Spectral Sensitivity of the NbN Single-Photon Superconducting Detector

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SUMMARY We report our studies on the spectral sensitivity of superconducting NbN thin-film single-photon detectors (SPD's) capable of GHz counting rates of visible and near-infrared photons. In particular, it has been shown that a NbN SPD is sensitive to 1.55-µm wavelength radiation and can be used for quantum communication. Our SPD's exhibit experimentally measured intrinsic quantum efficiencies from 20% at 800 nm up to ~1% at 1.55-µm wavelength. The devices demonstrate picosecond response time (< 100 ps, limited by our readout system) and negligibly low dark counts. Spectral dependencies of photon counting of continuous-wave, 0.4-µm and 1.33-µm, and 1.55-µm laser-pulsed radiations are presented for the single-stripe-type and meander-type devices. Key words: single-photon optical detector, quantum efficiency, infrared radiation, NbN superconducting thin film, quantum communication, spectral sensitivity

1. Introduction

Single-photon detectors (SPD's) represent the ultimate sensitivity limit for any radiation-type detectors. At present the main problem is the development of SPD's for infrared (IR) wavelengths. The 1.55-µm wavelength is the most important because of fiber-optic telecommunications needs. Efficient detection of single IR photons remains the major technological challenge since these photons carry significantly less energy than those of visible light, making it difficult to engineer a substantial electron cascade. The existing commercial silicon avalanche photodiodes [1] have a spectral sensitivity limited to below ~1-µm wavelength, restricted by the Si bandgap, while photodiodes based on narrow-gap semiconductors exhibit unacceptably large dark counts [2].

Superconducting devices are the natural choice for fast and ultrasensitive radiation detection because of their quantum nature and low-noise cryogenic operation environment. The typical superconducting energy gap 2Δ (Cooper-pair pairing energy) is two to three orders of magnitude smaller than in a semiconductor; thus, the photon absorption in a superconducting detector creates a very large number of excited quasiparticles (broken Cooper pairs). We have recently demonstrated that a single 790-nm photon generates an avalanche of above 300 quasiparticles in an NbN film [3]. Superconducting detectors should be sensitive well into the IR range. In addition, energy relaxation time constants of quasiparticles in superconductors are in the picosecond time range for both the low-temperature [4] and high-temperature [5] superconductors, assuring gigahertz repetition rates for superconducting SPD's.

Recently, we proposed a superconducting SPD based on ultrathin, submicron-width NbN thin film [6]. This type of device can be qualified as a new type of superconducting hot-electron photodetector. The detection mechanism is based on supercurrent-assisted hotspot formation of a resistive barrier across a very narrow superconducting stripe, kept at a temperature well below the material's superconducting transition Tc. The physics of operation of an NbN SPD has been described in detail in Refs. [6] and [7]. Here, we concentrate on the spectral sensitivity measurements of the NbN SPD devices, manufactured as short, single stripes and long, meander-type structures. Special emphasis is placed on the detection of 1.55-µm photons because of the significance of this wavelength for communications.

2. Device Fabrication and Geometry

We use nominally 0.2-µm-wide strips, patterned by electron-beam lithography from 10-nm-thick NbN films, deposited on a sapphire substrate by reactive dc magnetron sputtering in an Ar + N2 gas mixture [8]. The studied devices were either 1-µm-long microbridges, or meander-type structures, covering 4-µm by 4-µm or 10-µm by 10-µm active areas. A scanning electron microscope (SEM) image of a 10 × 10-µm2 device is presented in Fig. 1.

3. Experimental Setup

Our experimental setup is very similar to one we used earlier [6]. The NbN SPD was mounted on a cold...
plate ($T = 4.2\, \text{K}$) inside an optical, liquid-helium cryostat. We used cold glass filters to block the room-temperature background radiation from falling onto the sample. The sample was dc biased in a constant voltage regime and mounted on a semirigid coplanar transmission line, connected to a cryogenic, low-noise amplifier coupled with a cryogenic isolator and characterized by 30-dB gain and 1- to 2-GHz bandwidth. Outside the cryostat, the signal passed through a second broadband power amplifier (9 GHz bandwidth; 20-dB gain) before going to a 12-GHz-bandwidth single-shot oscilloscope for display and/or to a 200-MHz, variable-voltage-level threshold counter for real-time event counting and statistical analysis.

Photon sources were either 100-fs-wide pulses with an 82-MHz repetition rate at 1.55-µm wavelength from a self-mode-locked titanium-sapphire laser, coupled with an optical parameter oscillator, or 40-ps-wide pulses with 1-MHz repetition rate from Hamamatsu pulse laser diodes, operating at 0.63-µm, 1.33-µm, and 1.55-µm wavelengths. The intensity of our optical pulses was attenuated using banks of neutral-density filters. In addition to pulsed-laser experiments, the wavelength dependency of SPD’s detection efficiency (DE) was measured using a grating spectrometer and a cw blackbody radiation source.

