Superconducting nanostructured detectors capable of single-photon counting in the THz range

G. Gol'tsman, A. Korneev, O. Minaeva, I. Rubtsova, I. Milostnaya, G. Chulkova, B. Voronov,
K. Smirnov, V. Seleznev, W. Słysz, J. Kitaygorsky, A. Cross, A. Pearlman, and Roman Sobolewski

***Abstract*—We present the results of the NbN superconducting single-photon detector sensitivity measurement in the visible to mid-IR range. For visible and near IR light (0.56 — 1.3µm wavelengths) the detector exhibits 30% quantum efficiency saturation value limited by the NbN film absorption and extremely low level of dark counts ($2x10^{-4}$ s^{-1}). The detector manifested single-photon counting up to 6 µm wavelength with the quantum efficiency reaching 10^{-2}% at 5.6 µm and 3 K temperature.**

***Index Terms*—Infrared optical detectors, single-photon counters, superconducting devices, NbN superconducting films**

I. INTRODUCTION

At present the expansion of the traditional single-photon counting detectors such as avalanche photodiodes (APD) and photomultiplier tubes (PMT) to the middle IR and far-IR (THz) ranges is significantly hampered. The main reason of this is in fact that the typical bandgap of semiconductors and electronic work function of a metal (in case of PMT) become higher than the energy of the IR photon at the THz frequency. Superconducting devices, on the other hand, seem to be very prospective for these purposes. As the typical energy gap of superconductors 2Δ is several orders of magnitude smaller than the bandgap of semiconductors (2Δ~2meV for NbN at 4.2 K). For example, an absorbed 1-µm wavelength photon is able to produce an avalanche of ~100-1000 excited electrons in the NbN superconductor detector vs only one electron-hole pair in the APD. Picosecond energy relaxation time in superconductors allows one to create a photon counter with GHz counting rate. Cryogenic operation environment significantly reduces thermal fluctuations and as the consequence provides very low dark counts rate eliminating complicated biasing circuits common for APDs.

We have already reported on the successful development and fabrication of the superconducting single-photon detector (SSPD) for IR radiation [1]-[3]. The SSPD is made of 4-nm-thick NbN film deposited on the double-side polished sapphire substrate. The film was patterned by the electron beam lithography into a meander-shaped 100-nm-wide strip, covering the square area of 10x10 µm^2. The fabrication process did not affected the superconducting properties of the NbN film, i.e. the critical temperature T_c, the transition width ΔT_c and the critical current density j_c remain as high as they were for the unpatterned film (T_c=10-11 K, ΔT_c~0.3 K, j_c=6-7×10^6 A/cm^2 at 4.2 K). The detector exploits a combined detection mechanism, in which avalanche quasiparticle multiplication and the bias supercurrent jointly produce a transient voltage response to a single absorbed photon, via formation of a normal hotspot and phase-slip-centers in a quasi-two-dimensional superconducting strip [1],[4]. Being operated at 2 K, the SSPDs are capable of GHz-rate IR single photon counting with a record low dark counts rate. In this paper we present the result of our research on the SSPD spectral sensitivity up to 6µm wavelength.

II. EXPRIMENTAL SETUP

The SSPD is placed inside the optical liquid helium cryostat and maintained at the constant temperature in 2-5 K range. The SSPD is wire-bonded to a coplanar transmission line and then connected to the cryogenic bias-T. The bias-T, in turn, is connected to the very stable, constant-voltage bias source and the output RF circuitry. Constant voltage operation regime assured a rapid return to the superconducting state after the photon detection by the SSPD and prevented self-heating of the device. The SSPD photoresponse was amplified by the chain of the room temperature amplifiers (total gain is 70 dB, and 0.05 to 2 GHz-bandwidth) and then fed to the oscilloscope and the pulse counter for statistical analysis.

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G. Gol'tsman (phone: +7(095)2461202; fax: +7(095)2466321; e-mail: goltsman00@mail.ru), A. Korneev, O. Minaeva, I Rubtsova, I. Milostnaya, , G. Chulkova, V. Voronov, K. Smirnov, V. Seleznev are with the Moscow State Pedagogical University, Moscow 119345, Russia.

W. Slysz, J. Kitaygorsky, A. Cross, A. Pearlman and R. Sobolewski are with the University of Rochester, Rochester, NY 14627, USA; W. Slysz is also with the Institute of Electron Technology, PL-02668 Warszawa, Poland. R. Sobolewski is also with the Institute of Physics, Polish Academy of Sciences, PL-02668 Warszawa, Poland.

To study the SSPD spectral sensitivity in 1-6 μm wavelength range we used the infrared grating spectrometer as the light source. The mirrors of the spectrometer focused the radiation in a rather uniform light spot with the diameter of about 1 cm. We used silicon input windows of the cryostat and also placed cold silicon filters inside to cut the parasitic visible and near IR (below 1 μm) radiation. We used a Gollay cell detector and a lock-in amplifier to calibrate the output power of the spectrometer in the whole range of 1-6 μm.

