

High Sensitive Single Photon Detection Technology using Superconducting Nanowire

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In the field of various kinds of applications, photon detection technology is one of the key technologies and there is a strong demand to improve detector's performances. Superconducting nanowire single photon detector (SSPD) is expected as a promising candidate to achieve excellent performances (high detection efficiency, fast response speed, short timing jitter, and low dark count rate) as compared to semiconductor avalanche photo diode which is mostly used at present. In this paper, we introduce the mechanism and features of SSPD and report on the development of multichannel SSPD system.

1 Introduction

Photon detection technology offering the ultimate method of measuring visible to near-infrared light is fundamental technology necessary for advancing all kinds of research and development in quantum optics, quantum information communication technology, biomedical measurements, etc. A variety of photon detectors for different wavelength ranges are currently available, but in recent years the Superconducting Nanowire Single Photon Detector (hereinafter referred to as SSPD^[1]) has suddenly begun attracting a lot of attention. It is relatively recently that research and development on the SSPD has taken off, so there are still many aspects of it that remain in the developmental stages, but what people need to focus on is its great potential, because even at this stage, it has already proven itself to outperform semiconductor devices. Great expectations are held for its low jitter, low noise, and gigabit-class speed, and because of its extremely wide-ranging wavelength sensitivity, it is able to cover the entire sensitivity range of the Si avalanche photodiode (APD) and the InGaAs/InP-APD. It also differs from the telecommunication wavelength APD in that it does not require gate synchronization, making its system configuration dramatically simpler. The method of cooling SSPDs and their low detection efficiency were practical application issues that were often pointed out, but these are on the verge of being resolved^{[2][3]}. From now on, research into SSPD application is set to take off^{[4]-[7]}.

In this document, we will first look at the operating principles behind the SSPD and its characteristics. After

that, we will look at the multi-channel SSPD system developed at NICT, and report on the building of the device, its mounting, system configuration, and system performance vital for its application.

2 Principle of SSPD and its characteristics

As shown in Fig. 1(a) the SSPD device consists of a meander-shaped nanowire made of a superconductive thin film. When a bias current I_b slightly weaker than the superconducting critical current I_c is passed through the device cooled to below the superconducting critical temperature T_c , a resistance component is not generated because a supercurrent is flowing through the nanowire. In this state, when a single photon with adequately greater energy than the superconducting gap energy 2Δ enters or is absorbed by the nanowire, the cooper pair within the superconductive thin film is destroyed creating a normal conduction (hot spot) area (Fig. 1(b)(i)). A supercurrent flows through the nanowire except at the hot spot (Fig. 1(b)(ii)), but the current density is increased, leading to the hot spot expanding out to cover the entire width of the nanowire (Fig. 1(b)(iii)) creating a resistance component (Fig. 1(b)(iv)). Excited electrons within the hot spot diffuse the energy to restore it to a superconductive state, but this change in resistance of the device due to recovery after the generation of the hot spot is what creates a voltage pulse, allowing it to be measured as a signal (Fig. 1(c)).

To boost the single incident photon detection efficiency of the SSPD device, the hot spot must be generated so it

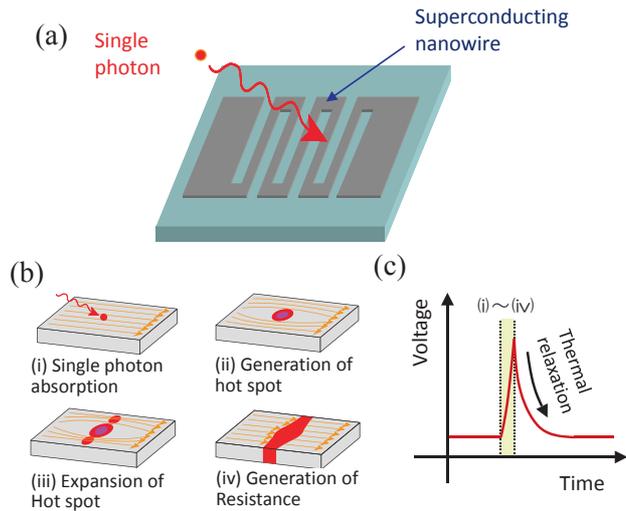


Fig. 1 (a): Schematic drawing of the SSPD device (b): The mechanism behind single photon detection by the superconducting nanowire