4. Experimental Results and Discussion

The current-voltage ($I$-$V$) characteristics of an NbN microbridge, operated at 4.2 K, is shown in Fig. 2. The $I$-$V$ curve is slightly hysteretic and is typical for a long, superconducting constriction [9]. We see that the device critical current $I_c$ is approximately 48 µA, while the normal-state resistance is equal to $\sim 1\, \text{k}\Omega$. The broken line is the 50-Ω load line that corresponds to the device switching process between the zero-voltage state (point A) and the metastable region (point B). We note that point B cannot be accessed under dc operating conditions when the device is biased below its $I_c$ and no light is incident upon the microbridge. Photon absorption leads to a transition from A to B, and as a result, a voltage signal can be observed at the device terminals with the amplitude corresponding to the voltage level at point B. The signal duration depends on the dynamics of formation and subsequent healing of the resistive hotspot induced by the photon absorption [7]. A hysteretic feature in the $I$-$V$ curve sets the highest possible bias current and, thus, the sensitivity limit of our device.

True single-photon counting requires that the photon detection probability is a linear function of the number of photons incident on the device area [6]. Figure 3 shows the probability of a 1-µm $\times$ 0.2-µm detector producing output voltage transients as a function of the average number of 1.55-µm photons per pulse, incident on the device. The counting probability dependence is very similar to one presented in Ref. [6].
for 0.81-µm-wavelength radiation. The vertical axis in Fig. 3 corresponds to the number of detector counts per second (equivalently, per $82 \times 10^6$ laser pulses), based on the average number of counts detected by SPD over a 60-s counting period. At extremely low photon doses, our experimental data points leveled off at $\sim 1$ count/s, which can be interpreted as the laboratory photon background radiation level. The intrinsic dark count rate (when the optical input was completely blocked) of our SPD was below 0.001 count/s and was limited by the device thermal fluctuations at 4.2 K and the long-term stability of the bias source.

In Fig. 4, we present a counting rate versus the bias current dependence for three different photons energies, for the same device as in Fig. 2. We note that in each case the counting rate, when the device is biased very close to $I_c$ (above 0.93 $I_c$ at 0.63-µm wavelength and above 0.95 $I_c$ at 1.33-µm and 1.55-µm wavelengths), follows the exponential law (dashed fitting lines in Fig. 4). In this region, the device is biased in the hysteretic $I$-$V$ curve, between low and high critical currents (Fig. 2) and the counts are not due to photon absorption, but due to random switching between the zero-voltage and resistive parts of the $I$-$V$ characteristics. Actually, the low value of the hysteretic $I_c$ in Fig. 2 sets the highest stable bias current when our device operates as the photon counter. Unfortunately, hysteretic features vary from device to device, and highest possible bias has to be established for each device independently.

The counting rate versus bias current dependence for a meander-type device with $4 \times 4$-µm$^2$ active area at different wavelengths is presented in Fig. 5. The meander-type devices have consistently less-pronounced $I$-$V$ hysteretic features, and the maximal bias current is above 0.97 $I_c$ independent of the photon wavelength. Just below 0.97 $I_c$ bias, the counting exhibits saturation-like behavior, when DE is maximal and the device operation is stable. As can be seen in Fig. 5, the maximum counting rate at this optimal bias level depends on the radiation wavelength.

Spectral dependencies of DE for various meander-type devices are presented in Fig. 6. We stress that while the quantum efficiency (QE) of our SPD’s is defined with respect to the actual device active area, DE is a global parameter referring to the number of photons registered by the detector, normalized to the incident beam size. Figure 6(a) presents DE versus the radiation wavelength, while Fig. 6(b) shows the same experimental DE data, but plotted as a function of the photon energy $h\nu$. As can be seen, the DE dependencies have an activated-type character with $DE \sim \exp(-E_g/h\nu)$, where $E_g$ is the activation energy. The physical origin of such behavior and actual values of activation energies [solid lines in Fig. 6(b)]: $E_g \sim 70$ meV at $h\nu < 0.65$ eV, and $E_g \sim 0.6$ eV at $h\nu > 0.65$ eV, need future clarification. The activation character of DE is clearly universal for all our tested devices. The exponential DE dependence on photon energy results in the DE of SPD at 1.55-µm being $\sim 1.5$ order of magnitude lower, as compared with the 0.81-µm-wavelength results. Nevertheless, the intrinsic QE of our NbN SPD at 1.55-µm wavelength can be estimated as $\sim 1\%$, which is favorably comparable with semiconductor single-photon detectors.

Finally, we want to mention that we performed extensive atomic force microscopy (AFM) image studies of our SPD structures and found that the absolute DE values were directly correlated with the uniformity level of the superconducting strip edges. The devices with higher uniformity demonstrated significantly higher DE, as shown in Fig. 7, where a “good” device (open circles) has DE almost an order of magnitude...
Fig. 6 Spectral dependence of detection efficiency of meander-type devices versus the photon wavelength (a) and energy (b). Closed circles—device 1 (10 × 10 μm², 0.2-μm width); gray triangles—device 2 (4 × 4 μm², 0.2-μm width), open squares—device 3 (4 × 4 μm², 0.1-μm width), T = 4.2 K. Closed triangles—device 1, T = 6.5 K.

Fig. 7 Detection efficiency versus wavelength dependencies for two 10 × 10-μm² devices (both with 0.2-μm width) with different edge uniformity levels (see the text).

larger than the “bad” one (closed circles). Improvements in electron-beam lithography should allow us to produce more uniform devices with maximal DE.

5. Conclusions

We have measured the response of superconducting NbN thin-film SPD’s to cw and pulsed laser radiation. Spectral sensitivity follows the exponential-type dependence, and decreases with the quantum energy decrease. The practical wavelength limit of our current devices is about 3-μm wavelength. At 1.55-μm radiation our detector exhibited a respected ∼1% QE.

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