Properties of Cascade Switch Superconducting Nanowire Single Photon Detectors

M. Ejrnaes[1], A. Casaburi[1,2], R. Cristiano[1], O. Quaranta[2], S. Marchetti[2], N. Martucciello[2,3], S. Pagano[1,4], A. Gaggero[5], F. Mattioli[5], and R. Leoni[5]

[1] Istituto di Cibernetica "E. Caianiello" del C.N.R., 80078 Pozzuoli, Italy
m.ejrnaes@cib.na.cnr.it
http://www.cib.na.cnr.it/
[2] Dipartimento di Fisica "E. R. Caianiello", Università di Salerno, 84081 Baronissi, Italy
[3] Laboratorio Regionale SuperMat, CNR-INFM Salerno, 84081 Baronissi, Italy
[4] Dipartimento di Matematica e Informatica, Università di Salerno, 84081 Baronissi, Italy
[5] Istituto di Fotonica e Nanotecnologie del C.N.R., 00156 Roma, Italy

Abstract. Superconducting nanowire single photon detectors have been realized using an innovative photon induced cascade switch of parallel nanowires. We demonstrate that this configuration allows, at the same time, a fast response and a large active area, with the additional advantage of signal pulses with a larger signal to noise ratio. These improvements are obtained maintaining the good quantum efficiency of traditional meandered superconducting detectors. We show that due to the high speed of the parallel nanowire detector special attention is needed to avoid latching, a phenomenon which in the parallel nanowire detector degrades the detector efficiency. We describe how the latching problem can be avoided using a proper nanowire configuration.

Keywords: Single photon detector, detector design, non-equilibrium superconductivity, nanotechnology.

1 Introduction

Superconducting nanowire single photon detectors (SNSPDs) are object of significant research mainly because they offer very good performance at 1550 nm wavelength. Quantum efficiencies as high as 57%, 70 ps timing jitter and low dark count rates have been reported [1,2,3,4]. High efficiency is obtained using 100 nm wide nanowires made from 4 nm thick ultrathin NbN films [5]. To achieve area coverage, many light absorbing nanowires are connected in series using a meander pattern. The serial connection makes the total detector inductance, L_{DET}, sizeable due to the high kinetic inductance of each nanowire. This limits the time constant, $\tau = L_{DET}/Z$, where Z is the impedance of the SNSPD (usually formed by the 50 Ω coaxial readout), of the current return into the SNSPD after a photon detection event. Because the bias current increases

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exponentially the SNSPD efficiency the use of a serial connection turns out to be the main limitation of the maximum obtainable count rate of meander SNSPDs [3]. Furthermore, the serial connection makes the maximum count rate of meander SNSPDs inversely proportional to detector area and is around 50 MHz for 10x10 μm^2 SNSPDs, which is significantly below the possibilities offered by NbN material. An open issue is how to obtain high SNSPD maximum count rate with a large active area without degradation of other key performance parameters. Current research is now investigating the use of parallel nanowires, which offer the possibility to sidestep the serial connection and thereby increase the maximum count rate, to fully exploit the speed of NbN. However, the use of parallel nanowires is not trivial: when a photon is absorbed in a nanowire the other parallel nanowires creates a shortcircuit and this makes it difficult to measure the signal pulses.

2 The Cascade Switch SNSPD

One way to enable the use of nanowires connected in parallel for single photon detection is to solve the read out problem by forcing *all* the parallel nanowires to develop normal state regions when a photon is absorbed in one nanowire. We have shown that this can be accomplished by polarizing all the parallel nanowires close to their critical currents [6]. Since SNSPDs usually are biased close to their critical currents, this is not a problem. For convenience we briefly review how the cascade switch works when M nanowires are connected in parallel. When a nanowire becomes resistive due to a photon absorption event, it will deviate its bias current onto the other $M-1$ parallel nanowires and the load. In order to confine the current within the parallel nanowires at this stage, an inductor is inserted in series with the load. When the other $M-1$ nanowires are biased close to their critical currents, the extra current will make the total current flowing through these nanowires exceed the critical current of each nanowire. This will drive all the parallel nanowires normal and subsequently they will all deviate their bias current onto the load and a signal will appear. The reduction of current in the parallel nanowires reduces the Joule heating and permit the cooling to recover superconductivity again. At this point, the current will return into the detector which is then ready for another photon. A key point is that the in series inductance can be realized using a serial connection of blocks of parallel light sensitive nanowires. This configuration mimics the serial connection used in the meander SNSPD, with the difference that each element has a M times lower inductance while it covers M time more area. For this reason, the inductance of a SNSPD based on parallel nanowires is reduced by a factor M^2 when compared to a meander SNSPD. Another key point is that the signal pulse of the parallel SNSPD is higher since more current is deviated onto the load. Finally, it is important to remember that the parallel SNSPD does not change the nanowires themselves, it only acts on their interconnection. This should leave the key detector properties, efficiency and dark count rate, unchanged, since they are only related the nanowires themselves. In this work we present measurements of

