Spectral Sensitivity and Temporal Resolution of NbN Superconducting Single-Photon Detectors

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Abstract

We report our studies on spectral sensitivity and time resolution of superconducting NbN thin film single-photon detectors (SPDs). Our SPDs exhibit an experimentally measured detection efficiencies (DE) from ~ 0.2% at λ =1550 nm up to ~3% at λ =405 nm wavelength for 10-nm film thickness devices and up to 3.5% at λ =1550 nm for 3.5-nm film thickness devices. Spectral dependences of detection efficiency (DE) at λ =0.4 –3.0 µm range are presented.

With variable optical delay setup, it is shown that NbN SPD potentially can resolve optical pulses with the repetition rate up to 10 GHz at least. The observed full width at the half maximum (FWHM) of the signal pulse is about 150-180 ps, limited by read-out electronics. The jitter of NbN SPD is measured to be \sim 35 ps at optimum biasing.

Introduction

NbN ultrathin film superconducting single-photon detectors (SPDs) are promising for their fast response time and ultimate sensitivity from ultraviolet to near infrared ranges [1-4]. Simultaneously, with the quantum-counting property, dark counts of the detector are negligibly low under the cryogenic operation environment [5,6]. As the result, superconducting NbN SPDs offer some obvious advantages over any modern semiconductor single-photon detectors [6].

The single photon counting property of NbN SPDs has been investigated thoroughly, and a model of hot-spot formation process has been introduced to explain the photon-counting mechanism of NbN SPDs [7, 8].

However, it is of great interest to study spectral sensitivity characteristics and time characteristics of NbN SPD. Another very important time-related characteristic is the time jitter. The last characteristic is responsible for an accuracy of photon event registration in time scale.

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SPD's fabrication and experimental setup

The devices used in our experiments are meander-structured NbN superconducting stripes with thickness of d = 10 nm and 3.5 nm, and width of w ~200 nm. The T_c of the devices is about 10.5 K for 10-nm thickness film, and about 10 K for 3.5-nm thick film devices, with critical current density j_c at 4.2 K up to 5×10⁶ A/cm². The fabrication process of NbN SPDs is as follows: first of all, the ultra-thin NbN films are deposited on doubleside polished sapphire substrates by reactive dc magnetron sputtering method in the Ar + N₂ gas mixture. The maximum values of the critical film parameters (T_c and j_c) are reached at the partial Ar pressure of $5x10^{-3}$ mbar, the partial N₂ pressure of $9x10^{-5}$ mbar, the discharge current value of 300 mA, the discharge voltage of 300 V and the substrate temperature of 850 °C. Next, the film is patterned into a meander-type stripe occupying an area of $\sim 10 \ \mu m \times 10 \ \mu m$ or 4 $\mu m \times 4 \ \mu m$ by e-beam lithography after the outer Ti-Au contact pads are fabricated by lift-off optical photolithography. Thereafter the NbN film is removed from the whole surface of the substrate except the meander-type structure and contact pads by ion milling in Ar atmosphere through supplementary Ti mask, which is created on the surface of NbN meander-type and contact pads. Finally, the last process is to remove Ti mask in diluted hydrofluoric acid. SEM image of the device with $10\mu m \times 10\mu m$ working area is shown in Fig.1.



Fig. 1. SEM image of Meander-structured NbN SPD fabricated by the magnetron sputtering method with covered area of 4 μ m × 4 μ m, average stripe width w = 210 nm.

Typical I-V curve of the 10-nm-thick SPD at 4.2 K is shown in Fig. 2. We bias the SPD at currents below critical current I_c (e.g., point A on superconducting branch). After the absorption of the photon the resistive barrier across the full width of NbN stripe appears, and detector is switched from superconducting state (point A in Fig. 2) to meta-stable state (point B in Fig. 2) with a voltage signal generated.



Fig. 2. I-V curve of 10-nm-thick, $4 \mu m \times 4 \mu m$ area NbN SPD at 4.2 K.

Experimental setup

The schematic diagram of our experimental setup is shown in Fig. 3. The device is wire-bonded to a microstripe line and then connected to the bias and output circuits through a bias tee. The vacuum cryostat that holds the SPDs is cooled by liquid helium and maintained at 4.2K. Optical sources were either 100-fs-wide pulses with a 82-MHz repetition rate at 405 nm, 810 nm, and 1.55-µm wavelengths from a self-mode-locked Ti-sapphire laser, coupled with the parametrical optical amplifier, or CW laser diodes. The intensity of incident radiation was attenuated using banks of neutral density filters. In addition, the wavelength dependency of SPD's detection efficiency (DE) was measured using a grating spectrometer and a CW blackbody radiation source.



