

New Generation of Nanowire NbN Superconducting Single-Photon Detector for Mid-Infrared

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Abstract— We present a break-through approach to mid-infrared single-photon detection based on nanowire NbN superconducting single-photon detectors (SSPD). Although SSPD became a mature technology for telecom wavelengths (1.3 - 1.55 μm) its further expansion to mid-infrared wavelength was hampered by low sensitivity above 2 μm . We managed to overcome this limit by reducing the nanowire width to 50 nm, while retaining high superconducting properties and connecting the wires in parallel to produce a voltage response of sufficient magnitude. The new device exhibits 10 times better quantum efficiency at 3.5 μm wavelength than the “standard” SSPD.

Index Terms—Infrared single-photon detectors, superconducting device fabrication, superconducting NbN films, thin film devices.

I. INTRODUCTION

RECENTLY there has been a dramatic increase in interest in single infrared photon manipulation. Many scientific and practical applications including telecommunication and optical systems, quantum key distribution, operation with entangled photons and characterization of single-photon sources need fast and sensitive detectors [1], [2].

Whereas in visible and near IR ranges, there exist commercially available single-photon detectors, Si and InGaAs avalanche photodiodes (APD) and vacuum photomultipliers (PMT), at wavelength greater than 1 μm (for Si APD and PMT), and 1.7 μm (for InGaAs APD) they are unusable due to a rapid decrease of sensitivity.

The superconducting detectors are an alternative to the semiconductor devices. Their main advantages are greater sensitivity in near and mid-IR, provided by orders of magnitude lower energy gap and less noise due to cryogenic operation temperature. The best quantum efficiency of ~95% is exhibited by tungsten transition-edge sensors (TES) [3]. But these devices are slow (maximum counting rate is of order of 10^4 Hz) and are easily saturated by room-temperature background. Furthermore, they operate at 100 mK and require

complex cryogenic equipment.

Another superconducting device in the IR range is the superconducting single-photon detector (SSPD) [4] based on ultrathin NbN film. It exhibits quantum efficiency (QE) up to 30% at wavelength of 1.3 μm at 10 dark counts per second rate [5] and single-photon sensitivity up to 5.6 μm wavelength [5], Temporal resolution (jitter) of 74 ps was measured using start-stop correlation technique [6]. The minimum measured dark counts rate was as low as 10^{-4} s [5], i.e. a count per several hours of data accumulation, although it is worth noting that such a low dark counts rate is achieved at a price of significant QE reduction. Quantum efficiency of the standard SSPD, patterned as 120-nm-wide meander-shaped strip, decreases exponentially with increasing wavelength, limiting the use of SSPD in mid-IR. To overcome this limitation, in this work we investigate a new topology of the detector with the sensitive element patterned as multiple parallel nanowires twice narrower than the standard SSPD strip, i.e. we managed to fabricate 50-nm-wide superconducting strips without any noticeable damage of superconductivity. Although a cascade switching mechanism in parallel nanowires has already been reported [7], we were for the first time able to reduce the wire width significantly and demonstrate improvement of SSPD sensitivity in the mid-IR.

II. RESULTS

A. New Topology of the Samples

As it was shown in [8], [9] the size of the normal region (“hot spot”) formed by the absorbed photon decreases with decreasing photon energy. To increase the quantum efficiency QE at wavelengths longer than 1 μm , one needs to reduce the strip width so that a smaller “hot spot” covers a larger portion of the strip cross-section, increasing the current density in the “sidewalks” around the “hot spot”.

Unfortunately with the reduction of the strip width the critical current I_c is also reduced, limiting bias current and simultaneously reducing the photoresponse signal which is proportional to the bias current. For a 120-nm-wide meander-shaped SSPD strip, the photoresponse pulse was distinguished clearly above the level of thermal electrical noise in the circuit. For 50-nm-wide strip the signal-to-noise ratio SNR is reduced to ~1 making such a device impractical.

To improve the SNR we realized an approach similar to [7]:

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we connected the strips in parallel. Such “parallel-wire” SSPD utilizes a cascade switching for signal preamplification: a photon absorbed by a single strip switches it to the resistive state. After that, the bias current starts redistributing among the other strips. When the currents in these strips exceed their I_c the strips become resistive as well. Thus, the whole device becomes resistive. Since the total critical current is proportional to the number of strips (which is about 50) the response voltage of such a device is by a factor of 50 higher compared to the meander-shaped device with a 56-nm-wide strip.

