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Investigation of WSi and NbN superconducting single-photon detectors in mid-IR range

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Abstract. Spectral characteristics of WSi and NbN superconducting single-photon detectors with different surface resistance and width of nanowire strips have been investigated in the wavelength range of 1.3-2.5 μm . WSi structures with narrower strips demonstrated better performance for detection of single photons in longer wavelength range. The difference in normalized photon count rate for such structures reaches one order of magnitude higher in comparison with structures based on NbN thin films at 2.5 μm .

1. Introduction

Presently superconducting single-photon nanowire detectors (SNSPD) have found wide application only in those areas where it is necessary to detect single photons in the visible and near-infrared range 0.4-1.5 μm [1-9]. However, when we move to the longer wavelength range 1.5-4 μm , quantum efficiency of such detectors drops significantly [10] making them almost untapped not only in the field of practical applications but also in various scientific fields. In accordance with the model of the "hot spots" [11] the principle of operation single photon detector based on photon absorption by narrow and thin superconducting strip with the formation of the resistive region. If we move towards longer wavelengths, we have to reduce the cross-section of the strip in order to decrease the photon energy required for the destruction of superconductivity within this area [10]. However, this approach has its own limitations due to manufacturing issues in the detector development process. For example, the roughness of the strip edges plays significant role when its width approaches the limits of electron beam lithography. The width deviation of 5% gives a significant reduction in the quantum efficiency by one order of magnitude. In addition, narrowing the width of the strip leads to a reduction of the effective area of the detector [12]. In order to increase the quantum efficiency, we need to increase the filling factor of the meander [13]. However, it leads to an increase in the overall length of the superconducting strips with increasing its kinetic inductance which limits the performance of the detector [14]. The fabrication of such structures encounters technical difficulties due to additional requirements for high quality fabrication of long and narrow superconducting strips. Another disadvantage is the reduction of the critical current in such superconducting structures which leads to the decrease in the amplitude of the recorded signal and signal-noise ratio giving the worse jitter.



Moving towards longer operating wavelength region of single-photon detectors can contribute to the investigation of materials with lower energy gap or with lower superconducting transition temperature. Among such materials we can mark WSi [14] and VN [15]. Amorphous WSi does not require high quality substrate in comparison with detectors based on NbN where the quantum efficiency depends on the crystalline phase of the NbN [16] or defects on the surface of the substrate. Another direction to increase the quantum efficiency of the detectors is the reduction of the thickness of the superconducting film or fabricating films with more disordered structure [17]. This direction does not require high resolution electron beam lithography is therefore more technological.

Therefore, it seems reasonable to investigate the properties of superconducting films based on different materials such as WSi, and NbN, varying both the disorder degree in the films and its geometrical parameters, providing a high quantum efficiency of the detectors with low level of dark counts and jitter.

2. SNSPD fabrication technology and experimental setup

Thin NbN and WSi films were deposited on sapphire and silicon substrates by reactive magnetron sputtering in AJA International Orion-8 [18] and VUP-11M, correspondently [19, 20]. The thickness of such a film was ~ 7 nm, the surface resistance was 300-500 Ohm/sq. The width was 80-100 nm. The strip has a meander shape and covers a square area of $15 \times 15 \mu\text{m}^2$ with a filling factor (the ratio of the area occupied by the superconducting meander with respect to the nominal area of the device) as high as 0.5–0.6. The critical temperatures are $T_c = 8\text{--}10$ K for NbN films and $T_c = 2.7\text{--}3.3$ K for WSi films. Superconductive strips were formed in a gas mixture of SF_6 and argon by e-beam lithography and subsequent plasma-chemical etching. Au contact pads were made using the lift-off process and resistive evaporation. Photolithography and subsequent plasma chemical etching were used in order to remove the superconducting film from the substrate surface except the working region and contact areas. The wafer was cut into separate chips by using scriber.

To determine the relative number of counts, we used a standard technique for measuring the input in-fiber radiation power at a particular wavelength and the number of voltage pulses appearing on the detector during absorption of this radiation. Radiation from infrared spectrometer was coupled with the detector through multimode fiber. The output power from the fiber at different wavelengths was calibrated with InAs infrared detector (Hamamatsu P10090-21). The spectral range of measurements was limited by the wavelength of 2500 nm due to bandwidth of the multimode optical fiber. The samples were cooled down to the temperature of 1.7 K by pumping helium vapors from a thermally-insulated insert. The electrical output signal and the detector bias current were transferred through CuNi coaxial cables and hermetically sealed SMA connectors. It should be noted that films with close surface resistances were selected to compare the spectral characteristics of samples based on different materials.

3. Results and discussion

We have studied the relative spectral quantum efficiency of detectors based on superconducting WSi and NbN films with different surface resistance. Figure 1 shows the relative number of counts vs. wavelength of incident radiation for NbN and WSi structures with different surface resistances and strip width.

The bias current for all samples was set to $0.9I_c$, where I_c is the critical current of superconducting film. We normalized all dependencies at the wavelength of 1300 nm in order to observe more clearly the behavior of relative counts. It can be seen that NbN structure with narrower strip width of 80 nm and lower surface resistance R_s 340 Ohm shows dramatic exponential decreasing of counts by two orders of magnitude with increasing of wavelength by almost two times from 1300 nm to 2500 nm. However, NbN structure with almost the same strip width of 84 nm and higher surface resistance R_s 487 Ohm exhibits one order of magnitude decrease in the number of counts. Such behavior of counts for two samples with different surface resistance is a reasonable expectation because absorption coefficient should be higher for high resistive superconducting films. WSi structures show weaker

dependencies of counts in comparison with the structures based on NbN films. The number of counts for WSi structure with strip width of 100 nm decreases by two times (Figure 1 and 2). However, the structure with strip width of 80 nm exhibit fluctuation in counts within 20%. The narrowest WSi strip gives the highest absorption which stays almost constant within a wavelength range of 1300-2500 nm.

