Fiber Coupled Single Photon Detector with Niobium Superconducting Nanowire

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Abstract. We have fabricated Niobium-based superconducting single photon detector (Nb-SSPD) for realizing high detection efficiency and fast reset time. The Nb-SSPD consisted of a 7 nm-thick and 200 nm-wide Nb meander line and exhibited the critical temperature and critical current density of 4 K and 4.6×10^5 A/cm^2, respectively. The Nb-SSPD was coupled to an optical fiber, and the reset time of 2.5 ns was observed with illumination of laser pulses at 1550 nm wavelength.

Keywords: Superconducting nanowire single photon detector, Niobium, Kinetic inductance

1 Introduction

Single photon detectors are indispensable devices in the field of quantum information and communication. Especially in the quantum key distribution (QKD) based on the optical fiber links, it is important to develop the detector at the telecommunication wavelength (1550-nm). Niobium Nitride-based superconducting single photon detectors (NbN-SSPDs) are one of the promising detectors because of their low jitter [1] and low dark count [2]. NbN-SSPDs have been successfully employed in the QKD, boosting both transmission distances and key generation rates [3]. However, the maximum count rate [4] and detection efficiency (DE) [5] of NbN-SSPDs are not adequate in order to further improve the performance of the QKD. The maximum count rate of NbN-SSPD is limited by the long reset time resulting from a large kinetic inductance (KI). The KI can be reduced because of the smaller penetration depth. Recently, from this point of view, several groups have reported on the development of SSPDs by using NbTiN or Nb thin film [6],[7],[8]. Moreover, a sophisticated technique is required for fabricating high-quality NbN films, and the integration of a complete optical cavity structure to improve an absroptance in the nanowire is difficult. Therefore, we employed Nb as the superconducting material, which can be easily fabricated utilizing a standard Josephson junction process. The KI of the Nb-SSPD can be reduced because of the smaller penetration depth. In this paper, we report the fabrication and characterization of the fiber-coupled Nb-SSPD for 1550-nm wavelength.

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2 Device Fabrication

Figure 1(a) shows a microscope image of the fabricated Nb-SSPD. Thin Nb nanowires were fabricated with a lift off process on a silicon dioxide/silicon substrate. First, a meander pattern was formed by electron beam lithography, and then the Nb was deposited by dc magnetron sputtering. The meander structure consists of a 200 nm-wide lines covering a 10×10 μm^2 area with a filling factor of 50%. Finally, superconducting Nb leads with a thickness of 50 nm were fabricated using the lift-off process. Figure 1(b) shows the AFM image of the meander structure with the nanowire thickness of 7 nm.

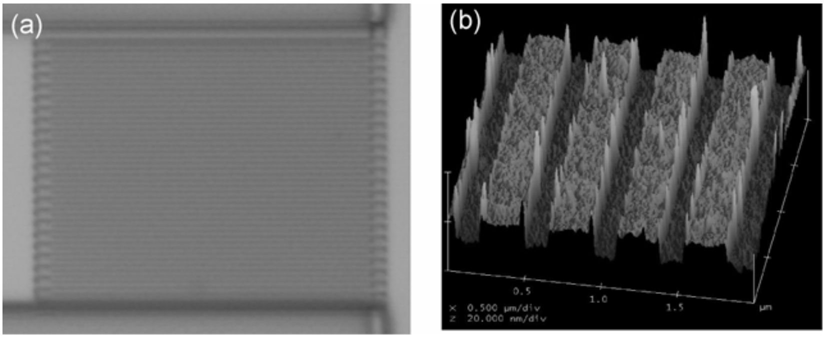

Fig. 1. (a) Micrograph of a meander pattern of 200-nm-wide nanowire covering 10×10 μm^2 area. (b) AFM image of the meander structure.

3 Experiment Setup

The fabricated Nb-SSPD was directly coupled to a single mode optical fiber and was mounted on a cold plate in a liquid-helium refrigerator. A schematic of the readout