Fig. 1 presents a SEM image of the parallel-wire SSPD with $10\ \mu\text{m} \times 10\ \mu\text{m}$ area and consisting of 46 strips each 56-nm-wide.

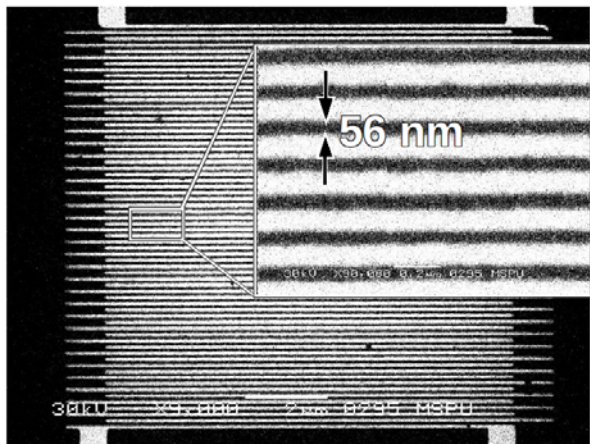


Fig. 1. SEM image of parallel-wire SSPD. Black is NbN film, white is the etched areas. We manage to produce 56-nm-wide strip retaining high superconducting properties.

As Kerman, et al. showed [10], the response time of the standard meander-shaped SSPD is limited by the kinetic inductance of the detector. Our novel devices consisting of N parallel wires are characterized with a kinetic inductance which is N^2 times smaller compared to standard SSPD, providing subnanosecond response time.

For these devices, the latching in the resistive state [11] becomes an issue requiring special treatment. Indeed, after photon absorption a typical resistance of the standard SSPD is about $1\ \text{k}\Omega$ which is much higher than $50\ \Omega$ impedance of the transmission line. When such a device switches to the resistive state the bias current drops significantly, Joule heating of the resistive area reduces and the superconductivity is spontaneously restored. The novel devices in a photon-induced resistive state have a resistance comparable to the impedance of the transmission line and no significant reduction of the bias current takes place. Thus, once triggered to the resistive state, the parallel-wire SSPD does not return to the superconducting state.

To enable spontaneous return to the superconducting state one needs to use a transmission line with reduced impedance, which is not practical. Another option is to connect a small resistor in parallel to the SSPD. In our case, a $3\ \Omega$ resistor was enough to enable spontaneous restoration of superconductivity. Although this solution leads to a reduction of the response voltage, the SNR is still high enough for practical usage.

B. Fabrication of the Samples

The fabrication of the parallel nanowire superconducting single-photon detector is similar to the one described in [12]. Superconducting NbN film with the thickness of 3-4 nm is deposited on m-cut or c-cut sapphire (Al_2O_3) substrate by DC reactive magnetron sputtering in Ar and N_2 mixture (partial pressures are 5×10^{-3} mbar and 2.5×10^{-4} mbar respectively). The substrate is first heated to 850°C .

Alignment marks are formed by photolithography with AZ1512 photoresist from a 100-nm-thick gold layer which is deposited either by DC magnetron sputtering, in the in-situ process with the NbN film, or by a thermal evaporation.

Then, via direct electron beam lithography, the superconducting parallel strips are patterned. We use 75-nm-thick electron resist ZEP-520A-7 which is more robust in reactive ion etching and enables higher resolution e-beam lithography compared to PMMA 950K, which we used before. We use a JEOL 6380 upgraded to e-beam writer. We used 30 kV accelerating voltage with anode current ranging from 2 to 5 pA. As a developer we used ZED N50. During the e-beam process, we expose the gaps between the superconducting strips. All strips are patterned having equal width in the range of 50-60 nm. The smallest gap between the strips we managed to produce is about 45 nm. Then the NbN film is removed by reactive ion etching process in a Corial 200R machine. In the final stage, the contact pads are formed using gold via photolithography process.

In spite of the two-fold decrease of the strip width, the supercurrent critical density remains high, e.g. $2.5 \times 10^{10}\ \text{A}/\text{m}^2$ for parallel wire SSPD consisting of 70 wires, each 55-nm-wide, and $4.1 \times 10^{10}\ \text{A}/\text{m}^2$ for meander-shaped SSPD with 104-nm-wide strip made from the same film, both measured at 3 K. This fact, together with similar critical temperatures for both devices, indicates the high quality of the superconducting NbN film and non-destructive character of the fabrication processes.