covers the entire width of the nanowire. This means that the nanowire must be made of superconductive material that has sufficiently less 2Δ than the incident photon, and it must be ultrathin and uniform. The superconductive niobium nitride (NbN) thin film has sufficiently less energy of $2\Delta \sim 5$ meV than the incident photon (up to 0.8 eV @ 1,550 nm), and it also allows ultrafine processing making it currently the most commonly used material for nanowires. The meander-shaped light receiving part of the device must also be large to capture single photons efficiently. However, making this light receiving part big involves simply increasing the length of the nanowire, making it difficult to achieve uniformity, and also lowering its actual response speed, which will be explained later. This means that what is required is ample surface area for receiving light combined with advanced light concentrating and mounting technology under conditions of ultra low temperatures. In addition, because the nanowire is made of extremely thin superconductive thin film of a few nanometers in thickness, its detection efficiency is limited by the light absorption rate (for example, around 30% in the case of NbN) of the nanowire layer^{[8][9]}. To improve the absorption efficiency of the nanowire layer we proposed and implemented the optical cavity structure^{[2][3][10]}.

The actual response speed of the SSPD device is dependent on the energy relaxation time of the excited electron, so when an NbN thin film is used, the relaxation time is extremely short, being around 30 ps^[11]. This makes its essential operating frequency equivalent to a few 10s of GHz. But the actual response speed of the SSPD device is limited by the kinetic inductance L_k of the device, which is

based on the length of the long nanowire. So in reality, its actual operating speed is limited to 10s to 100s of MHz^[11]. Therefore, how kinetic inductance can be lowered is key to shortening the response speed of the device.

3 Development of the SSPD system

3.1 The SSPD device

The SSPD device consists of a nanowire part made of an NbN ultrathin film, an electrode part, and also a cavity layer to boost the light absorbing efficiency of the nanowire. (Fig. 3) As mentioned in the previous paragraph, it is necessary to create an ultrathin and uniform nanowire, in order to create a highly sensitive SSPD capable of responding quickly. We used an ultrathin NbN film formed on a single-crystal magnesium oxide (MgO) substrate by DC reactive sputtering, grown epitaxially from the initial growth film, as the nanowire layer. The NbN thin film formed through this process has good superconductive properties of around 120 $\mu\Omega\text{cm}$ resistance at T_c up to 12 K, even at the ultrathin level of around 4 nm^[11]. The NbN thin film is a 100 nm width nanowire with a meander-shaped pattern formed through e-beam lithography technology and reactive ion etching. Figure 2(a) shows a photomicrograph of the created SSPD device. The surface area of the light receiving part is around 15 to 20 μm squared in order to boost the efficiency of optical coupling with the incident single photon.

3.2 Fiber-coupled packaging technology

To achieve high optical coupling efficiency between the incident photon and the light receiving part of the device, we developed mounting technology as shown in Fig. 4^[2]. The mounting block consists of a block for the device and a block for attaching the fiber, and the SSPD with an optical cavity is fixed to the block for the device. Because the optical cavity structure is attached on top of the nanowire, the incident light must be coupled from the back of the substrate. To allow the efficient coupling of single photons with the light receiving part through a substrate thickness of 0.4 mm, a small GRIN lens fused on an optical fiber was fixed on a block as shown in Fig. 4(b), and attached to the back of the device mounting block. The focal point of the GRIN lens is set to the light receiving part, and it has been designed so that the diameter of the light spot is around 10 μm . If the surface area of the light receiving part of the device is 15 μm squared, a light coupling rate of over 98% can be achieved if it is aligned accurately, as in Fig. 4(c).

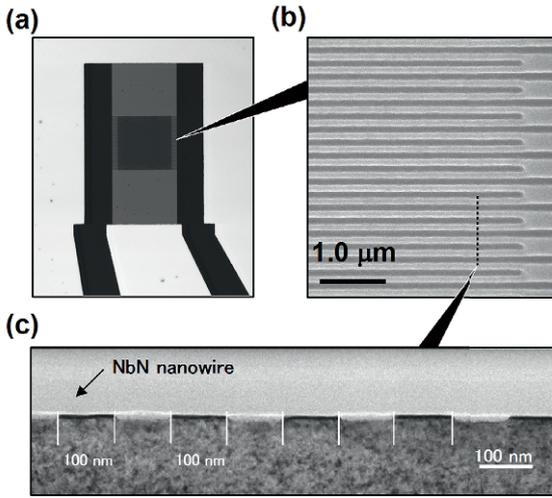


Fig. 2 Photograph of the SSPD device (a): Photograph of the light receiving part under an optical microscope (b): Photograph of the nanowire seen under an SEM (c): Cross sectional photograph of the nanowire seen under a TEM

