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Superconducting single-photon ultrathin NbN film detector

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***Abstract*. Superconducting single-photon ultrathin NbN film detectors are studied. The development of manufacturing technology of detectors and the reduction of their operating temperature down to 2 K resulted in a considerable increase in their quantum efficiency, which reached in the visible region (at 0.56 μm) 30 % – 40 %, i.e., achieved the limit determined by the absorption coefficient of the film. The quantum efficiency exponentially decreases with increasing wavelength, being equal to $\sim$ 20 % at 1.55 μm and $\sim$ 0.02 % at 5 μm. For the dark count rate of $\sim 10^{-4}$ s^{-1}, the experimental equivalent noise power was 1.5×10^{-20} W Hz$^{-1/2}$; it can be decreased in the future down to the record low value of 5×10^{-21} W Hz$^{-1/2}$. The time resolution of the detector is 30 ps.**

Keywords: *single-photon detector, thin superconducting films.*

At present the development of single-photon near-IR detection technique is restricted by the absence of highly sensitive and fast detectors. Thus, the sensitivity of widely used Si avalanche photodiodes is restricted by the energy gap width of silicon. The single-photon quantum efficiency η_q of InGaAs avalanche photodiodes in the 1.2 – 1.6-μm range achieves 20 %; however, the time delay Δt of the leading edge of the pulse in these photodiodes is very unstable and their dark count rate is high, $R = 10^4$ s^{-1}. To reduce the latter, avalanche diodes are commonly used in the time-gated mode, which allows one to obtain the photon count rate up to 10^7 s^{-1}. For example, although FPD5W1KS avalanche photodiodes (Fujitsu) have the quantum efficiency $\sim$ 16 %, their count rate is 5×10^6 s^{-1} ($\Delta t \sim$ 200 ps) for $R = 500$ s^{-1} (in the time-gated mode). The situation with photomultipliers is similar. Thus, the quantum efficiency of one of the best R5509-42 STOP PMT photomultipliers (Hamamatsu) is $\eta_q \sim 1$ % and $R = 1.6 \times 10^4$ s^{-1} for the maximum photon count rate of 9×10^6 s^{-1} ($\Delta t \sim$ 150 ps).

Superconducting devices are very attractive for using as single-photon detectors because their energy gap is a few orders of magnitude narrower than the typical energy gap in semiconductors. For example, the energy gap width of NbN is $\sim$ 2 meV. Therefore, each absorbed photon produces many quasi-particles (in the case of NbN and a 1-μm photon, about 300). In this paper, we present the results of our study of a superconducting ultrathin NbN single-photon detector (SSPD).

The manufacturing process of detectors is described in detail in [1]. Briefly, it consists in the reactive magnetron spattering of a superconducting 4-nm thick NbN film on a double-side polished sapphire substrate. The active element of the detector is a meander narrow strip covering the 10 × 10-μm area. The typical width of the strip is 100 – 120 nm and the filling factor (the ratio of the area covered by the superconductor to the total area of the device) achieves 0.6 – 0.7 (Fig. 1).

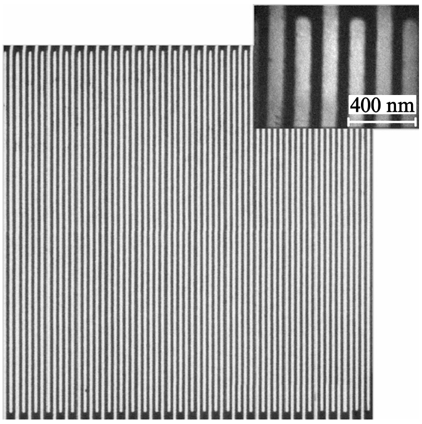

Figure 1. Detector image obtained with a scanning electron microscope.

