Ultrathin NbN film superconducting single-photon detector array

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Abstract. We report on the fabrication process of the 2x2 superconducting single-photon detector (SSPD) array. The SSPD array is made from ultrathin NbN film and is operated at liquid helium temperatures. Each detector is a nanowire-based structure patterned by electron beam lithography process. The advances in fabrication technology allowed us to produce highly uniform strips and preserve superconducting properties of the unpatterned film. SSPD exhibit up to 30% quantum efficiency in near infrared and up to 1% at 5-µm wavelength. Due to 120MHz counting rate and 18 ps jitter, the time-domain multiplexing read-out is proposed for large scale SSPD arrays. Single-pixel SSPD has already found a practical application in non-invasive testing of semiconductor very-large scale integrated circuits. The SSPD significantly outperformed traditional single-photon counting avalanche diodes.

1. Introduction
Advances in the state-of-the-art thin superconducting NbN film processing nanotechnology allowed us to create a new type of single-photon detector - superconducting single-photon detector (SSPD). We already reported that by such characteristics as maximum counting rate, jitter, dark counts rate SSPD outperform the state-of-the-art avalanche photodiodes (APD) and photomultiplier tubes (PMT) which are traditionally used as single-photon detectors in visible light and near infrared [1,2]. Although single-pixel SSPD has already found practical application there is a range of potential SSPD applications that require spatial detector resolution. In this paper we report on the SSPD array fabrication.

2. SSPD design and fabrication process
The detector active element is a meander-shaped narrow strip patterned from superconducting film and covering the square area of 10 µm × 10 µm. The strip width is typically 100-120 nm and the meander filling factor (the ratio of the area occupied by the superconducting meander to the device nominal area) can be as high as 0.6-0.7. The length of the strip reaches up to 500 µm. Figure 1 presents the SEM image of the meander. The devices are fabricated using the process based on the direct electron beam lithography and the reactive ion etching [3].
Figure 1. SEM image of the SSPD

Table 1 presents the main steps of the fabrication process. The 4-nm-thick NbN superconducting film is deposited on the c-cut double-side-polished sapphire substrate by the DC reactive magnetron sputtering in an Ar and N₂ gas mixture. The residual gas pressure is $1.5 \times 10^{-6}$ mbar whereas the N₂ and Ar partial pressures are $10^{-3}$ mbar and $5 \times 10^{-3}$ mbar respectively. The substrate is heated up to 850°C leading to an epitaxial growth of the deposited thin film. The film is characterized by the surface resistance $R_s = 500 \, \Omega$/sq, critical temperature $T_c = 10 - 11 \, K$, current density $j_c = 6 - 7 \times 10^6 \, A/cm^2$ at 4.2 K.

**Table 1. SSPD fabrication process.**

| ID# | Sketch | Comments |
|-----|--------|----------|
| 1. | ![Substrate sketch](image) | Deposition of a NbN film by dc reactive magnetron sputtering. Substrate: double-side-polished, 300-µm-thick sapphire. Residual pressure $1.5 \times 10^{-6}$ mbar. Substrate temperature 850°C. N₂ partial pressure $10^{-4}$ mbar. Ar partial pressure $5 \times 10^{-3}$ mbar. |
| 2. | ![Alignment marks sketch](image) | Patterning of alignment marks. Lift-off process. Ti/Au 5/100 nm alignment marks. Vacuum resistive evaporation at room temperature. Optical lithography process with AZ1512 photoresist. |
| 3. | ![Stripe windows sketch](image) | Patterning of stripe windows in preparation for a meander structure. Direct electron beam lithography process with PMMA 950K (2%, 0.08 µm) electron resist. Process parameters: $I = 25$ pA, $U = 25$ kV. The developer: toluene and isopropanol 1:10 mixture. Reactive ion etching of NbN film in SF₆. Removal of electron resist layer. |
| 4. | ![Contact pads sketch](image) | Patterning of outer contact pads. Lift-off process. Ti/Au 5/200 nm contact pads. Vacuum resistive evaporation at room temperature. Optical lithography process with AZ1512 photoresist. |
| 5. | ![Meander structure sketch](image) | Final patterning of meander structure. Photolithography process with AZ1512 photoresist. Chemical etching of unprotected areas of NbN film in CP-4 (HNO₃/HF/CH₃COOH (5:3:3)). Removal of electron resist layer. |

Then the meander structure is formed. The areas under which the superconductor is removed are exposed in the resist during electron beam lithography. We use the electron resist PMMA 900K (2%, 80-nm thick), as a developer we use a mixture of toluene and isopropanol 1:10. The resist is later removed from the superconductor using the reactive ion etching in the SF₆. The choice of the 80-nm resist thickness ensures a reliable protection of the superconducting film. Significant reduction of the
resist thickness allowed us to fabricate meanders with a filling factor of up to 0.7 and improve the superconducting strip uniformity and achieve a reasonable yield of good devices.