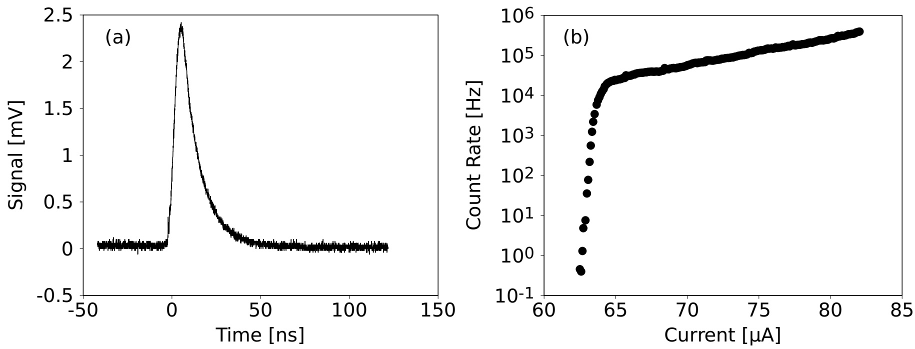

Fig. 1. (a) Parallel SNSPD signal pulse. (b) Measured photon count rate of a parallel SNSPD.

parallel SNSPDs showing that the efficiency at 850 nm is comparable to reported efficiency values of comparable meander SNSPDs. We also present measurement of the bias current dependence of the detector response at 1550 nm that is similar to what has been observed in meander SNSPDs.

In figure 1a we have shown a typical signal pulse from a parallel SNSPD biased in the useful bias range. The signal pulses are characterized by a short risetime and a significantly longer falltime, governed by the inductance of the parallel SNSPD. As seen, the signal to noise ratio (SNR) of the signal pulse is very good due to the large amount of current deviated onto the load. Also shown in figure 1b is the rate of photon induced signal pulses as a function of bias current, clearly demonstrating the presence of a useful bias range where the cascade switch works and solves the read-out problem.

3 Optical Experiments with Parallel SNSPD

Extensive details concerning the fabrication, configuration and measurements of the parallel SNSPDs reported in this work can be found in [7]. In brief, the parallel SNSPDs were made from 9 nm ultra-thin NbN film deposited on MgO substrates and patterned into 100 nm wide nanowires which were configured into parallel SNSPDs with M=4, 8, 12 and 24. In figure 2b we have shown a scanning electron micrograph of one of the parallel SNSPDs. All the devices covered an area of 5x6 μm^2, and the devices with M=8, 12 and 24 incorporated an on-chip in series inductance implemented using a wider NbN strip to ensure sufficient confinement of the bias current during the cascade switch stage. The devices were measured in a continuous flow cryostat with an optical window through which the parallel SNSPDs were illuminated using laser light pulses at 850 nm and 1550 nm. During operation the parallel SNSPDs were current biased through cold RC-filters and read out through a coaxial cable as shown in figure 2a. At room temperatures the signal pulses were amplified with a 1 GHz bandwidth RF amplifier and digitized with either 1 GHZ or 9 GHz bandwidth oscilloscopes.

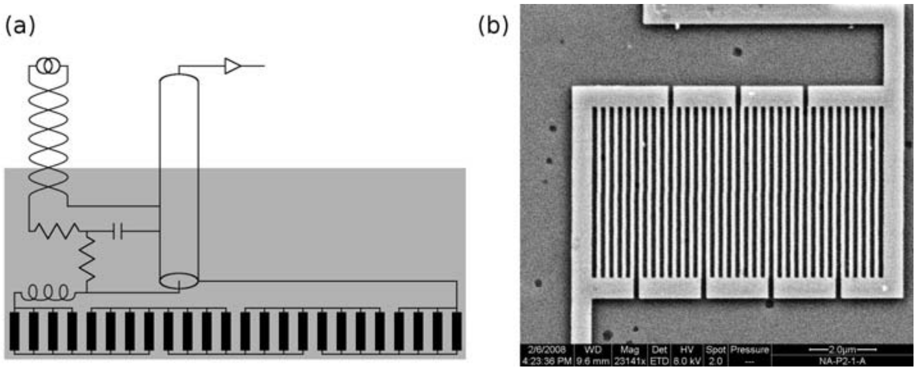

Fig. 2. (a) Diagram of the electrical biasing and readout of the parallel SNSPDs used in the measurements. The grey box indicates the parts located on the cold finger in the cryostat. (b) Scanning electron micrograph of the parallel SNSPD based on a serial connection of blocks each using four parallel nanowires.