The operation principle of the detector is based on the use of the resistive region in a narrow superconducting film appearing due to the combined action of the absorbed photon and a transport current. Unlike superconducting bolometers, which operate at temperatures close to the superconducting-transition temperature T_c, a SSPD operates at a temperature T that is considerably lower than T_c. For example, $T_c = 10 - 11$ K for NbN, whereas the operating temperature of a SSPD is 2 – 4.2 K.

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Absorption of a photon gives rise to the formation of the avalanche of quasi-particles and results in the local suppression of superconductivity. The electric current is redistributed in the vicinity of the produced normal region, by flowing around it. As a result, the current density begins to exceed the critical value and the entire section of the strip transfers to the normal state, which is accompanied by the appearance of an electric voltage on it. The concentration of quasi-particles in the normal region relaxes due to diffusion to the equilibrium value and superconductivity is restored. The mechanism of the detector response is described in more detail in paper [2], where the number of quasi-particles in the avalanche was calculated and the size of the normal region was determined. The characteristic thermalisation and energy relaxation times, which lie in the picosecond range for the NbN film, provide the fast response of the detector.

To prove the ability of the detector to detect single photons, we studied earlier [3] the probability of appearance of the detector response as a function of the laser pulse energy. We found that this probability is directly proportional to the laser pulse energy, and the response appears even when the average number of photons in the pulse is considerably smaller than unity.

The detector photoresponse was studied at wavelengths 0.56, 0.67, 0.94, 1.26, and 1.55 μm (cw semiconductor lasers), 0.85 μm (a pulsed GaAs laser emitting 20-ns pulses with a pulse repetition rate of $f \leqslant 100$ Hz), 0.637, 0.845, and 1.554 μm (Hamamatsu pulsed lasers emitting 40 – 60-ps pulses with a pulse repetition rate of 1 – 103 kHz), and also in the 1 – 5.5-μm range (an IKS-31 IR spectrometer). Figure 2 shows the shape of the detector photoresponse, which achieved after 40-dB amplification. The FWHM of the photoresponse pulse was 150 ps. Note that, unlike avalanche diodes and photomultipliers, the SSPD photoresponse amplitude does not virtually changes from pulse to pulse and is mainly determined by the detector current. The pulse front jitter is 35 ps and is determined to a great extent by the intrinsic instability of the measuring equipment.

The quantum efficiency η_q was measured at the wavelengths 0.56, 0.67, 0.94, 1.26, and 1.55 μm by using cw lasers. The radiation power coupled into a sample through a multimode fibre was measured with power meters based on silicon (400 – 1060 nm) and InGaAs (800 – 1600 nm) photodiodes. Figure 3 shows the dependences of η_q and the dark count rate R of the detector at a temperature of 2 K on the ratio of its operating I_b and critical I_c currents. Of most practical interest is the region where η_q has maximum values ($0.8 < I_b/I_c < 0.9$). We believe that a 'plateau' observed for the visible light (at 0.56 μm) in this region can be explained by the fact that each absorbed photon causes the detector response. From the point of view of applications, the telecommunication wavelengths 1.3 and 1.55 μm are most interesting. The values of η_q are 30 % and 17% for these wavelengths, respectively. The quantum efficiency at 1.3 μm is very close to its limiting value determined by the absorption coefficient of the film. Note that the 4-nm thick NbN film, from which the detector was made, has the surface resistance of about 400 Ω cm^{-2}. Because this value is close to the wave resistance of vacuum, the film has a very low reflection coefficient and high absorption achieving 30 % – 40 %.

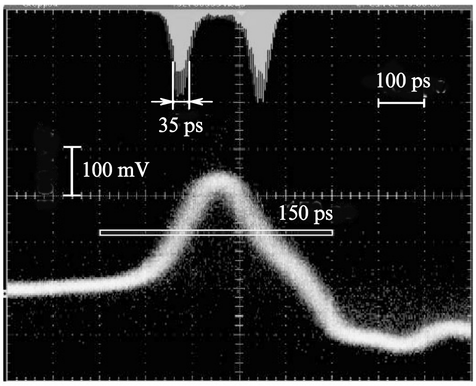

Figure 2. Detector photoresponse. The pulse FWHM is ~ 150 ps. The histogram in the upper part of the figure is the jitter of Δt of the pulse front.