C. Experimental Setup

We characterized the parallel-wire SSPD by direct measurement of its QE at wavelengths of $1.26\ \mu\text{m}$ and $1.55\ \mu\text{m}$ in a setup similar to the described in [6]. We also measured spectral sensitivity with an infrared spectrometer.

For direct measurement of the QE , the SSPD was coupled to a single-mode optical fiber (we estimate coupling efficiency to be above 90%). QE was determined as a ratio of photon counts N_c to the number of photons at the input of the fiber N_{ph} :

$$QE = N_c / N_{ph} \quad (1)$$

N_{ph} was determined from the light power measured at the input of the fiber with New Focus 2011 or Thorlabs PM20 powermeters. As a light source we used LED for $1.26\ \mu\text{m}$ and a cw laser diode for $1.55\ \mu\text{m}$ wavelength. The light polarization was not controlled.

The SSPD was wire-bonded to a co-planar waveguide. A $3\ \Omega$ resistor was soldered to the same waveguide in parallel to the SSPD. Then it was cooled down to 2 K temperature and biased by very stable home-build constant-voltage DC source

through a standard Mini Circuits ZFBT-4R2GW bias-T. The SSPD photoresponse voltage pulses are amplified by one Mini Circuits ZFL-1000LN amplifier (28 dB gain, 10 MHz - 2 GHz band) and fed to Agilent 53131A pulse counter and Tektronics DPO71604 single-shot oscilloscope.

Measurements of the spectral sensitivity of the detector in the range 1 μm - 3.5 μm were conducted in an optical cryostat. For better accuracy we measured both standard SSPD and parallel-wire SSPD in one experiment. Both devices were mounted on the same holder and wire-bonded to the metal pads of the printed-circuit board, which was mounted on the same holder. A 3 Ω resistor was soldered on the board parallel to the parallel-wire SSPD. The printed-circuit board was connected to two RF-coaxial lines, one for each device. The RF lines were connected to room temperature Mini Circuits ZFBT-4R2GW bias-Ts. The DC ports of the bias-Ts were connected to very stable constant-voltage DC bias sources. The AC ports of the bias-Ts were connected to Mini Circuits ZFL-1000LN amplifiers and then to a Tektronics DPO71604 single-shot oscilloscope and a Agilent 53131A pulse counter. The signal from standard SSPD was amplified by two amplifiers, whereas for parallel-wire SSPD, one amplifier was enough, as it had a high response voltage.

As a source of radiation, we used an infrared grating spectrometer with a black body source (glow bar). The light was delivered to the SSPDs as a free space propagating beam. In this set-up it was very difficult to measure the beam size with the reasonable accuracy and as the consequence it was impossible to determine the number of photons falling on the SSPD. Therefore we calibrated the output power of the spectrometer with a Golay cell and determined SSPD relative quantum efficiency RQE as a ratio of the detection events to the measured power divided by the photon energy:

$$RQE = \frac{N_{det}}{W / h\nu} \quad (2)$$

where N_{det} is number of detection events, W is the measured power, $h\nu$ is the photon energy. Then we used QE measured at 1.26 μm wavelength in the fiber-coupled set-up as a reference point to obtain absolute QE at different wavelengths.

In the cryostat we used BaF₂ as input window and as a cold filter on the 40K shield inside the cryostat to cut-off a part of the room-temperature background radiation.

D. Results of the Measurements

Fig. 2 presents the results of the QE and dark counts rate measurements vs bias current performed for single-mode fiber coupled parallel-wire SSPD at 2 K temperature. The SSPD consisted of 46 wires, 55-nm-wide each.

One can see the maximum QE values are 3.7% and 2.6% at 1.26 μm and 1.55 μm respectively. These relatively small efficiency are attributed to smaller fill factor of this device which was 0.38, in contrast to 0.6 for a typical meander-shaped SSPD, and defects of the fabrication process. It is interesting to compare QE values at 1.26 μm and 1.55 μm . For this device their ratio is 1.4, whereas previously reported [5] best values of QE at these wavelength at 2 K temperature were 30% and 17% respective and their ratio was almost 1.8. It is also worth comparing QE at a practical dark counts rate of 10

counts per second. For this device they are 1.8% at 1.26 μm and 1.3% at 1.55 μm , and their ratio is also 1.4, whereas previously reported values for commercially available [13] fiber-coupled SSPD-based single-photon receiver were 10% at 1.3 μm and 4% at 1.55 μm giving the ratio of 2.5.

