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Large Signal Amplitude and Bias Range of Cascade Switch Superconducting Nanowire Single Photon Detectors

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Abstract— Cascade switch superconducting nanowire single photon detectors has been fabricated of ultrathin NbN films deposited by DC-magnetron sputtering at room temperature on MgO substrates. Detectors using 4 to 24 nanowires in parallel, having an area coverage of 5x6 μm^2 and a filling factor of 40%, have been investigated. Signal amplitudes increase with the number of parallel nanowires and reaches 12.3 mV with a signal noise of 20 μV. The range of bias currents where the detectors emit signal pulses also increase with the number of parallel nanowires and exceeds the nanowire critical current.

Index Terms **— Nanotechnology, Superconducting radiation detectors, Infrared detectors, Thin films.**

I. INTRODUCTION

SUPERCONDUCTING nanowire single photon detectors (SNSPDs) are object of current research due to high count rate, low dark count rate and high efficiency for single infrared photons [1-4]. At the moment the detector material of choice is niobium nitride (NbN) due to the small coherence length, fast electron-phonon interaction, and fast phonon escape time. Nanowires of ultrathin NbN films, typically 100 nm wide and 4 nm thick, are used to maximize efficiency for single infrared photons. The maximum count rate of current detectors is still well below the capacity of NbN [1,3], due to the high kinetic inductance of the nanostructured NbN. Furthermore, the small cross-sectional area of the nanowires limit the signal amplitude and results in low values of the signal to noise ratio (SNR) of the signal pulse.

Recently, two new configurations based on the use of parallel nanowires has been introduced, both with documented single photon sensitivity. The first exploits a cascade switch of several parallel nanowires to significantly increase the signal pulse SNR [5], the second exploits a single summed read-out channel of several parallel nanowires to achieve pseudo photon number resolution [6-8] and fast signal recovery time [9] while decreasing the signal pulse SNR. Both new configurations increase the maximum count rate due to the reduced detector inductance, although it still remains limited by the kinetic inductance of the nanowires [5,9].

The cascade switch mechanism is promising because SNSPDs based on a series of blocks of parallel nanowires [10] can achieve large area coverage with high maximum count rate. Also, the cascade switch mechanism allows high signal pulse SNR even when the individual nanowires have a low critical current. This in turn allows a substantial reduction of the nanowire width which could increase the SNSPD sensitivity at long wavelengths [2,11,12]. Alternatively, it can facilitate the integration with other technologies where limits in available substrates and deposition temperatures could decrease the NbN film quality. In particular, it is advantageous to use many parallel nanowires, since both for area coverage and reduced nanowire width, better SNSPD performances can be achieved.

In this paper we report on the fabrication, characterization and operation of different types of parallel SNSPDs, based on the cascade switch mechanism, all having an area coverage of 5x6 μm^2 and a filling factor of 40%, which is comparable to typical current meander SNSPDs.

II. DEVICE FABRICATION

The superconducting NbN films were deposited on MgO substrates at room temperature by reactive dc magnetron sputtering in a mixture of Ar and N_2 gases. The total pressure of the Ar and N_2 gases during sputtering were 1.2 mTorr with a 16% partial pressure due to the N_2 content. The DC sputtering power was kept constant at 440 W resulting in a growth rate of 1.27 nm/s. The film thickness was 9 nm and the critical temperature was 12.9 K. The SNSPDs used a 60 nm Ti/Au film for contacts and markers which was patterned by a lift-off procedure using electron beam lithography (EBL) with PMMA for electronic resist. The definition of the mask for the NbN film was done again by EBL using a negative hydrogen silsesquioxane electronic resist. The unwanted NbN was removed in a reactive ion etching process using a SF_6/CHF_3 gas mixture.