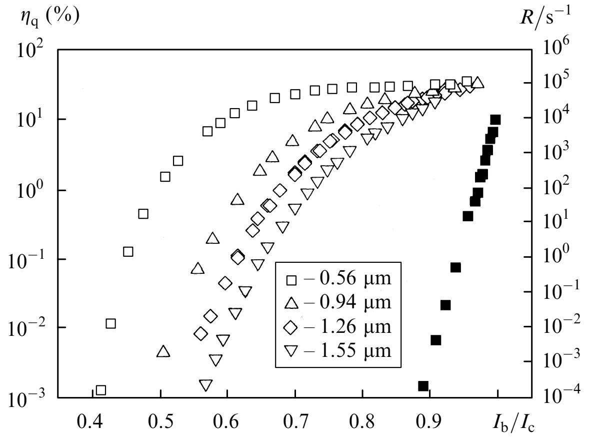

Figure 3. Dependences of the quantum efficiency η_q (light triangles and squares) and the dark count rate R (dark squares) on the detector current at 2 K.

The dependence of the dark count rate R on the normalised detector current I_b/I_c is exponential in the range $0.87 < I_b/I_c < 0.99$ studied in the paper. The exponential dependence $R(I_b)$ is observed within seven orders of magnitude in R. The minimum measured value of R was 2×10^{-4} s^{-1} at $I_b/I_c = 0.89$ and was limited by the measurement time: to accumulate several counts, eight hours were required. Note that the combination of such a low value of R and η_q exceeding 10 % at the telecommunication wavelengths at 2 K provides the equivalent noise power as low as 1.5×10^{-20} W Hz$^{-1/2}$. In this case, even a small decrease in I_b/I_c, for example, down to 0.874 allows the reduction of the equivalent noise power down to 5×10^{-21} W Hz$^{-1/2}$. Although to confirm this experimentally, a long time is required for measuring the dark count rate, this can be fulfilled by using the available equipment.

We studied the spectral sensitivity of the SSPD in the range from 1.2 to 5.6 μm at 3 K. For the current $\sim 0.9 I_c$, the SSPD is sensitive in a broad IR range. The single-photon detection regime was observed over the entire spectral range at least up to 5.6 μm, which makes our detector in fact the only quantum detector operating in the mid-IR range (Fig. 4).

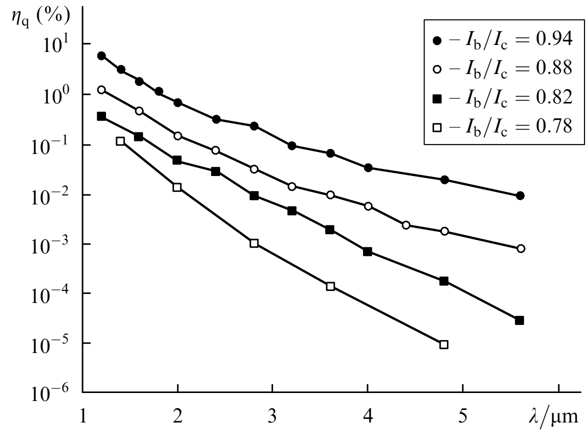

Figure 4. Spectral sensitivity of the detector measured for different currents at 3 K.

Note in conclusion that the SSPD has already found practical application in the contactless method for VLSIC testing [4] and also appears promising for the use in a number of other fields such as the study of fluorescence of single molecules, investigation of quantum-dot emitters, and in quantum computers. Of special interest is the application of a superconducting single-photon detector in communication systems (both fibreoptic and operating in a free space) for the transmission of a quantum-cryptographic key.

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