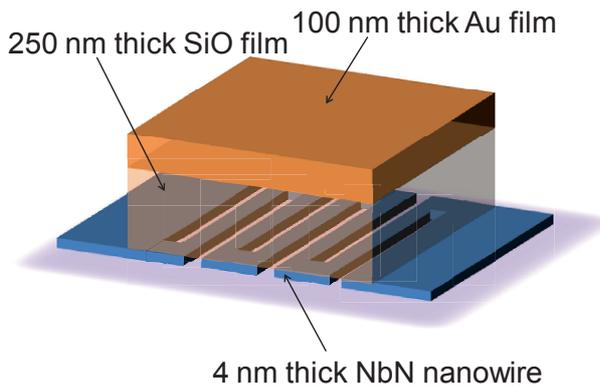


Fig. 3 The structure of the SSPD device with an optical cavity structure

Because the mounting block is small it is possible to install many of them in the freezer system we will mention later. This makes it possible to create a single photon detector system that has numerous ports in just one freezer system.

Figure 5 shows a schematic drawing of an SSPD system and a single photon detector efficiency testing system. The SSPD system we developed allows the installation of a maximum of six device-mounted packages, each with its own input-output port. The lowest end-point temperature is 2.9 K with a margin of error within 10 mK. The device was first connected to a bias tee via a coaxial cable. A bias current was drawn through the DC port of the bias tee, and the output voltage, which passes through the RF port, was amplified via a low noise amp, after which it was measured with a counter. SM fibers for a wavelength range of 1,550 nm were installed in the packages, and single photons were fed into the system. As a source of the single photons, a

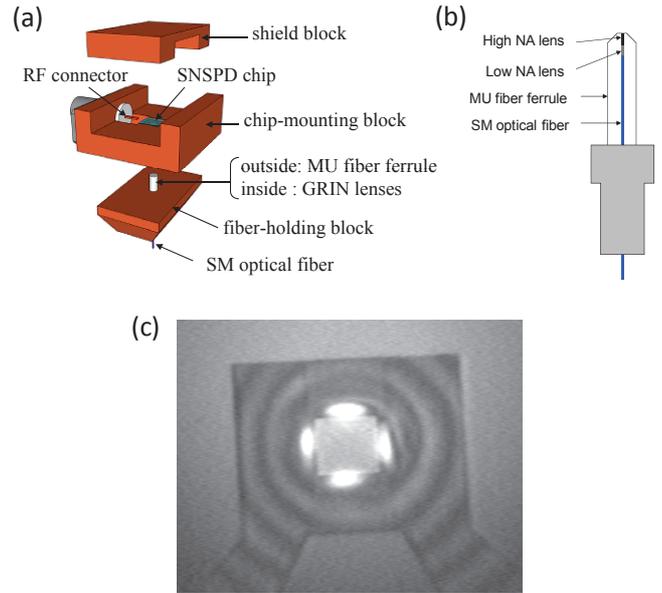


Fig. 4 (a): Diagram of mounting block for high efficiency optical coupling (b): Optical fiber with GRIN lens (c): The light receiving part of the SSPD device and the incident light spot after alignment

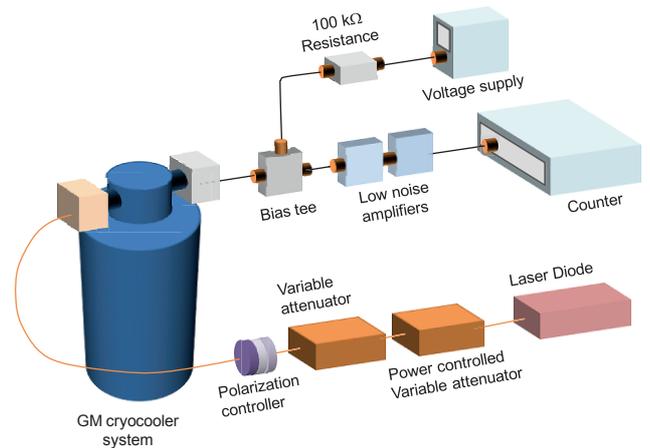


Fig. 5 Schematic drawing of an SSPD system and a single photon detector efficiency testing system

1,310 to 1,550 nm wavelength range continuum source was attenuated sufficiently so that the energy fed into the system input port was adjusted to 10^6 – 10^7 photons/sec. A polarization controller was installed before the input port, and its polarization was set to maximize the sensitivity of the device. The detection efficiency of the system is defined as the output signal generation probability relative to the set number of photon input.

