Superconducting Single-Photon Detectors for GHz-Rate Free-Space Quantum Communications

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ABSTRACT

We report our studies on the performance of new NbN ultrathin-film superconducting single-photon detectors (SSPDs). Our SSPDs exhibit experimentally measured quantum efficiencies from ~ 5% at wavelength $\lambda = 1550$ nm up to ~10% at $\lambda = 405$ nm, with exponential, activation-energy-type spectral sensitivity dependence in the 0.4-$\mu$m – 3-$\mu$m wavelength range. Using a variable optical delay setup, we have shown that our NbN SSPDs can resolve optical photons with a counting rate up to 10 GHz, presently limited by the read-out electronics. The measured device jitter was below 35 ps under optimum biasing conditions. The extremely high photon counting rate, together with relatively high (especially for $\lambda > 1$ $\mu$m) quantum efficiency, low jitter, and very low dark counts, make NbN SSPDs very promising for free-space communications and quantum cryptography.

Keywords: single-photon detector, thin-film superconductivity, quantum cryptography, ultrafast communications.

1. INTRODUCTION

Optical free-space communications has been recognized in recent years as a high-performance alternative to microwave-based systems 1. Optical power can be collimated in a form of a tight beam even from small apertures, with the beam divergence only limited by diffraction. Most importantly, optical system is a communication channel with extremely large information capacity. Optical communications is very promising for satellite-Earth links 2, due to relatively low total atmospheric distortion in visible and near-infrared (IR) ranges. Even more attractive is communications within a satellite network in space, due to the total absence of atmospheric absorption.

The need for secure communications grows very rapidly in modern world and presently optical quantum cryptography (QC) appears to be the key technology for practical implementations 3. Unbreakable QC is possible in actual physical environments due to the Heisenberg indeterminacy principle: it is impossible to measure the state of a quantum bit without altering it. Thus, the communications must be performed as exchange of individual photons and their polarization is used as the quantum bit information for the communication protocol. A recent theoretical paper by Gilbert and Hamrick 4 proved that unconditionally secret, high-speed QC based on real-time Vernam encryption (one-time pad) is practical, providing that the data transmission rate is high enough to overcome the intrinsic system losses. The one-time pad cryptosystem ensures (in a form of a rigorous mathematical proof) that without a copy of the original Vernam cipher key, there is no method available to extract the plaintext. QC provides a radical improvement over today methods for secure communications. The exchange of the quantum
key using the Vernam cipher method and the subsequent secure encryption and single-photon communication of the ciphertext are invulnerable to any computer attack of any strength, including quantum computations. Even a simplified version of QC, based on secure, quantum key distribution (QKD), followed by conventional encryption and transmission of the ciphertext is virtually unbreakable, assuming realistic, physical abilities of the intruder (Eve).

The essential practical requirement, in order to incorporate QC in modern telecommunication systems, is that both the transmitter (Alice) and the receiver (Bob) must operate at transmission rates of at least 10 Gbit/s in the full Vernam cipher encryption or at at least 1 Gbit/s in for the QKD operation. An actively mode-locked laser can be used as the high-speed source of coherent single photons, so Alice can readily operate at the GHz rate. A serious problem, however, exists at the Bob (receiving) end, which should demonstrate not only a very efficient detection of photons, but the one with negligible dark counts and very low jitter. Thus, the overall success of any practical QC project hangs on the availability of GHz-speed, high quantum efficiency (QE), single photon counting devices.

Semiconductor avalanche photodetectors (APDs) and photo-multiplier tubes (PMTs) are presently commonly used in QC communication experiments. Unfortunately, both devices have serious limitations. The APDs and PMTs cannot work at counting rates above 100 MHz and their practical speed is even more limited. For noise reduction purposes, they have to be used in a time-gated mode, what reduces their counting rates to 10 MHz and below. APDs and especially GaAs IR APDs are characterized by very large dark counts. The most effective way to decrease fluctuations is to decrease the device physical temperature. However, semiconductor single-photon detectors become impractical at liquid helium temperatures, because their response times become extremely long.

Superconducting devices have already become practical optical and IR sensors. Their energy gap between the superconducting state and the first excited-electron state is typically only a few meV (compared to a bandgap on the order of 1 eV in semiconductors); thus, individual optical photons are able to generate a large number of excited carriers, when hitting a superconducting detector. Measuring the resulting electrical pulse, allows a precise detection of the photon arrival. The most advanced type of superconducting single-photon detectors are superconducting tunnel junctions (STJs). The STJs can operate from x-ray to far-IR, however, their ultimate counting rate is \~10^7 photons per second, what is definitely not sufficient for practical QC needs.

