Single Photon counting detector for THz radioastronomy.

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***Abstract* — In this paper we present the results of the research on the superconducting NbN-ultrathin-film single-photon detectors (SSPD) which are capable to detect single quanta in middle IR range. The detection mechanism is based on the hotspot formation in quasi-two-dimensional superconducting structures upon photon absorption. Spectral measurements showed that up to 5.7 μm wavelength (52 THz) the SSPD exhibits single-photon sensitivity. Reduction of operation temperature to 1.6 K allowed us to measure quantum efficiency of ~1% at 60 THz. Although further decrease of the operation temperature far below 1 K does not lead to any significant increase of quantum efficiency. We expect that the improvement of the SSPD's performance at reduced operation temperature will make SSPD a practical detector with high characteristics for much lower THz frequencies as well.**

***Index Terms*— Superconducting single photon detector, Hot spot, Infrared range, ultrathin films.**

I. Introduction

The development of the teraherz instrumentation is closely connected with the improvement of teraherz radiation detectors. Although single-photon detection in terahertz range is very attractive for radioastronomy, realization of even middle infrared single-photon detection is still a challenging task. An increasing interest in the range of 3 μm - 5 μm (100THz - 60THz) is connected with the usage of the atmosphere window suitable for ground-based observation. Meanwhile such observation is significantly hampered by the Earth thermal background.

In our early papers we have already reported on the superconducting single-photon detector (SSPD) based on ultrathin NbN film that outperforms avalanche photodiodes and photomultiplying tubes by such parameters as counting rate, quantum efficiency and level of dark counts [1,2,3]. In this paper we report the result of our resent research on the quantum efficiency in the middle infrared range 3μm -5μm (100THz - 60THz).

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II. Topology and SSPD fabrication process.

The design of SSPD chip and the SEM image of the SSPD active area are presented in the figure 1. The SSPD consists of the sensitive element placed in the center of the chip between two golden contact pads designed for 50-Ohm coplanar transmission line.

The sensitive element of the SSPD is a narrow (80 - 120 nm) stripe patterned from 4-nm-thick NbN film as a meander-shaped structure covering a square area of 10x10 μm^2 with the filling factor up to 0.6 (the ratio of the area covered by NbN film to the whole area of the SSPD sensitive element). The total length of the meander reaches ~ 500 μm.

The superconducting NbN film used for SSPD fabrication is deposited on the sapphire substrate by reactive magnetron sputtering in the argon and nitrogen mixture. During the deposition process the substrate is heated up to 850°C temperature thus leading to the epitaxial growth of the film. The high quality of the film is proved by such parameters as surface resistance 400-500 Ohm/square, critical temperature T_c = 10-11 K, and superconducting transition width ΔT_c ~0.3 K. The sensitive element of the SSPD is patterned by the direct electron beam lithography and reactive ion etching. [5].

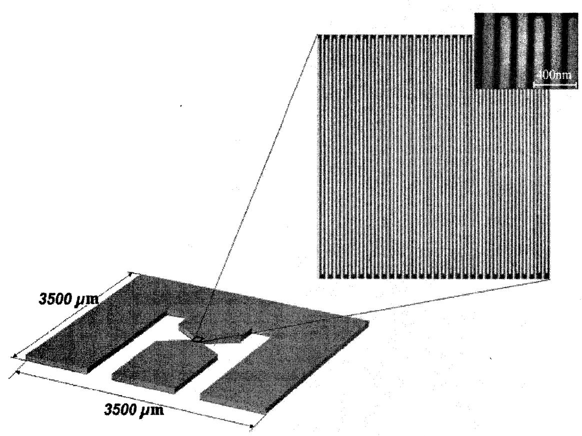

Fig. 1. Detector chip and photograph of SSPD sensitive element.

For optimal operation of the detector, it is important that the width of the superconducting stripe is uniform within the accuracy of several nanometers. Thus the reduction of the stripe edge nonuniformity allowed us to produce narrow enough stripe (80-120 nm), which lead to significant increase of the quantum efficiency.

III. SSPDs PHOTON-DETECTION MECHANISM

The single-photon detection mechanism by the superconducting stripe maintained at a temperature essentially below critical temperature and carrying current close to the critical is based on the local hotspot (normal region) formation in the place where a photon was absorbed [4].

Upon the absorption of a photon with the energy $\hbar\omega >> 2\Delta$ by a Cooper pair a high energy (nonequilibrium) quasiparticle appears. Due to electron-electron interaction, secondary excited quisiparticles are created in the avalanche multiplication process with the characteristic electron-electron interaction time .