The SNSPDs investigated all used 24 nanowires with a 100 nm width and 5.2 μm length. The 24 nanowires are placed to

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cover a total area of 5.2 μm x 6.0 μm with a 40% filling factor. The SNSPDs were designed to test the working principle of a series connection of blocks of parallel nanowires, and therefore all used this concept. A total of four different configurations were realized as follows: six blocks of four parallel wires, three blocks of eight parallel wires, two blocks of twelve parallel wires, and one block of twenty-four parallel wires (see figure 1). A total of 16 samples were fabricated, each containing one realization of each of the SNSPD.

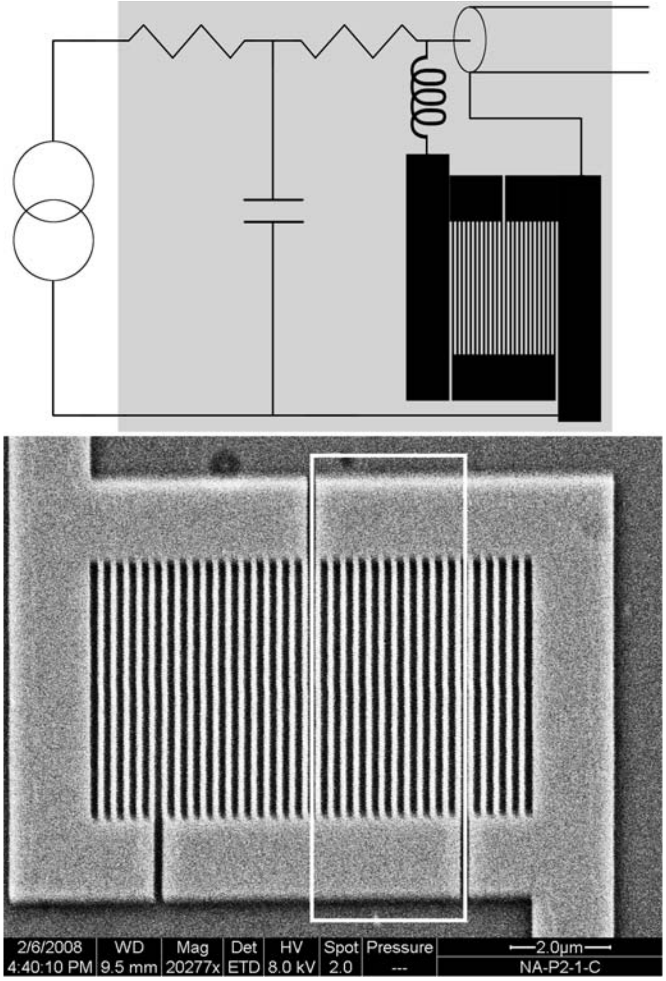

Fig. 1. Top: Measurement configuration. The SNSPD is biased through a cold T-shaped RC filter. It is operated with an inductor in series and the readout is performed through a co-axial cable. The SNSPD shown is based on a serial connection of two blocks of 12 parallel nanowires. The grey box indicates what is located at cryogenic temperatures. Bottom: SEM image of the SNSPD with two series connected blocks of 12 parallel nanowires. One block of 12 parallel nanowires has been indicated.

III. DEVICE CHARACTERIZATION

We have measured the room temperature resistances of all the realized SNSPDs and found that the resistance per unit square of the NbN film was 640 Ω. Likewise current voltage characteristics (IVC) of all the devices were measured at 4.2 K using a cryogenic insert in liquid helium. We measured a critical current per wire of 10.6 μA and a return current, i.e. the minimum current that can sustain a resistive state, per wire of 3.36 μA. If we compare this critical current to the RMS current noise of 575 nA (from a room temperature 50 Ω load in a bandwidth of 1 GHz) it is clear that such a low value of the critical current would complicate the bias stability of a standard meander SNSPD. Furthermore, the obtainable SNR of the signal pulses from a meander SNSPD with such a low critical current is not very high and this complicates reliable processing of the signal pulses. The critical current density, as inferred from the critical current, was 10^6 A/cm^2. This low value is probably due to a device critical temperature of 8.5 K. Nevertheless, this allows us to test if the cascade switch mechanism can successfully be used with such low critical current nanowires. Evaluating the measured IVCs, we found that 90% of the devices should work as detectors. We selected the four best chips based on the characterization for experiments under optical illumination. The obtained results were similar and we subsequently report only the obtained data from one of the devices.