The NbN thin-film superconducting single-photon detectors (SSPDs), recently developed by us, seem to be the most promising for QC applications. The devices are characterized by picosecond response times, sufficiently high QE, and single photon sensitivity from ultraviolet to near-IR ranges. The NbN-based SSPDs operate in a cryogenic environment and are able to reach GHz range counting rates and negligibly low dark counts. Especially in their IR operation, the NbN SSPDs significantly outperform any modern commercial APDs or PMTs. The physics of operation of NbN SSPDs is based on a hotspot formation process in an ultrathin, sub-micrometer-wide superconducting stripe and it has been confirmed in our latest studies devoted to the SSPD spectral sensitivity and the photon capture time experiments.

In this presentation, we review our most recent results on the performance of NbN SSPDs. In the next Section, we briefly present the detector fabrication process and our experimental setup. Section 3 is devoted to our experimental results with special emphasis on the SSPD detection efficiency (DE) spectral sensitivity and time resolution characteristics, namely, the detector risetime, response width, and jitter, as they are the most important in optical communication applications. In Sec. 3, we also give the performance comparison between the SSPD and the other state-of-the-art single-photon detectors. Finally, conclusions are presented in Sec. 4. We demonstrate that the latest generation of ultrathin, meander-type NbN SSPDs should be regarded as the devices-of-choice for practical QC and free-space optical communications.

### 2. EXPERIMENTAL PROCEDURES

#### 2.1. SSPD fabrication

The detectors used in our experiments were meander-structured NbN superconducting stripes with the thickness of \( d = 10 \text{ nm} \) and 3.5 nm, and the width \( w = 200 \text{ nm} \) or below. The superconducting transition temperature \( T_c \) of our devices was 10.5 K and \~10 K for the 10-nm and for 3.5-nm-thick stripes, respectively, with the critical current density \( j_c \) at 4.2 K always above \( 5 \times 10^6 \text{ A/cm}^2 \). The ultrathin NbN films were deposited on double-side-polished, optical-quality sapphire substrates by reactive dc magnetron sputtering in the Ar + N\(_2\) gas mixture. Using double-polished substrates allowed us to use our devices both in...
the reflection and the through-substrate transmission modes. The sputtering process parameters, leading to the best superconducting properties of our films were: Ar partial pressure $5 \times 10^{-3}$ mbar, $N_2$ partial pressure $9 \times 10^{-5}$ mbar, the discharge current 300 mA, the discharge voltage 300 V, and the substrate temperature 850$^\circ$C. The films were patterned by the e-beam lithography and ion milling into meander-type structures, occupying either 10-µm × 10-µm or 4-µm × 4-µm areas. A special supplementary Ti mask had to be created on the NbN surface, in order to protect NbN during the meander milling process. This Ti mask was removed in the final step, by chemical etching in diluted hydrofluoric acid. A scanning electron microscope (SEM) image of a 4-µm × 4-µm SSPD with external Ti-Au contact pads is shown in Fig.1.

Fig. 1. SEM image of a meander-structured, 4-µm × 4-µm SSPD, fabricated from a 3.5-nm-thick NbN film. The average stripe width $w = 210$ nm. The micrograph also shows large Ti-Au contact pads, patterned by the lift-off process.

Figure 2 shows typical $I$–$V$ characteristics of a 10-nm-thick meander-type SSPD, measured at 4.2 K. We observe a small hysteresis, which defines the superconducting fluctuation range and limits how close to the critical current $I_c$ one can bias the device. Thus, for our single-photon counting experiments, the SSPD is dc biased just below the hysteresis, e.g., at point A on the $I$–$V$ superconducting branch. After absorption of a photon, the resistive barrier across the width of the NbN stripe appears and detector is switched along the 50-Ω load line from the superconducting state (point A in Fig. 2) to a meta-stable resistive state (point B in Fig. 2) with a generation of a voltage signal.

Fig. 2. The $I$–$V$ curve of a 10-nm-thick, 4 × 4-µm$^2$-area NbN detector at 4.2 K.