4 The SSPD system performance

Figure 6(a) shows the detection efficiency of the SSPD system with an optical cavity plotted against the number of

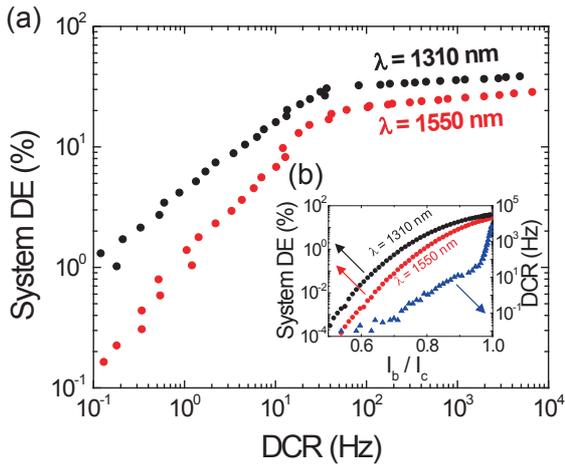


Fig. 6 (a): System detection efficiency plotted against number of dark counts in the SSPD system with an optical cavity (b): Dependence of the system detection efficiency and dark count rate on the bias current

dark counts. Figure 6(b) shows the dependence on the bias current. Increasing the bias current also boosts the detection efficiency, and the dark count rate is also high (>10 kc/s) in the vicinity of I_c, but a high detection efficiency of 28% at a wavelength range of 1,550 nm, and 40% at a wavelength range of 1,310 nm is achieved. Furthermore, at the bias range where the dark count rate is 100 c/s, the detection efficiency is 20% @ 1,550 nm and 35% @ 1,310 nm. The typical detection efficiency is 2–3% with a single layer structure without the optical cavity, while with the optical cavity we succeeded in dramatically boosting its performance.

Figure 7 shows the characteristics of the timing jitter of the SSPD device. The timing jitter was measured using a time correlated single photon counting device by measuring the time correlated histogram with the output pulse from the SSPD as the start signal, and the trigger signal from the femtosecond pulse light source as the stop signal. The SSPD device we tested this time had a light receiving surface area of 10 μm squared, but a slight timing jitter of 100 ps was observed across its radius. In application experiments such as in quantum cryptography key distribution, the timing jitter is a vital performance factor that affects the bit error rate, and great expectations are held for further improvement in reducing this jitter in the future.

Next, we will look at the characteristics of the SSPD response speed. As it was stated in 2, the response speed of the SSPD is determined by the kinetic inductance L_k of the device. Therefore, the smaller the photon receiving surface area, the faster the response speed of the device. Figure 8 is

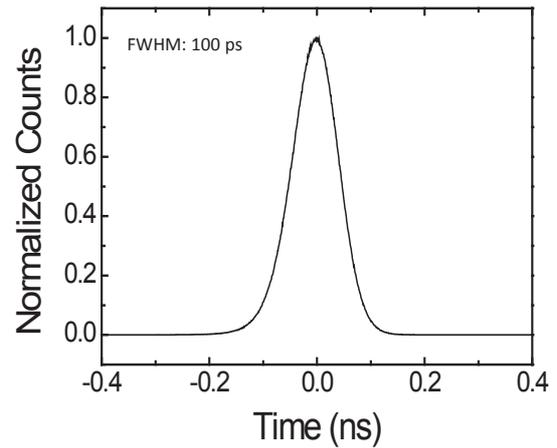


Fig. 7 Characteristics of the SSPD timing jitter

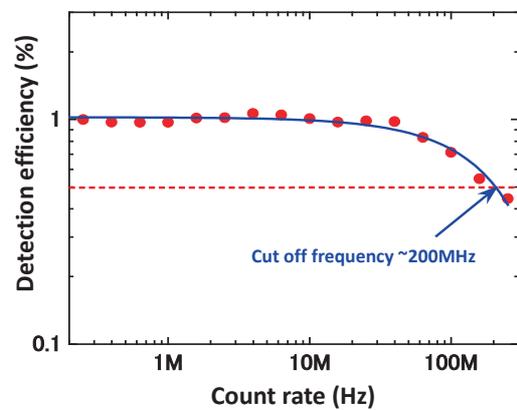


Fig. 8 Detection efficiency as a function of count rate of SSPD device with 5 μm square active area

a graph of the characteristics of the detection efficiency plotted against the count rate in a device with a light receiving surface area of 5 μm. It can be seen that as the count rate increases, the detection efficiency declines, and the device does not respond properly. But it was confirmed that the device operates normally up to around 40 MHz. This is sufficiently fast compared to APDs already on the market, but in the laboratory even the APD has been successfully operated at 100 MHz, and we hope to boost the performance of our device in the future.

5 Conclusions

We reported on the development of an actual SSPD system and its performance in terms of the operating principle behind the SSPD and its characteristics. The SSPD system has successfully been demonstrated to currently outperform the APD, and great expectations are held for its applications from the fact that it is already being used for a variety of purposes. We also have great

expectations for its future because its potential has not yet been fully realized and there is room for further improvement in its performance.

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