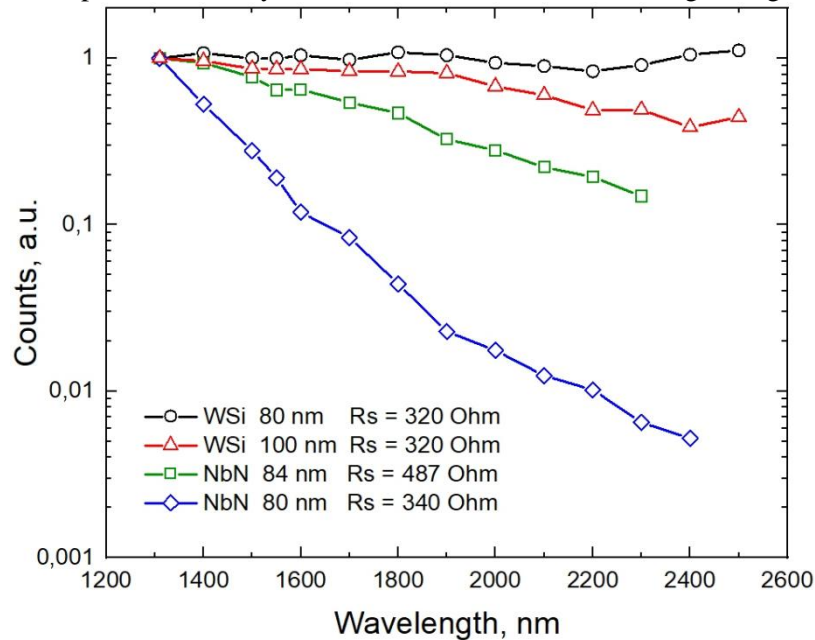


Figure 1. The relative number of counts vs. wavelength of incident radiation for NbN and WSi structures with different surface resistances and strip width. The bias current is set to $0.9I_c$. All counts are normalized at 1300 nm.

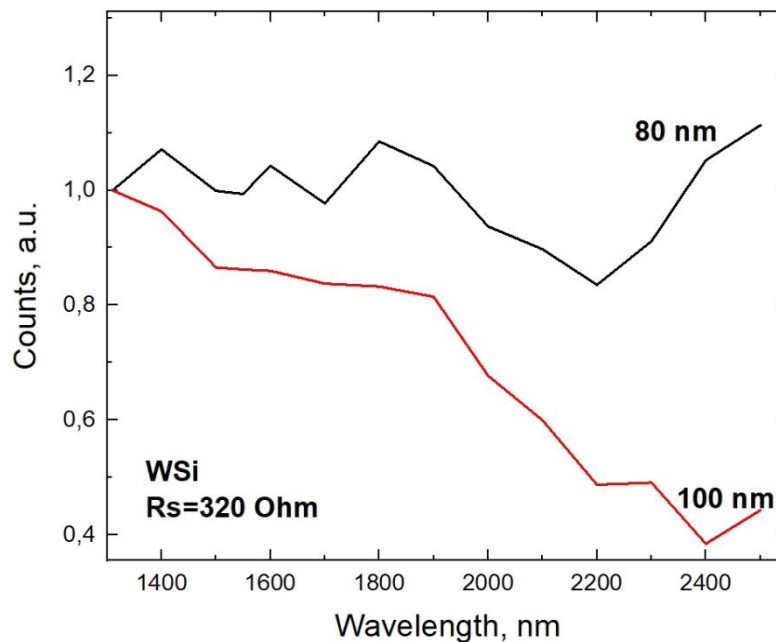


Figure 2. The relative number of counts vs. wavelength of incident radiation for WSi structures with surface resistances R_s 320 Ohm and different strip width 80 nm and 100 nm. The bias current is set to $0.9I_c$. All counts are normalized at 1300 nm.

Thus, the obtained measurements show that we can substantially improve the performance of single photon detectors towards longer operating wavelengths for practical applications by choosing WSi structures with the narrowest strip width and the highest film surface resistance. However, detectors based on WSi thin films have several significant disadvantages in comparison with NbN films. The critical temperature of superconducting WSi thin films are about 3 K, which is lower than the temperature of liquid helium 4.2 K. Also, they have low critical current about I_c 9 μ A at 1.7 K. It requires additional special cryogenic equipment to reach the temperature below 4.2 K, and low-noise amplifiers to get appropriate signal-noise ratio.

4. Conclusions

We investigated spectral characteristics of WSi and NbN superconducting single-photon detectors with different surface resistance and width of nanowire strips in the wavelength range of 1.3-2.5 μ m. WSi structures with surface resistances R_s 320 Ohm and strip width of 80 nm demonstrated better performance for detection of single photons in longer wavelength range. Superconducting single-photon detectors based on NbN and WSi thin films exhibit significant difference in quantum efficiencies for the long-wavelength region, which reaches one order of magnitude at 2.5 μ m. However, the proper operation of superconducting WSi structures requires deeper cooling in comparison with NbN structures due to its low critical temperature.

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