2.2. Experimental setup

A schematic diagram of our experimental setup is shown in Fig. 3. The NbN SSPD was wire-bonded to a microstrip transmission line and connected to the dc bias and rf output circuitry through a broadband, cryogenic bias tee. The whole
SSPD arrangement was placed on a cold plate inside a liquid-helium cryostat and maintained at 4.2 K. Photon sources were either 100-fs-wide pulses with a 82-MHz repetition rate at 405-nm, 810-nm, and 1.55-µm wavelengths from a self-mode-locked Ti-sapphire laser, coupled with an optical parametric oscillator, or cw laser diodes. The intensity of the incident radiation was attenuated using banks of neutral density filters. In addition, the wavelength dependence of SSPD’s DE was measured using a grating spectrometer and a cw blackbody radiation source.

In order to measure time-resolving capabilities of our NbN SSPDs, we included an adjustable optical delay stage in our experimental set up (Fig. 3). The laser beam was split into two optical paths with one of the beams sent through a delay stage and then merged back into the original beam by a second beam splitter. The minimum amount of the delay was 100 ps. The voltage signal generated as a result of the photon capture in the SSPD was transmitted outside the cryostat via a semirigid coaxial cable, amplified by a room-temperature broadband amplifier, and, finally, fed into either the Tektronix 7404 single-shot digital oscilloscope (synchronously triggered by the Ti:Sapphire laser) or counted by the SR400 photon counter. The room-temperature amplifier and the oscilloscope were characterized by the bandwidth of 0.01-12 GHz and 0-4 GHz, respectively. It should be emphasized that typical amplitude of the electrical pulse from generated detector was about 2 mV (see point B voltage value in Fig.2), which made our detector practically insensitive to external noise sources.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

3.1. Spectral sensitivity

The DE spectral dependencies of the four (two 3.5-nm-thick and two 10-nm-thick, meander-type SSPDs, tested in the wavelength range from 0.4 µm to 3.0 µm are presented in Fig. 4. In all cases, the DE exhibited an activated-type character with DE ~ \( \exp(-E_g/h\nu) \), where \( E_g \) is the activation energy. The activation character of DE and the \( E_g \) value behave similarly for all the tested devices with the same thickness[11] and are associated with the presence of fluctuations, both extrinsic (stripe
width) and intrinsic (superconducting). Figure 4 shows, however, that the new 3.5-nm-thick devices show a significantly smaller $E_g$ value and much higher DE, making them much more effective in photon counting, as compared to our old, 10-nm-thick structures.

We need to stress that the DE dependence presented in Fig. 4 is an experimentally measured quantity, corresponding to the actual probability of photon capture by our devices. By contrast to any APD or PMT, the working area of our detectors is always smaller and often much smaller that the incident photon beam size. In addition, the metallic stripe in the meander structure (see Fig.1) covers less than 50% of the nominal detector area. Thus, for, e.g., comparison with semiconductor devices, the actual active area of our devices must be taken into account and in calculating the intrinsic QE. In other words, DE must be normalized to the SSPD active area, i.e., divided by the ratio of the SSPD active area to the incident beam size.

Our best 10-nm-thick SSPDs (open triangles in Fig. 4) exhibit DE ranging from ~3% at $\lambda = 405$ nm to ~ 0.01% at $\lambda = 1550$ nm wavelength, what corresponds to QE ranging from ~70% to 0.2% [11]. At the same time, the latest 3.5-nm devices show DE over an order of magnitude higher, from >10% at $\lambda = 405$ nm to 3.5% at $\lambda = 1550$ nm. In case of the 3.5-nm devices, the calculated intrinsic QE reaches the theoretical maximum of 100% at all wavelengths below 1.2 µm.

![Graph](image.png)

Fig. 4. Spectral dependences of DE for three $10 \times 10 \mu m^2$ SSPDs with the film thickness of 10 nm (triangles and open squares) and 3.5 nm (closed squares).

### 3.2. Time resolution and jitter

With the variable time delay setup shown in Fig. 3 and the Tektronix 7404 oscilloscope, we have recorded the single-shot transients of our SSPD responses. The results are shown in Fig. 5. The signals (Fig. 5(a-e)) had a width of ~150 ps and a risetime of ~100 ps, both limited, as we mentioned earlier, by our read-out electronics. When the optical delay was adjusted to be 100 ps (Fig. 5(b)), the recorded pulse shape had an increased width and the evidence of the second, time-delayed pulse could be detected (see arrows). Clearly, the SSPD was able to independently record two photons arriving through the separate arms of the delay setup. The detection of two independent photons was completely evident in Figs. 5(c), 5(d), and 5(e), where the delay between the pulses was set to 330 ps, 650 ps, and 1080 ps, respectively. Since the superconducting state had to be recovered between the responses, for the detector to be able to respond to the second photon, Fig. 5 demonstrates that our devices time resolution is below 100 ps. Correspondingly, they should be able to detect photons with at least 10-Gbit/s counting rate.
Finally, we analyzed the signal jitter for our NbN SSPDs. The results are shown in Fig. 6, where we overlay recordings of many single-photon responses and simultaneously show their histogram analysis (Tektronix 7404 feature). We note from the histogram (top of Fig. 6) that the jitter is 35 ps. This value is the total jitter of our system and includes, besides the SSPD, the jitter from our output circuits, as well as the limited oscilloscope response; thus, the intrinsic SSPD jitter is expected to be much smaller.

