Superconducting photon counter for nanophotonics applications

N N Manova¹, Eu O Smirnov¹, Yu P Korneeva¹ A A Korneev¹,2, G N Goltsman¹,2
¹Institute of Physics, Technology, and Information Systems, Moscow State Pedagogical University, Moscow 119991, Russia
²National Research University Higher School of Economics, Moscow 101000, Russia

Abstract. We develop large area superconducting single-photon detector SSPD with a micron-wide strip suitable for free-space coupling or packaging with multi-mode optical fibres. The detector sensitive area is 20 μm in diameter. In near infrared (1330 nm wavelength) our SSPD exhibits above 30% detection efficiency with low dark counts and 45 ps timing jitter.

1. Introduction

One of the prospective detectors for nanophotonics and quantum optics is superconducting single-photon detector SSPD which is typically made of highly-disordered superconducting films of such materials as NbN, NbTiN, WSi, MoSi. These detectors became a device of choice in many optical applications ranging from non-invasive semiconductor integrated circuits debug to the study of single-photon sources, as well as quantum computing and quantum cryptography [1].

SSPDs are made from 3-to-5-nm-thick superconducting film in a shape of a strip, and are operated at a temperature which is well below the critical temperature but with the current close to the critical current of the strip $I_c$. For a long time the operation of the detector was explained by a 'geometrical' models [2] which predicted that for improved photon detection efficiency the strip should be comparable with the normal hot-spot produced by the absorbed photon, and this width is always smaller than 100 nm. For practical applications SSPDs are made as a meandering strip covering an area of about 100 μm² (typically as square of about 10x10 μm², or a circle with the diameter of 10 μm) which is sufficient for a good geometrical coupling to single-mode telecom optical fibres, such as Corning SM-28.

Meanwhile, practical quantum optics and photonics stimulate further development of advanced fast and efficient photon counters which are suitable for free-space coupling or packaging with multi-mode fibres. The traditional approach consists in increasing the sensitive area of SSPD covered by narrow meandering strip [3,4]. Such treatment contains two disadvantages: (1) the strip length increases up to several millimeters that leads to a higher probability of defects, constrictions and weak links, which restricts critical current and reduces the yield of good devices, and (2) the long strip has a large kinetic inductance restricting the dead time to hundreds of nanoseconds time scale [3,4]. There are also a more complicated approaches such as connection of several meandering strips in parallel, or using lenses integrated with the multi-mode fibre to focus the light on smaller area SSPD. The first approach is hampered by the lack of scalability: strips connected in parallel are operated in either avalanche regime near $I_c$, or arm-trigger regime at lower current as described by Marsili et al [5]. The practical applications
Experimental methods and results

Our samples are made from NbN film on sapphire substrate with $\lambda/4$ optical cavity layers consisting of 80 nm thick-Au and 198 nm-thick Si$_3$N$_4$ layers as shown in the inset of Fig1b. This cavity is optimized for increased absorption in wavelength range 1300-1600 nm. Figure 1b presents the calculated absorption spectrum of the cavity. The films are deposited by DC reactive magnetron sputtering of Nb target in nitrogen atmosphere. We varied substrate temperature, deposition rate and partial pressure of N$_2$ to achieve maximum critical current in 1-μm-wide strips.
The film thickness \(d\) is determined from the film deposition rate and deposition time. The critical temperature \(T_c\) is determined from the midpoint of the resistivity transition curve (the temperature at which the resistance is the half of the resistance in normal state at 20K temperature). The resistivity \(\rho\) of the films was derived from the sheet resistance and film thickness. The diffusion constant \(D\) is experimentally determined from the temperature dependence of the second critical magnetic field \(H_{c2}\).

The density of states at Fermi level \(N_0\) as well as coherence length \(\xi(0)\) at zero temperature, are calculated from resistivity \(\rho\) and diffusivity \(D\), which was extracted from dependence on critical temperature vs magnetic field measurements. The parameters of the devices are summarized in Tables I and II.

Table I. Superconducting parameters of studied samples. \(d\) - thickness film calculated from speed and deposition time, \(T_c\) is the critical temperature determined from the midpoint of the resistive transition, \(R_s(300K)\) and \(R_s(20K)\) are resistivity at \(T=300K\) and \(T=20K\), respectively. \(D\) - the diffusion constant is extract from the temperature dependence of the second critical magnetic field, \(\xi(0)\) – zero-temperature coherence length.

| Sample ID | d (nm) | \(T_c\) (K) | \(R_s(300K)\) (Ω/sq) | \(R_s(20K)\) (Ω/sq) | \(k\) | \(D\) (m²/s) | \(\xi(0)\) (nm) |
|-----------|--------|-------------|----------------------|----------------------|------|-----------|-------------|
| 2037#6    | 7.5    | 7.5         | 695                  | 1177                 | 0.59 | 0.46      | 5.16        |
| 2039#4    | 7.5    | 9.1         | 514                  | 775                  | 0.68 | 0.41      | 4.4         |
| 1762#1    | 5.4    | 8.58        | 453                  | 559                  | 0.81 | 0.2       | 3.18        |
| 1975#3    | 4.8    | 8.5         | 579                  | 772                  | 0.75 | 0.2       | 3.2         |
| 2115#3    | 5.7    | 8.4         | 625                  | 961                  | 0.65 | 0.46      | 4.88        |

Table II. Different currents of studied samples. \(I_c(4.2 K)\) and \(I_c(1.7K)\) are the critical current measured without shunt resistor at the \(T=4.2 K\) and \(T=1.7 K\). \(I_{dep}(0 K)\) and \(I_{dep}(4.2 K)\) are the calculated depairing currents at the \(T=4.2 K\) and \(T=1.7 K\) using Eq.2 from [7].