In figure 3a we show the signal pulse height for the four different parallel SNSPDs when measured at a bias current of 9.75 μA per nanowire and illuminated with 850 nm laser light pulses. A clear linear trend is found, confirming that all the parallel nanowires are participating in the signal formation mechanism. By attenuating the light pulse intensity, we confirm that the parallel SNSPD exhibits single photon response across the entire useful bias range. In figure 3b we also show the parallel SNSPD quantum efficiency defined as the probability of receiving a signal pulse per photon incident on the detector area for 850 nm light. In the useful bias range, the quantum efficiency shows a characteristic exponential increase also seen in comparable measurements of meander

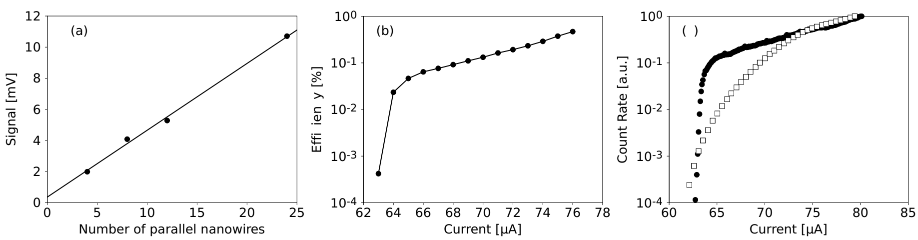

Fig. 3. (a) Measured maximum signal as a function of the number of parallel nanowires used in the parallel SNSPD. The bias current was 9.75 μA/nanowire and the temperature was 5 K. (b) Measured parallel SNSPD Efficiency vs bias current for a parallel SNSPD based on eight parallel nanowires. The measurement was performed at 5 K. The line is a guide for the eye. (c) Normalized parallel SNSPD photon count rate vs bias current for two different wavelengths: 850 nm (filled circles) and 1550 nm (open squares). The SNSPD was based on eight parallel nanowires and was measured at a temperature of 5 K.

SNSPDs [8]. Also the peak quantum efficiency of about 0.5% is in good agreement with previous measurements on meander SNSPDs with about the same thickness, width and at this temperature [5]. Finally we have also measured the parallel SNSPD photo-response when illuminated with 1550 nm laser light pulses (see figure 3c). The bias dependence of the detector count rate is found to be different from what is observed using 850 nm light. In detail, the onset of the detector response is smeared, probably due to lower energy available in 1550 nm photons. The presence of this difference is in qualitative agreement with what has been observed in thinner meander SNSPDs [2]. These measurements sustain the hypothesis that the parallel SNSPD can maintain the demonstrated detector efficiency of meander SNSPDs because it only changes the nanowire interconnections.

4 Parallel SNSPD Latching

The parallel SNSPD based on the cascade switch mechanism increases the maximum count rate roughly a factor M^2, where M is the number of parallel nanowires, and has been demonstrated working with up to at least 24 parallel nanowires [7]. Such a high speed gain easily triggers the new problem of SNSPD latching, which is the next limit of the maximum count rate in parallel SNSPDs. Latching occurs when the parallel SNSPD does not return into the superconducting state after a detection event, effectively stopping the detector from responding to subsequent photons, even if the bias current is lower than the critical current. For this reason, latching can be observed as an apparent reduction in the critical current (see figure 4a) of the detector which is detrimental because it inhibits detector operation in the bias range where it is most sensible to photons (see figure 4b).

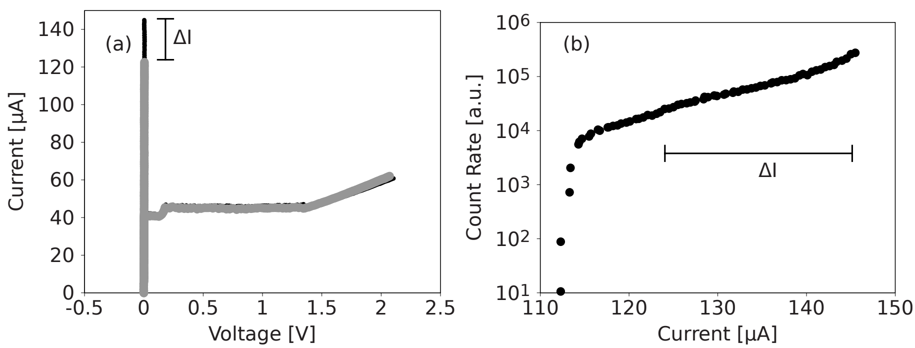

Fig. 4. (a) Current-voltage characteristics of the same parallel SNSPD measured with an extra in series inductance of 470 nH (small black circles) and 100 nH (large grey circles) demonstrating the difference in maximum bias current ΔI. (b) Measured photon count rate at 470 nH illustrating the missing bias region, ΔI.