3.3. Comparison of available single-photon detectors and NbN SSPD

In the Table I, we present the main characteristics of our SSPDs, in comparison with other modern single-photon detectors, such as semiconductor APDs, PMTs, and STJs. We compare DE (for APDs and PMTs DE defined by us is identical with standard QE), ultimate counting rate, jitter, and dark counting rates. The comparison is done for the 1.3-µm photons, which the very interesting wavelength for many applications, ranging from noninvasive VLSI chip testing to QC and optical communications.
TABLE I. Comparison of performance of different single-photon detectors, operating at $\lambda = 1.3$-µm.

<table>
<thead>
<tr>
<th>Detector Model</th>
<th>Counting rate (s$^{-1}$)</th>
<th>DE (%)</th>
<th>Jitter (ps)</th>
<th>Dark counts (s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FPD5W1KS InGaAs APD (Fujitsu) [17]</td>
<td>$5.0 \times 10^6$*</td>
<td>16</td>
<td>200</td>
<td>$500^{**}$</td>
</tr>
<tr>
<td>R5509-42 STOP PMT (Hamamatsu ) [18]</td>
<td>$9.0 \times 10^6$ [19]</td>
<td>0.1</td>
<td>150 [11]</td>
<td>$2.0 \times 10^4$ [18]</td>
</tr>
<tr>
<td>Si APD SPCM –AQR-16 (EG&amp;G) [20]</td>
<td>$5.0 \times 10^6$</td>
<td>0.01</td>
<td>350</td>
<td>25</td>
</tr>
<tr>
<td>Mepsicron II PMT (Quantar Tech.Inc) [21]</td>
<td>$1.0 \times 10^6^{***}$</td>
<td>0.001</td>
<td>100</td>
<td>0.1 [11]</td>
</tr>
<tr>
<td>STJ [7]</td>
<td>$5.0 \times 10^3$</td>
<td>60</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>SSPD (measured)</td>
<td>$10 \times 10^9$</td>
<td>5</td>
<td>35</td>
<td>&lt;1</td>
</tr>
<tr>
<td>SSPD (expected)</td>
<td>$30 \times 10^9$</td>
<td>&gt;10</td>
<td>20</td>
<td>&lt;0.01</td>
</tr>
</tbody>
</table>

*Gated regime with 0.1% per gate after-count probability.
** Calculated with $10^{-4}$ per gate probability.
***Data for a high-speed version; standard devices exhibit $1 \times 10^5$ s$^{-1}$.

As we can see from Table I, modern semiconductor single-photon detectors are not best suited for practical QC and 1.3-µm-based communications, because of their high dark counting rates and relatively low frequency of operation. Further, semiconductor single-photon devices have to operate in a gated regime, which additionally slows down their operation. In IR, even the best PMTs are characterized by a very low QE, what, together with their low counting speeds and bulky designs, makes them not applicable for communication applications. In the above context, only our SSPDs have the desired characteristics, such as very high (GHz) speed and low dark counts. Our recent advancement in fabrication, resulting in ultrathin devices, has further (significantly) increased their DE values, making SSPDs, in our opinion, the most prospective class of single-photon detectors for practical QC and optical free-space communications.

4. CONCLUSIONS

We demonstrated that developed by us SSPDs are applicable for practical QC and free-space optical communication systems. Our best 3.5-nm-thick, $10 \times 10^{-1} \mu m^2$-area NbN SSPDs reached the ultimate, 100% QE in the entire visible range of wavelengths and >35% in near IR. The superconducting detectors significantly outperform even the best semiconductor APDs and PMTs, especially at 1.3 µm and 1.55 µm, the most important fiber-communication wavelengths. The experimental time-resolved measurements have shown that our NbN devices can resolve photon trains with optical delays of less than 100 ps. Finally, the measured intrinsic jitter of our detectors was below 35 ps, making them very promising for ultrafast applications. The time resolution and jitter results show that NbN SSPDs have capability of reaching 10-GHz counting rates.

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