| Sample ID | \(I_c(4.2 K)\) (µA) | \(I_c(1.7 K)\) (µA) | \(I_{dep}(0 K)\) (µA) | \(I_{dep}(4.2 K)\) (µA) | \(I_c/I_{dep}(4.2 K)\) | \(I_{dep}(1.7 K)\) (µA) | \(I_c/I_{dep}(1.7 K)\) |
|-----------|----------------------|----------------------|------------------------|------------------------|------------------------|------------------------|------------------------|
| 1975#3    | 101.2                | 140                  | 244                    | 161                    | 0.63                   | 230                    | 0.61                   |
| 2039#4    | 167                  | 228                  | 305                    | 214                    | 0.78                   | 293                    | 0.78                   |
| 2115#3    | 95                   | 146                  | 230                    | 150                    | 0.63                   | 216                    | 0.65                   |

Then from the optimized films we patterned spiral-shaped detectors and studied their performance: detection efficiency, dark count rate, and timing jitter. Our experimental setup is presented in Fig. 1(a). Detector under study is cooled down to 1.7 K temperature in a special insert for storage Dewar. The light from the pulsed picosecond laser is delivered by the optical fibre. Detector is DC biased from a home-made DC source through the bias-T. The shunt resistor \(R_s\) enables the recovery of the superconductivity after photon absorption, the value of the shunt resistor is adjusted experimentally and usually is in range from 1 to several Ohms. Amplified photon-count pulses are fed either to pulse counter (for dark count rate and detection efficiency measurements) or to time correlator board for jitter measurement.

Figure 2a shows the voltage transient of the photoresponse electrical pulses recorded with the digital oscilloscope. The falling edge exhibits clear exponential decay due to kinetic inductance \(L_k\) of the sample. From the geometry of the spiral and sheet resistance of the film we estimate the total kinetic inductance to be about 23 nH which is much smaller compared to the traditional meandering SSPD with 100-nm-wide strip. Nevertheless, the decay time is not as short as could be expected due to the shunt resistor connected in parallel giving the characteristic fall time (a time during which the voltage drops
by a factor of $e$, where $e$ is the base of the natural logarithm) \( \tau = \frac{L_k}{R_{\text{shunt}}} = 2.5 \text{ ns} \). The inset shows the jitter, which is 45 ps. (b) Quantum efficiency measured at wavelengths of 636, 1064, and 1330 nm, and dark counts rate. The maximum quantum efficiencies correspond to the absorption curve of the optical cavity shown in Fig. 1b.

Figure 2(b) presents quantum efficiency (which is the probability of photon detection, also known as detection efficiency) of the detector at three wavelengths: 636, 1064, and 1330 nm. The quantum efficiency at 636 and 1330 nm clearly demonstrates saturation at high bias currents which hints that the maximum internal detection efficiency is achieved (i.e. each absorbed photon produces a 'click'). The non-monotonous behavior of the maximum quantum efficiency is due to the integration of the detector with the optical cavity. Although the ratios of quantum efficiencies at different wavelength correspond reasonably to the ratios of absorption according to the simulation in Fig 1b, the origin of low absolute value of quantum efficiency, which is 35%, is not clear.

3. Conclusion

We have demonstrated a novel approach to the development of large-area superconducting single-photon detector SSPD. We have made the detector as a double spiral of 1-\(\mu\text{m}\)-long superconducting strip covering a 20-\(\mu\text{m}\)-diameter circle. These detectors exhibit response time in nanoseconds scale with 45 ps jitter and 35% quantum efficiency.

Acknowledgments

This work is supported by the Russian Foundation for Basic Research grant No. 18-29-20100.

References

[1] C.M Natarjan, M.G. Tanner, R.H. Hadfield 2012 Supercond. Sci. Technol. 25 063001
[2] A. Engel, J.J. Renema, K.Ilin, A.Semenov 2015 Supercond. Sci. Technol. 28 114003
[3] C.L. Lv, H. Zhou, H. Li, L.X. You, Y. Wang, W.J. Zhang, S.J. Chen, Z. Wang, X.M. Xie 2017 Supercond. Sci. Technol. 30 115018
[4] G. Min, Z. La-Bao, K. Lin, Z. Qing-Yuan, J. Tao, W. Chao, X. Rui-Ying, Y. Xiao-Zhong, W. Pei-Heng, Z. Yong, X. Jin-Song 2015 Chin. Phys. B. 24 068501
[5] F. Marsil, F. Najafi, E. Dauler, F. Bellei, X. Hu, M. Csete, R. J. Molnar, K. Berggren 2011 Nano Lett. Technol. 11, 5 2048
[6] D. Yu. Vodolazov 2017 Phys. Rev. Appl. 7 034014
[7] Yu. Korneeva, D. Yu. Vodolazov, A. V. Semenov, I. Florya, N. Simonov, E. Baeva, A. A. Korneev, G. N. Goltsman, T. M. Klapwijk 2018 Phys. Rev. Applied. 9 064037
[8] J. Clem, K. Berggren, 2011 Phys. Rev. B. 84 174510
[9] A. Semenov, I. Charaev, R. Lusche, K. Ilin, M. Siegel, H.-W. Hubers, N. Bralovic, K. Dopf, D. Vodolazov 2015 Phys. Rev. B. 92 1745118
[10] D. Henrich, L. Rehm, S. Dörner, M. Hofherr, K. Il’in, A. Semenov, M. Siegel 2013 IEEE Trans. on Appl. Supercond, 23(3), 220405