

Time-resolved characterization of NbN superconducting single-photon optical detectors

J. Zhang,^(a) A. Verevkin,^(a) W. Slysz,^{(a),(b)} G. Chulkova,^(c) A. Korneev,^(c) A. Lipatov,^{(a),(c)} O. Okunev,^(c)G. N. Gol'tsman,^{(a),(c)} and Roman Sobolewski^(a)^(a)*Department of Electrical and Computer Engineering and the Laboratory for Laser Energetics, University of Rochester, Rochester, NY, 14627-0213, USA*^(b)*Institute of Electron Technology, PL-02-668 Warszawa, Poland*^(c)*Department of Physics, Moscow State Pedagogical University, Moscow 119435, Russia*

NbN superconducting single-photon detectors (SSPDs) are very promising devices for their picosecond response time, high intrinsic quantum efficiency, and high signal-to-noise ratio within the radiation wavelength from ultraviolet to near infrared (0.4 μm to 3 μm) [1-3]. The single photon counting property of NbN SSPDs have been investigated thoroughly and a model of hotspot formation has been introduced to explain the physics of the photon-counting mechanism [4-6]. At high incident flux density (many-photon pulses), there are, of course, a large number of hotspots simultaneously formed in the superconducting stripe. If these hotspots overlap with each other across the width w of the stripe, a resistive barrier is formed instantly and a voltage signal can be generated. We assume here that the stripe thickness d is less than the electron diffusion length, so the hotspot region can be considered uniform. On the other hand, when the photon flux is so low that on average only one hotspot is formed across w at a given time, the formation of the resistive barrier will be realized only when the supercurrent at sidewalks surpasses the critical current (j_c) of the superconducting stripe [1]. In the latter situation, the formation of the resistive barrier is associated with the phase-slip center (PSC) development. The effect of PSCs on the suppression of superconductivity in nanowires has been discussed very recently [8, 9] and is the subject of great interest.

In this presentation, we discuss the dynamics of hotspot formation in two-dimensional (ultrathin) superconducting stripes and establish the intrinsic speed of response of our NbN SSPD's to an incident photon flux at very low radiation intensities.

The schematic diagram of our experiment set-up is shown in Fig. 1. The devices used in our experiments are $4 \times 4 \mu\text{m}^2$ or $10 \times 10 \mu\text{m}^2$ meander-structured NbN superconducting stripes with $d = 10 \text{ nm}$ and $w = 200 \text{ nm}$. They have been fabricated by reactive magnetron sputtering in an $Ar + N_2$ gas environment on sapphire substrates and patterned with the electron beam lithography. The superconducting transition temperature T_c of our SSPD's is about 10.5 K and j_c at 4.2 K is about $5 \times 10^6 \text{ A/cm}^2$. The structures are attached to a cold plate kept at 4.2 K and connected to the bias and output circuits through a bias tee.

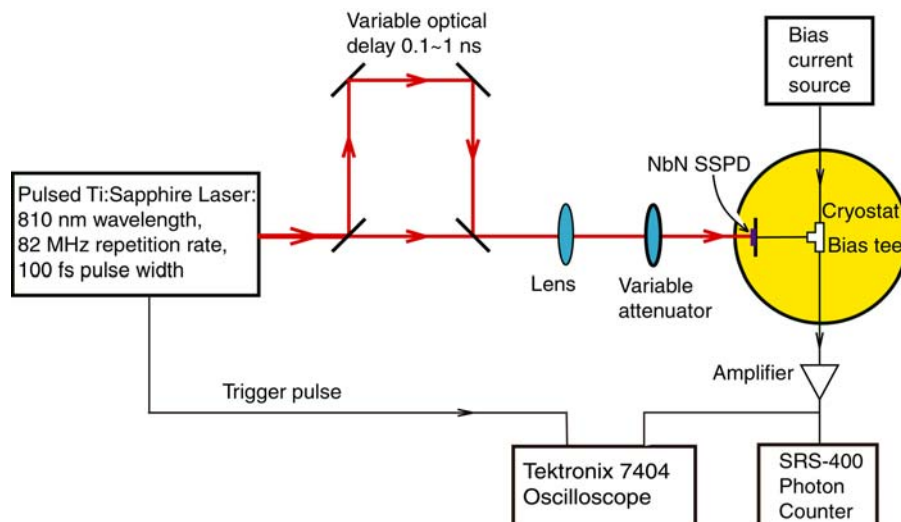


Fig. 1. SSPD experimental photon counting setup with a variable optical delay.

As the radiation source we use a Ti:Sapphire laser, generating 100-fs-wide pulses with the wavelength of 810 nm and the repetition rate of 82 MHz. In order to measure time-resolving capability of the NbN SSPD, we made a setup with adjustable optical delay (see Fig. 1). The laser beam is split into two beams by a 50/50 beam splitter and then one of the beams is first delayed by a delay stage and next merged back into the original beam by the second beam splitter. The minimum amount of delay is about 100 ps. With an adjustable neutral density attenuator after the focus lens, the power of radiation can be attenuated down to the picowatt level. The voltage signal generated by the incident photon flux in the SSPD is amplified by a room-temperature amplifier and then fed to the Tektronix 7404 digital oscilloscope (synchronously triggered by the Ti:Sapphire laser) or counted by a fast SR400 photon counter. The room-temperature amplifier and the oscilloscope have the bandwidth of 0.01-12 GHz and 0-4 GHz, respectively.

