Developing of NbN films for superconducting microstrip single-photon detector

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Abstract. We optimized NbN films on a Si substrate with a buffer SiO₂ layer to produce superconducting microstrip single-photon detectors with saturated dependence of quantum efficiency (QE) versus normalized bias current. We varied thickness of films and observed the maximum QE saturation for device based on the thinner film with the lowest ratio $R_s^{200}/R_s^{20}$.

1. Introduction
In Reference [1] the first time new type of superconducting single-photon detector, SSPD, was demonstrated. It is operation is based on the appearance of the resistive area in the superconducting nanostrip with the near-critical current after photon absorption. Typically, SSPD is fabricated as a strip about 100 nm wide patterned as a meander, covering the aria about 150 μm² for efficient coupling with single-mode fiber. By now, SSPD has been used in many science applications: quantum cryptography, non-invasive semiconductor integrated circuits debug, quantum computing, study of single-photon sources, polarization-dependent fluorescence correlation spectroscopy. The further expansion of SSPD applications requires an increase of the detector sensitive area to the value comparable with the size of multimode fiber core. But increase of nanowire length leads to increase of kinetic inductance and as a consequence, to reduction of count rate, increase of jitter and significant technology process complication. Reference [2] theoretically predicted the ability to detect single photon by wide (up to 100 μm) superconducting strip in the case when the current is sufficiently close to the depairing current ($I_{dep}$). In [3] the first single-photon detection by micrometer-scale NbN bridges (0.53μm to 5.15μm) was demonstrated. Now the fabrication of superconducting microstrip single photon detector (SMSPD) with large work area, high count rate, low jitter is feasible. The goal of this work is the investigation of film characteristics to produce SMSPD with saturated dependence of QE versus bias current. QE saturation means 100% internal quantum efficiency, when every absorbed photon is converted by the detector to voltage pulse.

2. Methods and experimental results
To choose the best film for SMSPD we produced a set of NbN films with different thicknesses from 3.5 nm to 7.3 nm. For all films we used Si substrate with an additional 250 nm SiO₂ layer as λ/4 optical cavity. The cavity is optimized to increase absorption in thin NbN film at 1550 nm wavelength. The calculated absorption spectrum of NbN film integrated in such kind of cavity is presented in figure 1 (b). For simulation we used thickness of NbN $h$=5 nm and refractive index of NbN $n^2=2.6996$. It should be noted that variation of NbN thickness leads to changes in absorption spectrum. But in our...
work we can neglect this change because the thicknesses studied here are not far from \( h=5 \) nm (change of absorption coefficient is less than 2%).

The NbN films were deposited by DC reactive magnetron sputtering of Nb target in nitrogen atmosphere. The partial pressure of \( N_2 \) and the temperature of substrate were constant in all processes. We changed the deposition time to produce films with thicknesses \( h \) ranging from 3.5 nm to 7.3 nm. We estimate thickness value by multiplying deposition rate by the time of deposition. The film sheet resistance \( R_s^{300} \) is measured by the van der Pauw method at \( T=300 \) K.

In order to obtain superconducting transition temperature \( (T_c) \) and residual-resistance ratio \( \text{RRR}=R_s^{300}/R_s^{20} \) we measured the temperature dependences of sheet resistance \( R_s(T) \) for each film (figure 2(a)). The obtained dependencies of \( R(T) \) is similar to conductivity behavior of the quasi-two-dimensional disordered metallic films \([4, 5]\). Lower \( \text{RRR} \) corresponds to more disordered metallic films. The increase of the film resistance with decreasing temperature can be explained by addition of the quantum corrections to the surface conductivity of the film in accordance with the Drude theory \([6-9]\). Critical temperature \( T_c \) is determined as temperature at which the resistance is equal to the half of \( R_s^{20} \). The main parameters of the films are summarized in Table 1.

