Expelling of the supercurrent by the HS is well described by 2D London equations, which has no scale except the Pearl length which is much greater than all the relevant scales [12]; hence, the distance the perturbation of the supercurrent density extends, and the HS interaction length, should be a combination of the strip width and the HS size. In case when the HS size is smaller than the strip width, the HS interaction should be cut off at the distance of order of w. In turn, the HS size can be estimated as $d_{HS} = 4l_{diff}$, where $l_{diff} = \sqrt{D\tau}$ with D the diffusion coefficient and τ the shortest of the inelastic times. Substitution of the parameters of our studied films gives $d_{HS} = 50...70\ nm$, which does not contradict to our observations for s, i.e. supports that we deal with the strips where $w > d_{HS}$. An

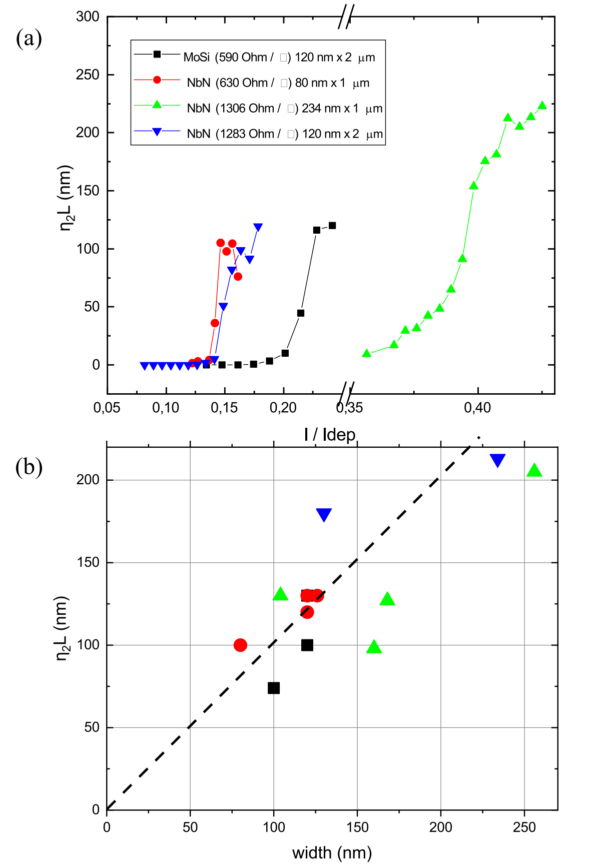

Fig. 3. (a) Bias current dependencies of double-spot IDE η_2, recalculated to the length as $L\eta_2$), vs. the bias current normalized to the calculated depairing current, I_{dep}, for four selected samples. (b) HS interaction length s, extracted as $L\eta_2^{sat}$, vs. the strip width w, for all 13 studied samples.

additional proof of the correctness of the above picture is the observed independence of the results for s on the parameters of the films, i.e. the sheet resistance and the material (NbN or MoSi).

Besides the importance for current practice, the study of HS interaction length has a more fundamental motivation (with a potential output for further applications). In the limits when the strip width is either smaller or much greater than the HS size, s gives directly this size. For the films there BCS theory works quantitatively, one expects that the size is set by the diffusion length, as discussed above. However, for the high resistance films (sheet resistance is comparable to the resistance quantum $R_Q = 2\pi\hbar/(2e)^2 = 6.45\ k\Omega$), and in particular to the films with an anomalous behaviour of resistance before the superconducting transition, – deviations related to the onset of "marginal" superconductivity are expectable [13], [14]. For instance, the built-in spatial fluctuation of the order parameter could slow down the diffusion and lead to more compact HS, which affects the operation of an SNSPD (making it more efficient for low-energy photons). While in the current work we do not study these problems, we stress that the development of method of measuring the HS interaction length we present here, has a direct meaning for such studies.

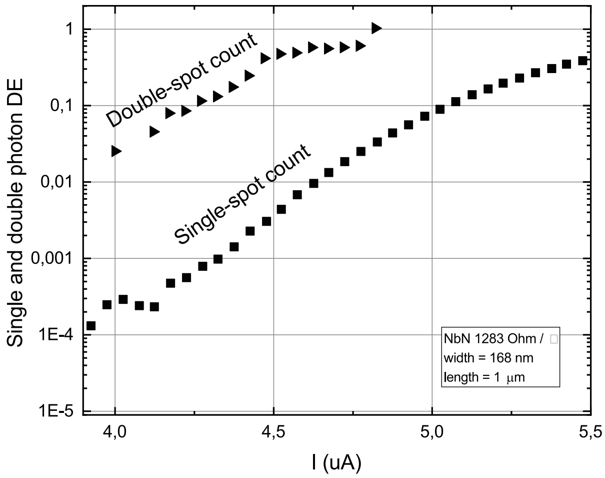

Fig. 4. At the point I= $4.6\ \mu A$, where η_2 is still close to 1, the ratio η_1/η_2 is as small as 0.02, which proves the ability to realize a high-fidelity two-photon counter.

We also investigated the fidelity of distinguishing between single and double photon counts, which would correspond to the SNSPD of total length equal to HS interaction length. In this case, the double-spot and double-photon detection efficiency coincide, and at saturation with the increase of bias current, $\eta_2 = 1$. Due to absence of dark counts far from the critical current (the range where saturation of η_2 is actually observed, see Fig. 3(a)), the remaining errors are a misidentification of a single-photon count as a double-photon count and a miss of a double-photon count. The accuracy of our measurements doesn't allow to determine probability of the miss (i.e., $1 - \eta_2$) at the saturation level, but counting on the analogous saturation regime for single-photon counts, one can expect that it can be referred to as small as several percent. The misidentification of the single-photon counts as the double-photon ones is due to nonzero single-photon efficiency in the range of currents where η_2 reaches saturation. The probability of such error is about $\eta_1(I_{sat})$. As one can see on Fig. 4, the bias current can be chosen to make this value smaller than 0.02.

IV. Conclusion

Summarizing, we measured the double-spot IDE η_2 in a branch of NbN and MoSi nanostrips with the width varying form 56 to 300 nm, and found a solid saturation of η_2 with the increase of the bias current. This allowed us to extract the HS interaction length s. For the whole array of samples, we found that s follows the strip width w, which indicates that the HS size is below 70 nm, in agreement with the estimate based on the model of simple diffusion. This holds even in the films with the smallest critical temperature and density of states (DOS) per square, where there are reasons to expect larger HS [15]). Measurement of HS size via quantum detector tomography needs significantly narrower strips.

We prove that the observed saturation of η_2 coexists with a small single-photon DE η_1 at the same bias current and with the saturation of η_1 at a greater bias current. This can be used to realize an efficient photon counter, which can be switched between single-photon and double-photon counting modes bu tuning the current. Finally, proven relation $s \approx w$ confirms that for a photon-number resolving SNSPD which utilizes "single-spot" double-photon events, as suggested by Nikolich *et al.* [2], [16], the error introduced by "double-spot" events is small and set by the ratio of the strip width to its length.

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