For better accuracy of the QE measurement we also calibrated the SSPD sensitivity at 1.26 and 1.55 μm wavelengths. In this case the SSPD was installed in a dipstick and maintained in the storage dewar. The light was delivered to the SSPD by the multi-mode optical fiber and fell on the SSPD through its sapphire substrate. As the light sources we used cw laser diodes. We used the InGaAs powermeter operating in the 800-1600 nm range to determine the number of the incident photons delivered by the fiber to the SSPD. We used calibrated optical attenuators and always measured separately the power of our light sources. For this purpose we mounted a small piece of the sapphire substrate (the same as we use for the SSPD fabrication) on the device holder instead of the SSPD and collected the light passing through the sapphire on the fiber coupled to the optical powermeter. From the power measurement we obtained the average density of the photon flux; considering that the light was rather uniformly distributed on the SSPD active area, we calculated an average number of incident photons. We define quantum efficiency QE as the ratio of the detection events registered by the counter N_{reg} to the number of incident photons N_{inc} for a given time interval per the device area:

$$QE = N_{reg} / N_{inc} \tag{1}$$

The measured QE at 1.26 μm together with the relative measurements with the spectrometer could be used for the SSPD QE calculation in the whole studied wavelength range.

The dark counts rate was studied in the dipstick setup. The SSPD was completely shielded. The cold metal shield prevented the illumination of the SSPD by the parasitic 300 K background radiation, which might manifest itself as extrinsic dark counts.

The temperatures below 4.2 K were achieved by the helium vapor pumping.

III. EXPERIMENTAL RESULTS

From the application point of view the telecommunication 1.3 μm and 1.55 μm wavelengths are very interesting. Fig. 1 presents the results of QE measurements performed with cw lasers at 0.56, 1.26 and 1.55 μm wavelengths and at the temperatures of 4.2 and 2 K. The QE was measured as a function of the normalized bias current I_b/I_c (i.e. the ratio of the SSPD bias current I_b to its critical current I_c at the given temperature). One can see that at 1.26 μm, the QE reaches 30% value, while at 1.55 μm, the maximum QE is 17%. At 4.2 K, the QE for IR light is much smaller. For example, the maximum QE at 1.55 μm at 4.2 K is only 3.7% and only for I_b approaching I_c (Fig. 1).

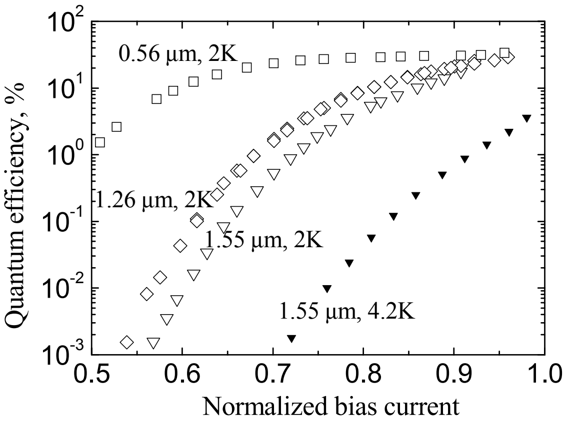

Fig. 1. SSPD QE measured using cw laser diodes at 4.2 K (solid symbols) and 2 K (open symbols) temperatures.

For comparison, we also present the QE vs. I_b/I_c measured with 0.56 μm cw laser at 2.0 K. One can note an obvious saturation-like behavior, which we explain as the achievement of the limit determined by the film absorption. For visible-light photons this limit reaches a ~30% value.

The results of our investigation of the SSPD spectral sensitivity are presented in Fig. 2. Our most recently fabricated devices exhibited single-photon counting up to 5.6-μm wavelength. The QE vs. wavelength was measured at 2 K temperature and four different bias currents. The spectral sensitivity strongly depends on the ratio of I_b/I_c. The highest detection probabilities are measured for I_b values very close to I_c. The decrease of the operating temperature for a given I_b/I_c improves QE, as well as extends the SSPD's single photon counting capabilities further into the IR wavelength range providing the QE of 10^{-2}% at 5.6 μm wavelength.

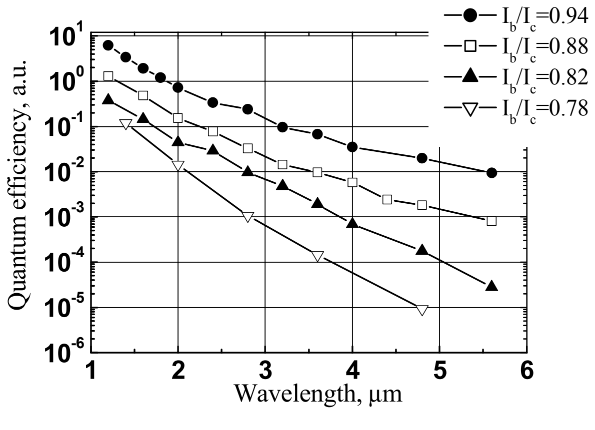

Fig. 2. QE (in arbitrary units) vs. wavelength measured at different I_b/I_c values and 2 K temperature.