**Table 1.** Main parameters of studied films.

| ID  | \( h \), nm | \( R_s^{300} \), \( \Omega/\square \) | \( \text{RRR} \) | \( T_c \), K |
|-----|-------------|-------------------------------|-------------|-------------|
| 2314 | 7.3         | 407                           | 0.72        | 9.88        |
| 2362 | 6.4         | 614                           | 0.67        | 9.15        |
| 2347 | 5.4         | 753                           | 0.59        | 8.01        |
| 2316 | 3.5         | 1027                          | 0.61        | 6.85        |

For each film we fabricated the set of 1-μm-wide and 10-μm-long straight strips. We used our standard technology based on electron beam lithography and reactive ion etching \([3]\). The SEM image of studied strip is shown in figure 1(a). We rounded both ends of the strip to avoid current-crowding effects at the sharp strip ends which can lead to an undesirable reduction of the critical current \( (I_c) \).

For all strips we define critical current at \( T=4.2 \) K from \( I-V \) curves. For each film we chose one strip with the biggest \( I_c \) and measured its QE at temperature \( T=1.7 \) K. The strip was mounted in dipstick placed inside a cryoinsert for a liquid He Dewar. Cryoinsert has a capillary that limits the rate of liquid helium penetration. Continuous evacuation of the helium vapor from the cryoinsert allows us to obtain a vapor pressure of 80-120 Pa. Therefore we can have the temperature of liquid He inside the cryoinsert as low as 1.7 K. The temperature is monitored by the carbon thermometer which is installed close to the strip.

Electrical contact is realized through springs and a coaxial cable connected to room temperature bias-T Mini Circuits ZFBT-4R2GW. We use home-made voltage source to bias the bridge. The voltage pulses from the strip are amplified by two room-temperature Mini-Circuits ZFL-1000LN+ (1-GHz band,46-dB total gain) amplifiers, and are fed to a digital oscilloscope and a pulse counter Agilent 53131A (225 MHz band). As kinetic inductance of our strips is small (approximately 1 nH) we should connect a resistor 7 Ω in parallel to the strip to avoid latching effect \([10]\). The shunt is installed in the strip holder close to the strip.
Figure 1. (a) SEM image of a 1-μm-wide and 10-μm-long straight strip. The black areas is the NbN film and the strip, the gray is the areas etched to the substrate, and the blue are the areas of NbN designed to prevent the current-crowding effect; (b) Blue solid line is the calculated absorption spectrum of NbN film (thickness 5 nm) integrated with λ/4 optical cavity. Insert shows the schematic structure of this cavity. Red dots are QE for strip 2347/d23 (thickness of NbN h=5.4 nm) measured at the wavelengths 405 nm, 636 nm, 828 nm, 946 nm, 1064 nm, 1310 nm, 1550 nm.

To illuminate the sample we use light emitting diodes (LED) with wavelengths 405 nm, 636 nm, 828 nm, 946 nm, 1064 nm, 1310 nm and 1550 nm. In our dipstick we use optical fiber SMF28 which is single-mode in range from 1260 nm to 1550 nm. For wavelengths below 1260 nm the fiber SMF28 becomes multimode. To produce uniform illumination of the strip at all wavelengths we mount the fiber ferule in a distance 80 mm from the sample [3]. Due to the small active area of our strips we do not package them with a single mode fiber as usually done with meander SSPDs [11, 12].

It is difficult to measure the number of photons that reach the strip, because we have the distance between the fiber ferule and sample. Therefore we calibrated our dipstick using traditional SSPD integrated in the same kind of optical cavity as our strips. Firstly, QE of SSPD (QE_{SSPD}) is measured in a single-mode fiber setup when SSPD is mounted and accurately aligned right on the pigtail of the fiber. Then we install this SSPD in our dipstick and choose the power of LED (P_{cal}) at which we have 10^6 counts (N_{cal}) at the I_{b} close to I_{c}. The input fiber radiation power (P) at a particular wavelength is measured by calibrated power meter Ophir PD300-IRG-V1. After calibration we can determine QE of any detector by formula:

$$QE = \frac{P \cdot S \cdot N \cdot QE_{SSPD}}{P_{cal} \cdot S_{cal} \cdot N_{cal}}$$

where factor $S/S_{cal}$ accounts for ratio of areas between SSPD used during calibration and the detector under the study, $N$ is the number of photons registered by the detector under the study.