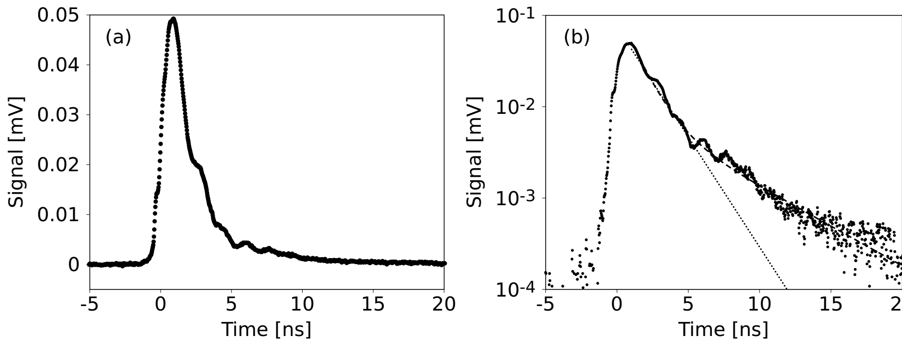

Fig. 5. (a) Averaged signal pulse of a parallel SNSPD based on four parallel nanowires (points). (b) Same as (a) but with a logarithmic signal amplitude scale. The lines are fit to the signal decay using a single exponential decay (dotted line) and a double exponential decay (dashed line).

The phenomenon has been observed in meander SNSPDs when the load impedance was increased or when the detector inductance was lowered [9]. Parallel SNSPDs are particularly susceptible to latching, probably due to the fact that operation is faster while the energy dissipation in the detector is higher [10]. Experimentally, this manifests itself as a need of large detector inductance values as increased M is used, to achieve proper operation [7]. By realizing the inductance with light sensitive nanowires one can achieve fast operation of large area detectors. Latching in parallel SNSPDs can be avoided, for a fixed load of 50 Ω, by properly choosing the number M according to the needed detector area. Smaller detectors must use smaller M whereas larger detectors can use more parallel nanowires without triggering the latching phenomenon. It is also likely that larger M can be used if the load resistance is reduced. According to [9] this could also speed up the SNSPD because the inductance can be reduced more than the load thereby lowering the time constant that limits the return of the current into the detector. This possibility comes at the cost of reduced signal pulse amplitude and therefore also reduces the signal to noise ratio of the detector signal.

In figure 5a we have shown a signal pulse from a parallel SNSPD based on four parallel nanowires measured with only 47 nH in series, i.e. going towards fast ($\sim$100 MHz) maximum count rate operation. In this condition we observe no latching and for this reason the efficiency should not be degraded. As can be seen the device is effectively ready for another photon after 10 ns. Interestingly, the high SNR have also allowed us to observe, for the first time, that the signal pulse decay is not well described by a single exponential decay in this condition (see figure 5b). This is contrary to what we have observed when slower operation is performed, where the decay is in fact well described by a single exponential. We can fit the data rather well with a bi-exponential decay. The time constant of the fast decay ($\tau = 1.2$ ns) can be identified with the electrical time constant whereas the origin of the second time constant ($\tau = 5$ ns) is not identified. The presence of this second exponential decay may impose a new limitation to overcome before very fast (> 1 GHz) maximum count rate of parallel SNSPDs can be achieved.

In conclusion, we have presented a new SNSPD configuration based on the use of parallel nanowires which can achieve significant gains in maximum count rate for large area SNSPDs. Measurements of the parallel SNSPD quantum efficiency and the change in detector efficiency with photon wavelength sustains that the parallel SNSPD maintains the good efficiency of meander SNSPDs. The gain in maximum count rate is however limited by new problem of SNSPD latching. We have discussed how latching can be avoided in parallel SNSPDs by increasing the detector size. Finally we have reported for the first time, that the signal pulse decay is not well described by a single exponential decay when fast operation is performed. In our measurements, the signal decay seems bi-exponential with a second fairly long time constant of 5 ns. This may have to be overcome if very fast maximum count rate is to be achieved with parallel SNSPDs.

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