The outer titanium and gold contact pads as well as the alignment marks are fabricated by the photolithography process. The Ti-Au layers are deposited by the vacuum resistive evaporation at the room temperature and then patterned in the photolithography process using the AZ1512 photoresist.

3. SSPD characterisation

![Figure 2](image_url)

Figure 2. SSPD quantum efficiency (QE) at 1.3\(\mu\)m wavelength at 4.2K and 1.8K temperatures (open symbols) and dark counts rate at 1.8K (solid symbols).

We performed measurement of SSPD quantum efficiency (QE) in visible light to middle infrared range. QE was defined as the ratio of detection events to the number of photons falling on the SSPD active area of 10 \(\mu\)m \(\times\) 10 \(\mu\)m during given period of time. The number of photons was determined by power measurement. The best achieved QE at 1.3 \(\mu\)m wavelength reaches 32\% at 1.8K temperature (fig. 2). The absence of significant QE increase with temperature reduction is worth noting. Such a behaviour was observed only for single best devices. This saturation can be explained as achievement of the ultimate QE value limited by NbN film optical absorption.

Figure 2 also presents SSPD dark counts rate. Dark counts decay exponentially with the decrease of transport current \(I_b\). Although for this particular device we measured dark counts rate to \(10^{-3}\) s\(^{-1}\) we already reported that it can be as low as \(2\times10^{-4}\) counts per second [1,2].

Typical dependence of QE on the radiation wavelength is presented in figure 3. One can see that reduction of the operation temperature leads to significant increase of the SSPD QE in middle IR. For example, at 3 \(\mu\)m wavelength the temperature reduction from 5 K to 3 K leads to 200 times increase of QE. We also studied SSPD QE at 5 \(\mu\)m wavelength with light emitting diode (LED). Figure 4 presents QE at 5 \(\mu\)m wavelength vs temperature at different SSPD bias currents. The experimental setup allowed us to reach 1.6 K operation temperature and SSPD exhibited QE up to 1\% [4].
Figure 3. SSPD QE vs radiation wavelength at 3K and 5K temperatures

Figure 4. SSPD QE at 5 μm wavelength vs temperature measured at bias currents in range 0.86$I_c$ - 0.95$I_c$

4. **2x2 pixel SSPD array and large-scale arrays multiplexing**

We designed 2x2 pixel SSPD array. Each pixel was 10 μm × 10 μm meander-shaped SSPD like those described above. The fabrication process was essentially the same. Figure 5 presents a sketch of the array. All 4 pixels had one common ground contact and 4 separate contacts that allowed us to perform independent characterization of each pixel. Figure 6 presents a SEM image of the inner part of the SSPD array.

As it will be shown below the most important parameter for large scale array implementation is the scatter of $I_c$ values because we in large arrays propose to connect single SSPDs in series. The scatter of QE is not so important because it can be corrected later in software.

For large-scale arrays we propose time-domain multiplexing. It is possible due to high counting rate and extremely low jitter. At present maximum counting rate is 120 MHz with 18 ps pulse-to-pulse timing jitter [5]. Figure 7 explains the idea. All the SSPDs in the array are connected in series (that is why $I_c$ scatter is very important) with delay lines and thus form a transmission line. Both ends of the transmission line are loaded by the input of amplifiers A1 and A2. Their outputs are connected to the S(set) and R(reset) inputs of an SR-trigger. When a photon is absorbed by a SSPD two response voltage pulses starts propagating along the transition line in the opposite directions. The time intervals between the pulses coming to the S and R inputs are different for each detector as they depend on the electric lengths difference between the detector and amplifiers A1 and A2 which are determined by the delay lines. Multiplexing of SSPD array elements will be realized by the determination of the pulse duration at the SR-trigger output.
5. Conclusions

Mature technology of thin-film superconducting devices allowed us to create single-pixel SSPDs and SSPD arrays operating in 0.4-5 μm wavelength range and demonstrating high performances. SSPD was successfully used for non-invasive testing of very large scale integrated circuits with a technique similar to IBM's PICA [6]. The work on the time-domain multiplexing for SSPD arrays shows its prospects. We plan to produce large-scale multipixel SSPD arrays as well as further improvement of single-pixel SSPD towards of the increase of quantum efficiency, expansion of the operational band to longer wavelengths.

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