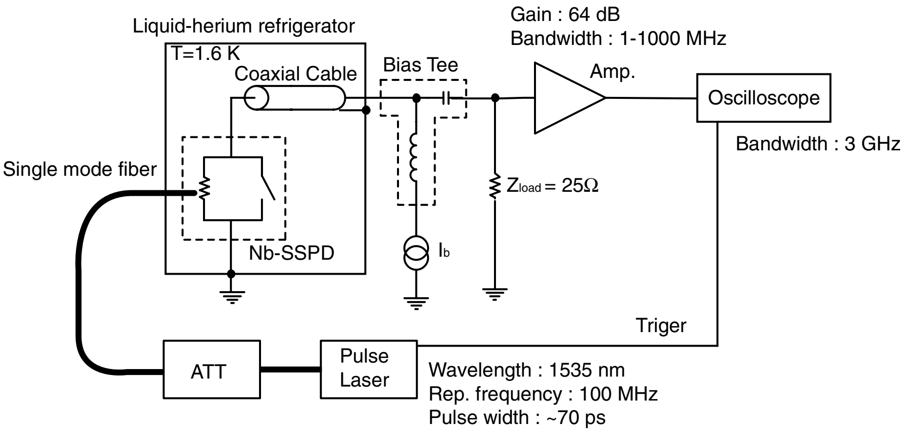

Fig. 2. Schematic of the measurement setup

circuit is shown in Fig. 2. The Nb-SSPD output was connected to a bias-tee placed at room temperature and then, to a 25-Ω parallel shunt resistance. A DC bias current is applied from a low noise voltage source in series with a large bias resistor. The bias-tee output signal was amplified using two cascaded amplifiers with 64 dB total gain, and observed with a 3-GHz bandwidth oscilloscope. We have used a pulsed laser light source at 1535 nm wavelength. The typical pulse width is approximately 70 ps. The repetition frequency of the pulsed laser was 10 MHz. The averaged laser power was strongly attenuated to the level of approximately ten photons in each light pulse.

4 Results

The Nb-SSPD showed the superconductivity at the temperature 4 K. The normal resistance at 10 K of the Nb-SSPD is 75 kΩ. Figure 3 presents a current-voltage (*I*-*V*) characteristic of the Nb-SSPD at temperature 1.6 K, measured with a constant current mode. From Fig. 3, the critical current I_c of the device is measured to be 5.5 μA.

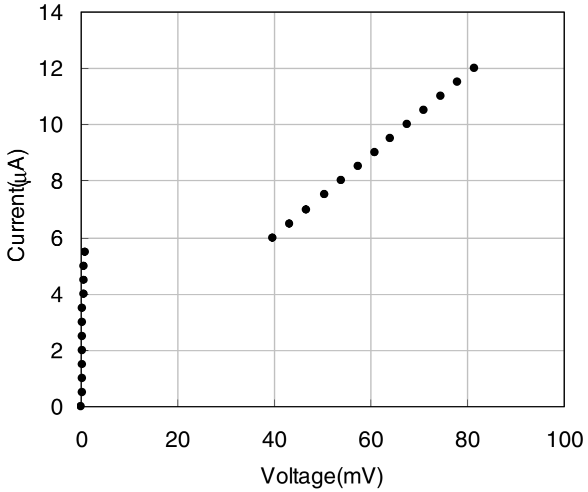

Fig. 3. I-V characteristics of the Nb-SSPD

Figure 4 shows the averaged output signal for the 1550-nm input pulse. In order to obtain the time constant of the signal, we have fitted the time-dependent signal shapes with following formula:

$$f(t) = A\left[\exp\left(-\frac{t-t_0}{\tau_{fall}}\right) - \exp\left(-\frac{t-t_0}{\tau_{rise}}\right)\right], \quad (1)$$

where A, t_0, τ_{fall}, and τ_{rise} are the pulse height, the laser incident time, the fall time, and the rise time, respectively. The best fitting values of these time constants are $\tau_{\text{rise}} = 1.5$

ns and τ_{fall} = 2.5 ns. The response speed of SSPDs are given by following equations, $\tau_{rise} = L_k/(R+R_s)$, $\tau_{fall} = L_k/R_s$, where R is a resistance which derives from hot spot. The value of R = 20 Ω was estimated from the pulse height of the average signal. The KI (L_k) calculated from these equations was approximately 56 nH which is two times lower than that of the NbN-SSPD with the same design.

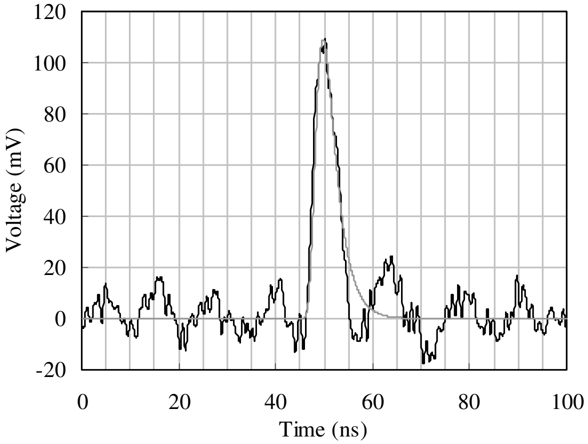

Fig. 4. Averaged signal response of the Nb-SSPD

5 Conclusion

We have reported on the superconducting properties and the signal response of the Nb-SSPDs. The Nb-SSPDs successfully showed the faster response such as τ_{rise} = 1.5 ns and τ_{fall} = 2.5 ns. The superconducting properties of our Nb-SSPD are consistent with the results of other group [8], and will be expected to show much faster reset time with the optimization of the Nb films.

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