As the average energy of the quasiparticales reduces, the number of quasiparticles increases to the amount of $\hbar\omega/2\Delta$ by the order of magnitude, it leads to the local suppression of superconductivity and hotspot formation. The initial size of the hotspot, $2\lambda_T$ (λ_T is the thermalization length, i.e. the length at which the average energy of the excited quasiparticles reduces to the value of Δ), is determined by the ratio $\hbar\omega/2\Delta$, by the thermalization time of nonequilibrium quasiparticles τ_T (i.e. the time during which the average energy of excited quasiparticles decreases to Δ) and by the diffusivity of normal metal D. During the time by the order of magnitude equal to the thermalization time, the hotspot grows due to diffusion of hot electrons (quasiparticles) from the center of the hotspot. The growth of the hotspot leads to the extrusion of the supercurrent from the normal part of the film to the sides of the stripe. If the transport current density around the hotspot exceeds the critical current density the entire cross-section of the film becomes resistive leading to the appearance of a voltage pulse with amplitude proportional to the magnitude of the transport current. Subsequent recombination of the quasiparticles leads to the decrease of the hotspot and superconductivity restores.

IV. EXPERIMENTAL SETUP AND MEASURED RESULTS

A. Experimental setup.

To research how quantum efficiency of the SSPD depends on temperature in the 1.6 K - 4.2 K range we used a double-wall cryogenic insert for transport dewar (see fig. 2). The temperature below 4.2 K was achieved by pumping of the helium vapour from the insert. Controlling the helium vapour preassure we reached desired temperature which was measured by the previously calibrated preasure sensor.

SSPD was mounted to a 50-Ohm coplanar line which was, in turn, connected to a rigid coaxial cable. The SSPD was illuminated by LEDs (light emitting diodes) operated at cryogenic temperature which were mounted on the same holder with the SSPD.

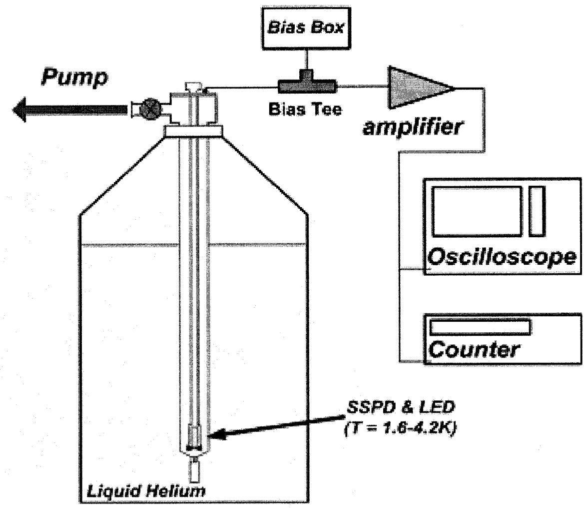

Fig. 2. Experimental setup for SSPD count measurements at 1.6K-4.2K temperature range for 3μm and 5μm wavelength.

DC biasing of the SSPD was performed with a home-built bias-T which consisted of a capacitor transmitting high frequency signal and a resistor of 20-100 Ohm in the DC arm of the bias-T. The response signal of the SSPD was amplified by room temperature amplifiers.

The voltage transients of the SSPD photoresponse were observed with the single-shot oscilloscope and were counted by the electronic counter. The SSPD was biased in the voltage source mode. The experimental setup is presented in the figure 2.

Broadband spectral characteristic of SSPD in the wavelength range of 0.6-5.7 μm were also studied in an optical cryostat. Pumping of helium vapour from the cryostat allowed us to perform experiments in temparature range 3 K-5 K. As the monochromatic light source we used the infrared spectrometer. The radiation was delivered to the detector installed in the optical cryostat as a free-space propagating beam and was focused by a set of mirrors. We used sapphire (in the wavelength range 0.6-1 μm) or silicon (in the range 1-5.7 μm) input windows of the cryostat. Electronic read-out was the same as described above.

Quantum efficiency (QE) was determined as the ratio of electrical photoresponse pulses of the SSPD to the number of photons incident on the SSPD active area of 10x10μm^2. The power of LEDs was controlled by their bias current thus ensuring that it remains constant during the experiment. The power of the spectrometer was calibrated separately with a Golay cell.

For better accuracy of QE measurements, as a reference point we used the value of QE measured at 1.3-μm wavelength in a calibrated setup similar to one described in our previous publications [3].

B. Experimental Results.

Figure 3 presents QE vs. wavelength measured at 3 K and

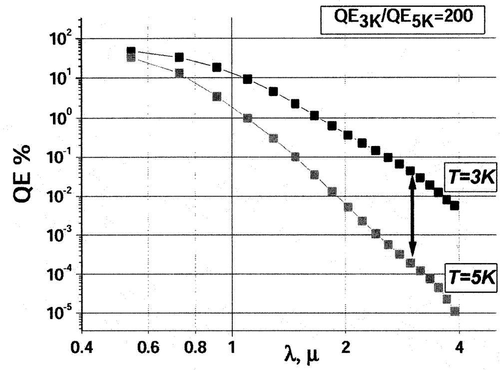

Fig. 3. Spectrum dependence of QE for SSPD at 3K and 5K both spectrum characteristics were researched at 0.94 Ic bias current.