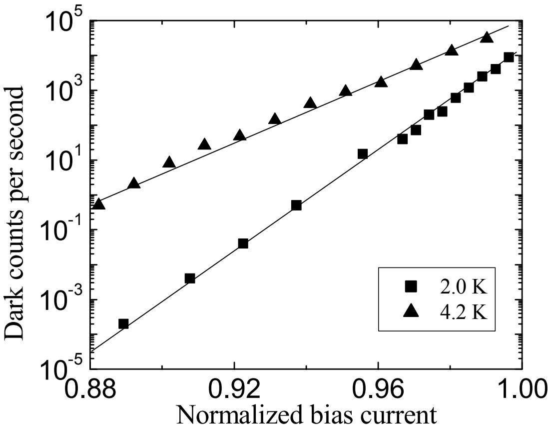

Fig. 3. Dark counts rate vs normalized bias current measured at 4.2 K (triangles) and 2 K (squares) temperatures.

Fig. 3 presents the dark count rate R vs. I_b/I_c. measured at 4.2 K and 2 K temperatures. The $R(I_b/I_c)$ dependence demonstrates the activation law in the whole biasing range used in our experiments ($0.87<I_b/I_c<0.99$):

$$R = a \cdot \exp\left(b\frac{I_b}{I_c}\right), \qquad (2)$$

where a and b are constants. The activation-type behavior of $R(I_b)$ at 2 K extends up to over seven orders of magnitude. The minimum measured R was as low as 2×10^{-4} s^{-1} and was limited by the duration of the experiment, i.e., accumulating several dark counts took about 8 hours. Lowering of the operation temperature also drastically reduces the dark counts rate.

An optimal operation regime of the SSPD is a trade-off between QE and R. The maximum value of QE corresponds to rather high (~1000 s^{-1} or above) R. Quantitatively this interplay between QE and R can be presented in terms of the Noise Equivalent Power (NEP), which can be defined for quantum detectors as:

$$NEP = \frac{h\nu}{QE}\sqrt{2R} \qquad (3)$$

where $h\nu$ is photon energy. We used the experimentally measured QE values presented in Fig. 1 and the result of the SSPD spectral sensitivity measurement presented in Fig. 2 to calculate the QE in the whole studied wavelength range. Then these data together with the dark counts rate at 2 K temperature (Fig. 3) allowed us to calculate NEP. The result of our calculation for I_b/I_c values of 0.94 and 0.88 is presented in Fig. 4. The NEP values for I_b/I_c=0.88 were calculated using the extrapolated value of dark counts rate. One can see, that the NEP level as low as $5\cdot10^{-21}$ W/Hz$^{1/2}$ can be achieved for photon at the telecommunication wavelengths at 2.0 K, whereas at 5 – 6 µm the NEP is about 10^{-18} W/Hz$^{1/2}$.

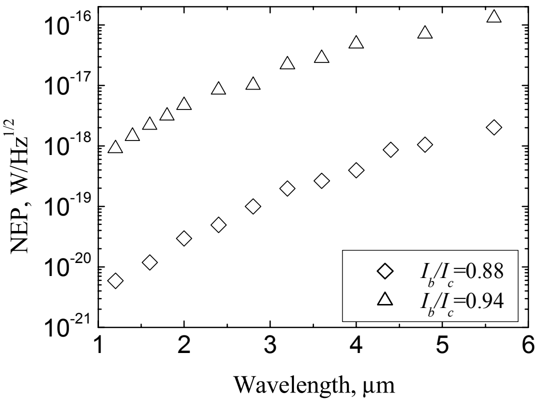

Fig. 4. Noise equivalent power (NEP) vs wavelength calculated from the measured QE and dark counts rate at 2 K temperature.

IV. CONCLUSION

In conclusion we would like to underline that our SSPD is the only practical quantum detector that exhibits single-photon sensitivity at 5 – 6 µm wavelength. Being operated at 3 K temperature it exhibits 10^{-2}% QE at 5.6 µm wavelength. On the other hand, in the visible range QE has already achieved its saturation value of 30% limited by the film absorption.

Further significant improvement of the SSPD performance in the mid-IR range is expected with currently undertaken implementation of superconductors with a narrow energy gap and low quasiparticle diffusivity. The use of a material with the low transition temperature will shift the sensitivity cutoff towards longer wavelengths. Depending on the material and operation conditions, such a detector should obtain a background-limited NEP below 10^{-21} WHz$^{-1/2}$ and a high dynamic range in THz frequencies, when exposed to 4-K background radiation.

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