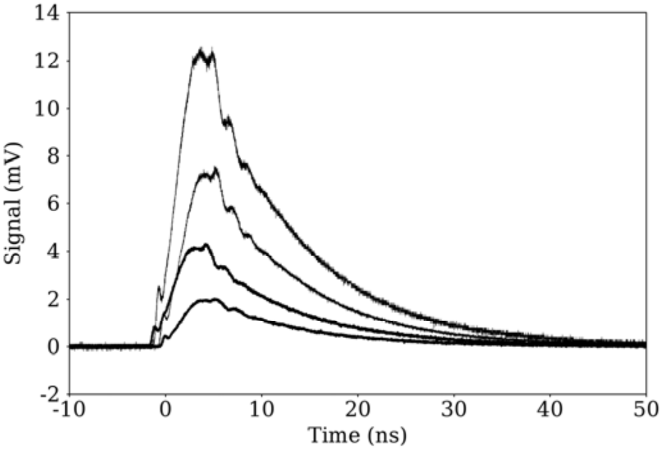

Fig. 2. Non-averaged signal voltage vs time for the four different parallel SNSPDs. Traces are in order bottom to top from the SNSPDs with four, eight, twelve, and twenty-four parallel nanowires all using an in series inductance of 470 nH. The bias currents were 39 μA, 80 μA, 140 μA and 255 μA respectively. The temperature was 5 K.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

Optical experiments were carried out in a continuous flow cryostat where the devices were mounted in a vacuum chamber. The SNSPDs were illuminated through an optical window with 850 nm laser light. From the measured temperature dependence of the critical current we estimate that the temperature under illumination is 5K. To obtain signal pulses that we can record and count accurately with our measurement bandwidth (DC-1GHz for recording, 80 MHz for counting) we slow down the devices by inserting a 470 nH inductor in series as shown in figure 1. The details of the measurement are reported in reference 5.

We observed that all SNSPDs worked as expected demonstrating the functionality of the serial connection of blocks of parallel nanowires. In figure 2 we show the non-averaged signal pulses obtained from the four types of SNSPDs. The signal pulses are all in the mV range and are measurable without the need of using RF amplifiers by modern oscilloscopes using a 2 mV/div sensitivity. It is seen that the voltage signal increases proportionally with the number of parallel wires in a block (i.e. with the bias current), indicating that all the parallel wires in a block are involved in the signal generation through the cascade switch mechanism. The standard deviation of the baseline signal was 20 µV for all SNSPDs resulting in a very high signal pulse SNR for all the devices, higher than 600 for the device with 24 wires in parallel. This demonstrates that the cascade switch mechanism makes it possible to obtain high signal pulse SNRs from SNSPDs made from NbN nanowires with a low critical current. The possibility of using nanowires with lower critical current could facilitate the integration with other thin film technologies, where the substrate lattice constant is non-ideal or where the substrate cannot be heated during NbN deposition. We note the same conditions can be realized using nanowires with a reduced width, using high critical current density NbN films. The cascade switch mechanism permits SNSPDs based on these narrow nanowires to achieve high area coverage, count rate and reliable operation. This could increase the SNSPD sensitivity at long wavelengths, which is particularly interesting because recent experiments have shown that current yield of meander type SNSPDs is not limited by the nanolithography but by the ultrathin film deposition process [12,13]. For this reason one can hope that a further decrease in linewidth will not decrease the yield significantly.