Fig. 3. Experimental setup with variable optical delay stage.

In order to measure the time-resolving ability of NbN SPDs, we have set up an adjustable optical delay stage. The laser beam is firstly split into two beams, and then one

of the beams is delayed by the optical delay stage and then merged back into the original beam by the second beam-splitter. The minimum amount of the delay is 100 ps. The voltage signal generated by the incident photon in the SPD is amplified by a room-temperature amplifier and then fed to the Tektronix 7404 single-shot digital oscilloscope (synchronously triggered by the Ti:Sapphire laser) or counted by SR400 photon counter, the room temperature amplifier and oscilloscope have bandwidths of 0.01-12 GHz and 0-4 GHz, respectively.

Experimental results

Spectral sensitivity

The DE spectral dependences for some $4x4 \ \mu m^2$ and $10x10 \ \mu m^2$ 10-nm film thickness SPDs at λ =0.4 –3.0 μm range are presented in Fig. 4. We notice here that DE is a global parameter referring to the number of photons registered by the detector, normalized only to the incident beam size. The DE dependences have an activated-type character with DE ~ exp(-Eg/hv), where Eg is the activation energy [4]. The activation character of DE and Eg value looks similar for all the tested devices with the same thickness. We observed some noticeable variations of the spectral sensitivity dependence slope with the stripe width, but it is a subject of more detail future study.





The preliminary results for 3.5-nm-thick devices show significantly smaller activation energy value, which is in agreement with prediction of hot-spot model. It makes thinner devices more promising for near-infrared and middle-infrared ranges.

Our 10-nm-thick SPDs exhibit an experimentally measured detection efficiencies (DE) from ~ 0.2% at λ =1550 nm up to ~3% at λ =405 nm wavelength. The devices with the film thickness of 3.5-nm shows DE up to 3.5% at λ =1550 nm. The intrinsic quantum efficiency of these devices is close to 100% at 1.2 µm wavelength (see notice above about definition of DE).

Time resolution

With the variable time delay setup, we have taken the single shots of the pulse-shape with Tektronix 7404 oscilloscope (100 ps rise time). The results are shown in Fig. 5. Signal pulse itself has a FWHM of about 150 ps, and rise time of \sim 100 ps. When the optical delay is adjusted to be 100 ps (Fig. 5b), pulse shape by oscilloscope is evidently wider than the pulse shape without delay, and the signature of the second delayed pulse can be detected. For comparison, pulses for the delays of 330 ps, 650 ps, and 1080 ps are shown in Fig. 5c, d, and e. Obviously, the superconducting state should be recovered for to detect next photon. As the result, we can make a conclusion that the device is capable to detect photons with 10-GHz counting rate.



Fig. 5. Pulse patterns at different optical delays: (a) delay = 0, (b) delay = 100 ps (we can see the signature of the delayed pulse), (c) delay = 330 ps, (d) delay = 650 ps, (e) delay = 1080 ps.

The signal pulse from our NbN SPD has an extremely small jitter. With the analysis of pulse shape by standard histogram method, we can find that the total system jitter is about 35 ps (as shown in Fig. 6) at the relatively high flux. This value of jitter includes jitters from the laser system (~4 ps), the output circuits and the oscilloscope performance, thus,



the intrinsic device jitter is expected to be smaller.

Fig. 6. Pulse shape at incident flux level of 1000 photons per second, with FWHM of about 180 ps, and jitter of about 35 ps.

Conclusions

NbN SPDs are sensitive to UV, visible, and IR radiation. Obviously, 3.5-nm film thickness devices are already in competition with the best semiconductor single-photon detectors at 1.55-micron communication wavelength.

The experimental results of optical pulse delay have shown that our NbN SPDs can resolve pulse trains with optical delay of about 100 ps. This ultra-fast responsive property makes NbN SPDs to be very promising detectors in a lot of application fields, such as fiber-optics communication and even Earth-satellites communication. Measured jitter of detectors is about 35 ps which makes our devices very promising for ultrafast applications.

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