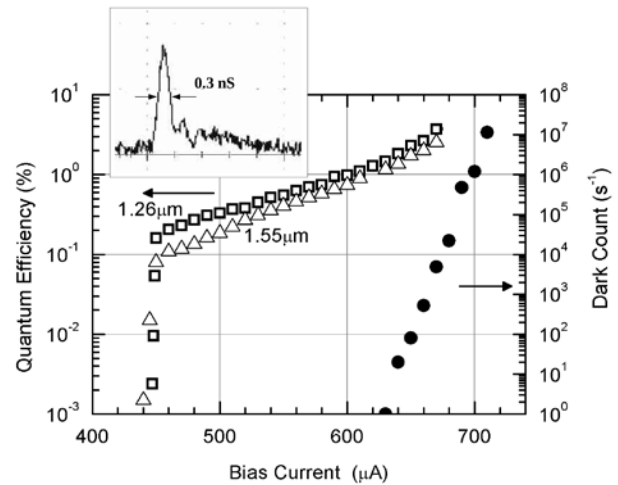


Fig. 2. Quantum efficiencies (left axis) at 1.26 μm (open squares) and 1.55 μm (open triangles) wavelengths and dark counts rate (solid circles, right axis) vs bias current measured for single-mode fiber-coupled parallel-wire SSPD at 2 K temperature. The maximum values are 3.7% and 2.6% for 1.26 μm and 1.55 μm respectively. The inset shows the waveform transient of the parallel-wire SSPD.

The inset in Fig. 2 shows the waveform transient of the parallel-wire SSPD photoresponse. The full width at half of the maximum (FWHM) is about 300 ps due to significantly reduced kinetic inductance.

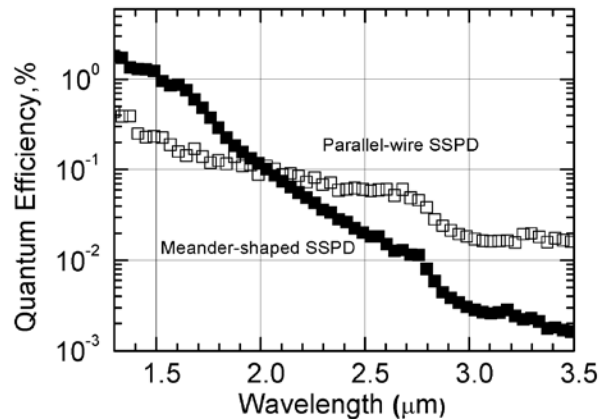


Fig. 3. Spectral sensitivity of the parallel-wire SSPD (open symbols) with 55-nm-wide strips, and 104-nm-wide meander-shaped SSPD (solid symbols) measured at 3 K temperature. At 3.5 μm parallel-wire SSPD exhibits an order of magnitude better QE than meander-shaped SSPD.

Fig. 3 presents spectral dependencies of quantum efficiency for “standard” meander-shaped SSPD with 104 nm wide strip and for the parallel-wire SSPD containing 70 parallel wires of 54 nm width made from the same NbN film and measured at 3 K temperature. Bias currents were set to a point where both devices have 20 kHz dark counts rate. One can see that, in the wavelength range from 1.3 μm to 3.5 μm , the QE of parallel-wire SSPD drops by a factor of 30 whereas QE of meander-

shaped SSPD drops by 3 orders of magnitude. It is also interesting to note that while parallel-wire SSPD had a worse QE in near infrared, at $3.5\ \mu\text{m}$ its QE is by an order of magnitude better compared to the standard device.

III. CONCLUSION

In conclusion, in order to improve SSPD sensitivity in the mid-infrared we developed a fabrication process that enabled us to reduce the strip width to 55 nm retaining its good superconducting properties (i.e., supercurrent density and critical temperature). To increase the response voltage of the SSPD, we utilized a cascade switching mechanism by patterning the device as multiple nanowires connected in parallel. Being coupled to single-mode optical fiber, our best devices exhibit quantum efficiency of 3.7% at $1.3\ \mu\text{m}$ at 2 K temperature. Compared to standard 104-nm wide meander shaped SSPD, the novel device exhibits 10-times better efficiency at $3.5\ \mu\text{m}$ wavelength.

Furthermore, parallel nanowire connection simultaneously dramatically reduced the device kinetic inductance: the novel device response time is about 300 ps, measured at half of the maximum, enabling a considerable increase of counting rates.

We believe that our break-through in the SSPD fabrication opens the way for middle infrared practical single-photon detector development.

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