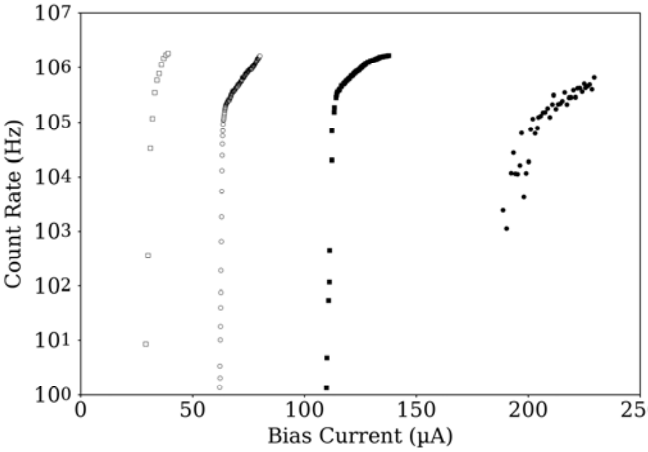

Fig. 3. Count rate vs bias current for the four different parallel SNSPDs subjected to 1 MHz pulsed 850 nm laser light. From left to right the data are from the SNSPDs with four (open squares), eight (open circles), twelve (closed squares), and twenty-four (close circles) parallel nanowires. The temperature was 5 K. The maximum count rate measured is slightly higher than 1 MHz due to a reflection in the illumination system.

For all devices the signal pulse risetime (falltime) is very similar and equal to 3.4 ns (21.3 ns), and should allow for a maximum count rate of 20 MHz. We underline, that for all devices, the external 470 nH in series inductance can be substituted by the kinetic inductance of more series connected blocks of parallel nanowires. This would significantly increase the SNSPD area, we estimate up to a factor 2200 for the device with 24 parallel wires [14], permitting the realization of 250 µm x 250 µm SNSPDs. Since the maximum count rate of such a SNSPD would be 20 MHz, these SNSPDs are interesting for applications in need of large area coverage [15,16]. For comparison, a meander type SNSPD would have a maximum count rate below 100 kHz at this area coverage.

We illuminate the SNSPDs with 6 ns long pulses of 850 nm laser light at a 1 MHz repetition rate. The light intensity used was intense (around 500 photons on the device per pulse) to get high count rates around the current threshold where the SNSPD efficiency is low. For fixed light pulse intensity we measure the count rate as a function of bias current (see figure 3) and find that all the SNSPDs show the presence of a threshold current where the count rate rapidly increase at least five orders of magnitude, which indicates the turn on of the cascade switch mechanism. The threshold current for all the SNSPDs is around 80% of the critical current, and increases slightly with the number of parallel nanowires. This increases the useful bias range (where the SNSPD outputs signal pulses) for SNSPDs with many parallel nanowires. The large useful bias range at high levels of bias current allowed for a very stable SNSPD operation because it was less sensitive to fluctuations in the bias current. Furthermore, since the signal pulse SNR is high in the entire bias range ΔI_b, processing of the signal pulses can be made independent of the SNSPD bias. The maximum count rate of the illuminated SNSPDs was observed to differ among the tested devices tending to decrease as the number of parallel wires is increased. We believe that this trend is likely to be caused by differences in the alignment of the illumination between experiments, however, we cannot exclude that the data reflect efficiency variations in the tested devices. If the trend is due to efficiency variations, further experiments are needed to clarify whether the efficiency decreases systematically as the number of parallel nanowires is increased. The 6 ns long light pulses used are too long for a proper measurement of the parallel SNSPD jitter. Work is in progress to measure this important parameter for parallel SNSPDs. We remark that, when the measurement is performed with attention to minimize the effects of stray capacitances, we do not see any after-pulsing effects.