With the optical delay setup presented in Fig. 1, we have taken the single-shot measurements of the SSPD output pulses, as is shown in Fig. 2. When the optical delay is 100 ps, the signal recorded by the oscilloscope is wider than the pulse at the zero delay (measured by blocking the delayed beam). Increasing the delay above 100 ps, the signature of the second pulse can be perceived. For comparison, the pulse shapes at the delays of 330 ps, 650 ps, and 1080 ps are shown in subsequent panels in Fig. 2. Thus, our experimental results indicate that the NbN SSPD can resolve incoming photons with the time resolution of about 100 ps.

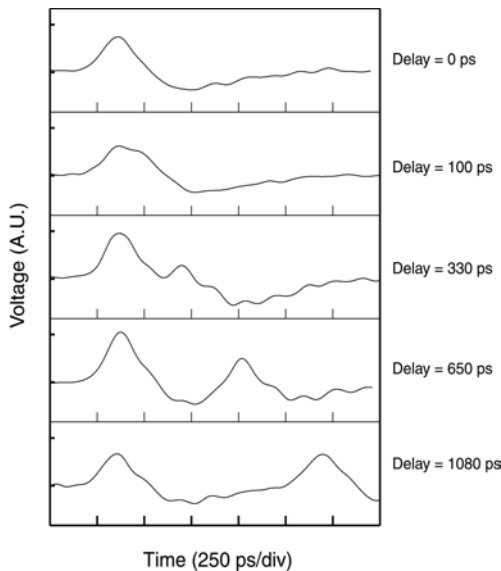


Fig. 2. Response pulse patterns at different optical delays. The signature of the second pulse can be perceived when the delay is ≥ 100 ps

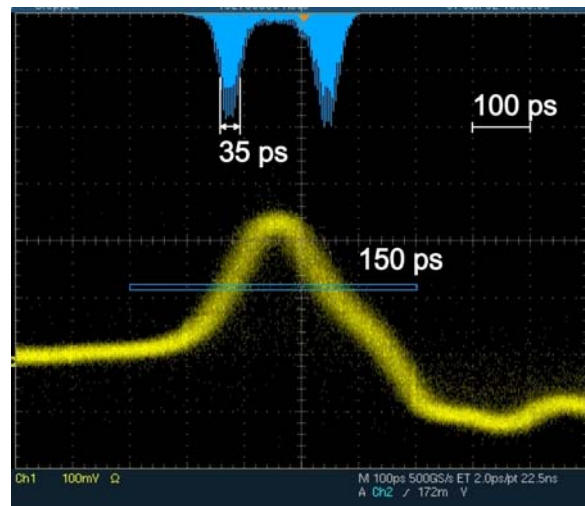


Fig. 3. Jitter of the signal pulse is measured to be about 35 ps. The FWHM of the signal pulse is about 150 ps.

The response time of the SSPD is determined by the dynamics of hotspot formation and relaxation process in the superconducting NbN stripe [4]. The total process includes the photon absorption, breaking of Cooper pairs and multiplication of quasiparticles, formation of the resistive barrier across the stripe within the electron-phonon collision time, and, finally, recovery of superconducting state through escaping of hot phonons into the substrate. Numerically, the total response time of the NbN SSPD is the sum of these temporal periods, which was found to be less than 100 ps for NbN films with the thickness of 3.5 nm [2]. In our measurements, the full-width-at-half-maximum (FWHM) of our signal, presented in Fig. 3, is about 150 ps. We must remember, however, that our devices are 10-nm-thick and in this case, the phonon escape time is significantly longer. In addition, our readout system (e.g., the oscilloscope) has the risetime ~ 100 ps, limiting the measured risetime of our SSPD.

The signal pulse from our NbN SSPD has a very small jitter. When analyzing the pulse shape by the standard histogram method, we have found that the total system jitter is about 35 ps, as is shown in Fig. 3. This value includes not only the SSPD performance, but also the laser system, the output circuit, and the oscilloscope. Thus, the intrinsic device jitter of our NbN SSPD should be significantly less than 35 ps.

In conclusion, we have measured the time-resolving ability of our NbN-based SSPD. The FWHM of the device response pulse is found to be about 150 ps, and the jitter <35 ps. The observed rise time ~100 ps is limited by our read-out system.

This work was supported by the AFOSR grant F49620-01-0463 and by the Schlumberger SS, San Jose, CA.

References:

1. G. N. Gol'tsman, O. Okunev, G. Chulkova, A. Lipatov, A. Semenov, K. Smirnov, B. Voronov, A. Dzardanov, C. Williams, and R. Sobolewski, *Appl. Phys. Lett.* **79**, 705 (2001).
2. K. S. Il'in, M. Lindgren, M. Currie, A. D. Semenov, G. N. Gol'tsman, R. Sobolewski, S. I. Cherednichenko and E. M. Gershenson, *Appl. Phys. Lett.* **76**, 2752 (2000).
3. A. Verevkin, J. Zhang, R. Sobolewski, G. Chulkova, A. Korneev, A. Lipatov, O. Okunev, A. Semenov, and G. N. Gol'tsman, *Appl. Phys. Lett.* (Submitted).
4. A. D. Semenov, G. N. Gol'tsman, A. A. Korneev, *Pysica C* **351**, 349 (2001).
5. A. M. Kadin and M. W. Johnson, *Appl. Phys. Lett.* **69**, 3938 (1996).
6. A. D. Semenov, R. S. Nebosis, Y. P. Gousev, M. A. Heusinger and K. F. Renk, *Phys. Rev. B* **52**, 581 (1995).
7. Michael Tinkham, *Introduction to superconductivity, second edition*, McGraw-Hill, Inc. (1996)
8. A. Bezryadin, C. N. Lau, and M. Tinkham, *Nature* **404**, 971 (2000).
9. C. N. Lau, N. Markovic, M. Bockrath, A. Bezryadin and M. Tinkham, *Phys. Rev. Lett.* **87**, 217003 (2001).