5 K temperatures with infrared spectrometer as the light source. The SSPD transport current was equal to 0.94 Ic. We have shown that the decrease of the operation temperature significantly improves quantum efficiency in the middle infrared range, i.e. the ratio of quantum efficiencies at 3 μm wavelength (marked by an arrow in fig. 3) is more than two orders of magnitude.

The spectral sensitivity is strongly dependent on the SSPD transport current I_b as well. The maximum QE was observed at currents very close to the critical current I_c (see fig. 4).

To determine how QE at 5-μm-wavelength depends on the temperature we used the experimental setup with cryogenic insert described above.

Figure 5 shows the temperature dependence of QE at different transport currents. One can see a significant increase of QE with the reduction of temperature from 5 K to 1.6 K. At transport current of $0.95\ Ic$ it is of about two orders of magnitude whereas at $Ib=0.86Ic$ the increase of QE is almost four orders of magnitude. At temperature below 2 K one can see that the dependence of QE on temperature becomes less steep compared to higher temperatures. This trend is much clear for 3 μm wavelength and 0.4-2.5 K temperature range: figure 6 presents SSPD

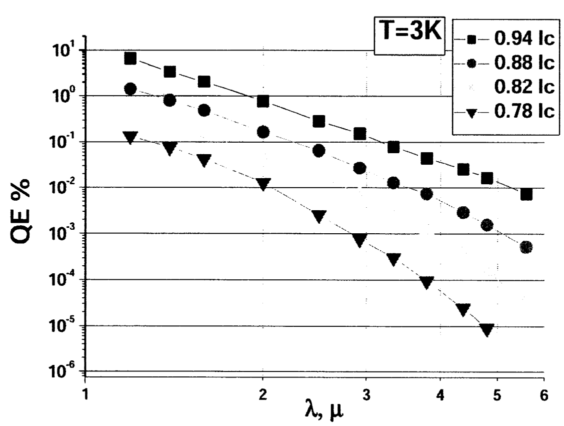

Fig. 4. Spectrum dependence SSPD at 3K temperature and different transport currents in range 0.78 to 0.94 of Ic.

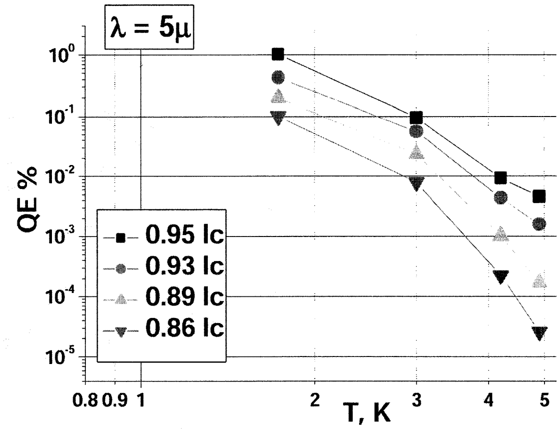

Fig. 5. QE versus temperature at the different bias current for 5μm wavelength.

count rate measured at constant LED power and constant ratio of Ib/Ic.

To compare the SSPD with traditional integrating detectors at 5 μm wavelength we estimated the noise equivalent power (NEP) of the SSPD. For single-photon

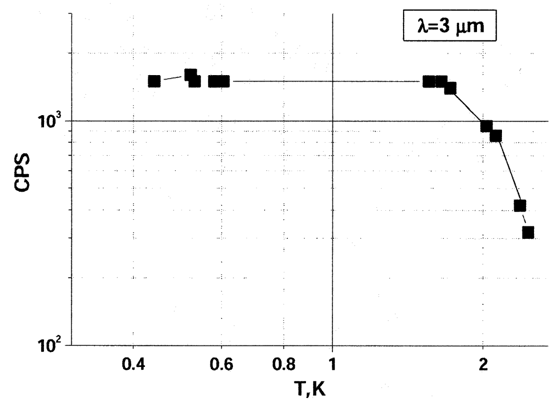

Fig. 6. Count per second versus temperature 3μm wavelength.

detectors NEP is given by

$$NEP = \frac{h \cdot \nu}{QE} \cdot \sqrt{2R},$$

where hν is the quantum energy, QE is quantum efficiency at a given wavelength and R is dark count rate. In [6] we reported that R exponentially drops with SSPD transport current decrease and at 2 K temperature the best measured value of R was $2\text{x}10^{-4}\text{s}^{-1}$ for Ib/Ic=0.89. Taking QE values from figure 5 we have the best NEP value of $8\text{x}10^{-21}$ W/Hz$^{1/2}$ at 5 μm and bias current 0.89 I_c.

V. Conclusion

We have demonstrated that the reduction of operation temperature leads to significant improvement of the SSPD quantum efficiency in the middle infrared range. At operation temperature of 1.6 K, the SSPD exhibits quantum efficiency of 1% at 5 μm wavelength.. Taking into account extremely low level of dark counts of $2x10^{-4}s^{-1}$ we obtained noise equivalent power of $8x10^{-21}$ $W/Hz^{1/2}$ at 5 μm wavelength (60THz). This makes SSPD a practical detector high frequency for THz astronomy.

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