Insight in the dynamical SNSPD behavior during the cascade switch can be obtained from the threshold current. In cascade switch SNSPDs, when a resistive state region appears in a nanowire, this will redistribute a significant fraction of the current flowing through it to the surrounding circuit. The extra current flowing through the parallel nanowires will subsequently induce normal state regions in all the parallel nanowires, at which point the bias current will deviate onto the load. To properly incite current assisted transitions to the normal state in the parallel nanowires, the bias current must be close enough to the critical current so that the extra current flowing through the nanowire makes the total current exceed the critical current. This fact manifests itself as a threshold current, and the cascade switch SNSPD will only emit signal pulses when the bias current is higher than the threshold current. When more nanowires are connected in parallel, each wire will receive a smaller extra current when the nanowire, that triggers the cascade switch, redistributes its current. Therefore, the threshold current will increase when more nanowires are connected in parallel. If the nanowire that triggers the cascade switch redistributes all its current evenly onto the other parallel nanowires, we can write the threshold current as $I_T/I_C=N/(N+1)$ for the case of zero load impedance and $I_T/I_C=(N-1)/N$ for the case of infinite load impedance. Here I_T is the threshold current, I_C is the critical current of the

SNSPD, and N is the number of parallel nanowires in a block.

In figure 4 we show the observed threshold current, obtained from figure 3, as a function of the number of parallel nanowires in a block. We see that the threshold current do indeed increase with the number of parallel wires. However, the observed bias range is significantly larger than expected for an even distribution of the extra current onto all the other parallel wires. In fact, an even distribution of the extra current predicts a bias range roughly equal to the critical current of a single wire, whereas we observe that the device with 24 wires in parallel has a bias range of about 40 µA which is four times larger the critical current of a single wire. Another mechanism which could be responsible for the cascade switch is thermal coupling between nanowires in a block. However, the threshold current corresponding to a purely thermal coupling should be independent of the number of parallel nanowires. We therefore believe, that the data indicates the presence of either a non-uniform redistribution of the extra current or a collaborative effect of extra current and a thermal coupling. In both cases it seems likely that the effect propagates primarily to the parallel wires close to the one in which the photon induced transition to the normal state occurred.

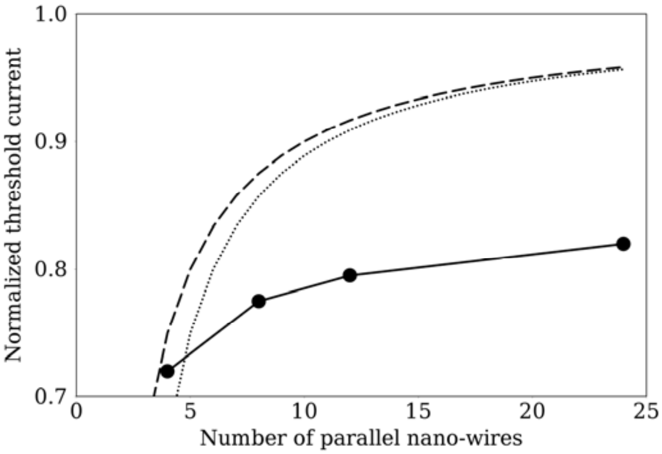

Fig. 4. Normalized threshold current vs the number of parallel wires for the four different parallel SNSPDs (filled circles). For each device the threshold current was normalized to the critical current of the device. Also shown is the expected threshold current for an even redistribution of the extra current during the cascade switch for the case of a high (dotted curve) and low (dashed curve) load impedance. Lines connecting the points have been added as a guide for the eye. The temperature was 5 K.

V. CONCLUSIONS

In conclusion, we have fabricated cascade switch SNSPDs based on ultrathin NbN films deposited at room temperature on MgO substrates. Successful SNSPD operation has been achieved with up to 24 parallel nanowires confirming the possibility of using a serial connection of blocks of parallel nanowires. Very high signal pulse SNR were obtained which increases with the number of parallel nanowires. The successful operation proves that the parallel SNSPD configuration can be based on nanowires with a low critical current, a fact that can be exploited to increase the sensitivity at long wavelengths or facilitate integration with other thin film technologies. The measurements also demonstrate that cascade switch SNSPDs permits reliable operation of devices with high area coverage which retains a high maximum count rate. The cascade switch SNSPDs were characterized by a large operating bias current range, easily exceeding the critical current of a single nanowire, which allows for very stable SNSPD operation and processing of signal pulses.

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