In figure 2(b) we present QE(I_{b}) normalized to its saturated value near $I_{c}$. The presence of the shunt and normal-metal contacts to the strip leads to the redistribution of the current between the strip and the shunt. Thus, the measured current is a bit higher (less than 10%) than the actual current flowing through the strip. To ‘recover’ the actual strip current we always renormalize the measured current by the factor $I/I_{c,sh}$, where $I_{c}$ is the critical current measured without the shunt, and $I_{c,sh}$ is the critical current measured with the shunt. For certainty, in Fig. 2(b) QE(I_{b}) is normalized to QE measured at $I_{b}=0.95I_{c,sh}$. The current is normalized to the depairing current $I_{dep}$. In figure 2(b) there is no data for film 2316, because we did not observe photo response for this film at all. We attribute this fact to high granularity of the film and low ratio of $I_{c}/I_{dep}$.
Analyzing figure 2(b) one can see that the best tendency toward saturation of QE is demonstrated by the thinnest film 2347 with the lowest RRR. We attribute such a behavior to a stronger suppression of superconducting gap by the absorbed photon, and a larger size of the hot-spot – the area where photon energy is redistributed in the electron subsystem of the film suppressing the superconducting gap as well. Compare e.g. with strip 2314/d4 (thickness \( h = 7.3 \) nm) which demonstrates the monotonic growth of QE with increasing current without any tendency toward saturation at all. The absence of a pure plateau region on the QE(\( I_b \)) dependence for our strips we connect with the non-optimal other parameters of film deposition (pressure of \( N_2 \), temperature of the substrate, etc).

For strip 2347/d23 made from the best film we represent the values of QE measured at 10 dark counts per second at different wavelengths in figure 1(b). Experimental values of QE are below calculated spectrum because we did not reach 100% internal quantum efficiency for our strip. The QE at wavelength 1550 nm is significantly lower than the absorption due to the reduction of the SMSPD internal detection efficiency at long wavelengths. The same behavior of QE spectrum was observed for SSPD based on different materials (NbN, \( \alpha \)-MoSi) [13, 14]. The QE at wavelength 1310 nm is equal to 53% and can be increased by multilayer antireflection coating [4].

3. Conclusion
We investigated QE of superconducting micron-wide strips made from NbN films with the thickness 3.5 to 7.3 nm on a Si substrate with a buffer SiO\(_2\). The best tendency toward QE saturation is observed for thinnest film with the lowest residual resistance ratio. For this device the highest QE is equal to 53% at 1310 nm wavelength at 1.7 K.

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References
[1] Goltsman G et al 2001 Appl. Phys. Lett. 79 705
[2] Vodolazov D 2017 Phys. Rev. Applied 7 034014
[3] Korneeva Yu et al 2018 Physical Review Applied 9(6) 064037
[4] Smirnov K et al 2018 Supercond. Sci. Technol. 31 035011
[5] Strongin M et al 1970 Phys. Rev. B 1 1078

Figure 2. (a) The experimental dependence of sheet resistance \( R_s \) on temperature \( T \) for NbN films; (b) Normalized quantum efficiency versus normalized current measured at the wavelength 1064 nm for the bridges 2314/d4, 2362/d6, 2347/d23.
[6] Anderson P 1979 Phys. Rev. Lett. 43 718
[7] Altshuler B et al 1979 Sov. Phys.-JETP 50 968
[8] Altshuler B et al 1980 Phys. Rev. Lett. 44 1288
[9] Altshuler B et al 1983 Zh. Eksp. Teor. Fiz. 84 2280–9
[10] Kerman A et al 2009 Phys. Rev. B 79 100509
[11] Miki S et al 2007 IEEE Trans. on Appl. Supercond. 17 285
[12] Slysz W et al 2006 Appl. Phys. Let. 88 261113
[13] Korneev A et al 2013 IEEE Trans. Appl. Supercond. 23 2201204
[14] Korneeva Yu et al 2014 Supercond. Sci. Technol. 27 095012