Fabrication of a superconducting niobium nitride hot electron bolometer for single-photon counting

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Abstract. Superconducting photodetectors offer an interesting alternative to traditional photon counting systems such as photomultiplier tubes and avalanche photodiodes for applications in optical quantum information processing. In these superconducting devices, different mechanisms are exploited to detect the photon absorption, depending on the type of detector (transition edge sensor, superconducting tunnel junction and hot electron bolometer (HEB)). The first two are briefly presented; more emphasis is given on HEB elaboration made with very thin superconducting NbN films due to their unique capability of fast single-photon detection. Constraints on NbN HEB elaboration and on electronic transport properties are presented in the perspective of further improvement of the quantum efficiency in the near-infrared.
1. **Importance of single-photon counters**

1.1. **Introduction**

Single photons are a very useful resource in quantum information since they are the best method of carrying a unit of quantum information (qubit) from one place to another. For this reason, single photons have naturally been used in long-distance quantum cryptography [1, 2] or quantum teleportation [3]. In quantum computation proposals, single photons are often seen as the natural way to move information from gate to gate. More recently, Knill et al [4] (see also [5]) have shown that single photons can even be made to interact using multiphoton interference effects [6] and a post-selection of events.

Single-photon systems require efficient devices at both ends: production and detection. As can be seen in this special issue, single photons on demand can now be produced in a variety of different ways. However, less attention has been devoted so far to the efficient detection and accurate counting of single photons [7]–[10]. Note that the demand for better photon counting technology comes not only from the quantum information community but also from other fields such as astronomy [11, 12].

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Table 1. Characteristics of different detectors. APD, avalanche photodiode; PM, photomultiplier; MCP, microchannel plate. For superconducting detector: HEB, hot electron bolometer; STJ, superconducting tunnel junction; and TES, transition edge sensor. Note that the energy resolution for HEB has not been measured experimentally and is only an estimate.

| Detector          | Quantum efficiency | Dark counts (s⁻¹) | Timing jitter | Maximum count rate (s⁻¹) | Energy resolution E/ΔE |
|-------------------|--------------------|------------------|---------------|--------------------------|------------------------|
| Si APD (Perkin-Elmer) | 0.7 at 800 nm      | 100              | 350 ps        | 10⁷                      | No                     |
| InGaAs/InP APD (Id quantique) | 0.1 at 1.55 µm    | 5 × 10⁴          | 800 ps        | 10⁵                      | No                     |
| Best APD 1 [7]   | 0.88 at 694 nm     | 2 × 10⁴          | No            |                          |                        |
| Best APD 2 [8]   | 0.7 at 702 nm      | 1.7 × 10⁴        | 2 ns          | 15                       |                        |
| PM (Hamamatsu)   | 0.4 at 500 nm      | 100              | 10⁷           | No                       |                        |
| PM-MCP (Hamamatsu) | 0.2 at 500 nm     | 2000             | 25 ps         | 10⁷                      | No                     |
| HEB (T = 4 K) [15] | 0.1 at 1.55 µm    | 10⁻¹             | 18 ps         | >10⁶                     | 1                      |
|                  | 0.2 at 1.26 µm     |                  |               |                          |                        |
| STJ (T = 0.2 K) [11, 16] | 0.5 at 200–500 nm | ≈0               | <2 ns         | 5 × 10⁴                  | 10                     |
| TES (T = 0.1 K) [17] | 0.2 at 200–1800 nm | 10⁻³             | 350 ps        | 2 × 10⁴                  | 15                     |

Long-distance quantum key distribution or quantum teleportation make use of low loss optical fibre at a telecom wavelength of 1.55 µm. At this wavelength, photon counting is currently performed by avalanche photodiodes that are far from ideal. Such detectors have, in particular, a very large dark count rate and a limited efficiency (cf table 1). There is, therefore, room and need for improvement of photon counting devices at this telecom wavelength.

The proposal for quantum computation with linear optics [4] requires very high-performance photodetectors. The photodetectors must have a quantum efficiency higher than 0.99 and the ability of resolving the photon number [13, 14]. Takeuchi et al [7] and Kim et al [8] have shown that specially designed avalanche photodiodes could reach quantum efficiencies of 88% [7] or exhibit photon number resolution ability [8]. There have been also proposals for photodetectors based on the absorption of light by a specific transition in an atomic vapour [9, 10]. These systems are expected to lead to quantum efficiencies higher than 99% while offering at the same time the possibility of resolving photon number.

In this paper, it will be shown that superconducting photocounters offer an interesting alternative for addressing both the near-infrared photocounting problem, and the realization of photon number resolving detectors.

1.2. Desirable properties of single-photon detectors

We have pointed out below four properties that we believe are important for applications in optical quantum information processing. Single-photon counters are also used in other fields...
such as astrophysics, where other properties such as possibilities of integration in a matrix might be of importance. In this paper, we will limit ourselves to the field of quantum information. Numbers for different detectors are given in table 1.

1.2.1. Quantum efficiency. This quantity is defined as the ratio of the detected photon number to the incoming photon number. In quantum cryptography, a non-ideal quantum efficiency amounts to losses in addition to the transmission losses between the two partners. These losses set an upper limit on the maximum distance for a fully secure quantum key distribution. Since the minimum attenuation in optical fibres is obtained at the wavelength of 1.55 \( \mu \text{m} \), it would be very useful to have detectors with good quantum efficiencies at 1.55 \( \mu \text{m} \). The best value we have found on the market is 10% ([www.idquantique.com](http://www.idquantique.com)). We think that specially designed superconducting detector can do as well and perhaps better than that in the near-infrared region. Indeed superconducting detectors have so far been designed for and tested mainly in the visible, UV and x-rays.

It should also be mentioned that quantum computation schemes with linear optics [4] require extremely high detector quantum efficiencies (>99%) [13, 14]. The best value reported so far is 88% at a wavelength of 694 nm for an avalanche photodiode [7]. Other propositions using the storage of light in atomic vapour have predicted quantum efficiencies higher than 99% [9, 10].

1.2.2. Dark count rate. This is the number of counts recorded with no illumination. A low dark count rate is obviously desirable since it represents the noise of the detector. In quantum key distribution, this parameter will contribute to the quantum bit error rate (QBER). Since the QBER has to remain below a threshold (11% for the Bennett Brassard protocol [18]) for the transmission to be secure, the dark count rate comes into the maximum transmission distance. The dark count rate of superconducting detectors is somewhat related on each detector principle and on its geometry, but in any case, it is also rather low in comparison to other semiconductor detectors mainly because the operating temperature is lower (0.1–4 K) and thermal activation of generated carriers is thus reduced. However, superconducting detectors are in principle sensitive in a window of deposited energy from 0.5 eV up to about few keV, but they are normally efficiently shielded from external radiations. In any case, owing to the energy sensitivity of these detectors, higher energy photons can be easily identified and filtered out. Superconducting detectors and Josephson readout circuits have also a low cross-section for more energetic photons and other particles, since they are composed of thin metallic layers deposited on intrinsic large energy gap, low loss substrates (sapphire, MgO). Finally, superconducting detectors have been found to exhibit a large hardness to radiation aging [19].

1.2.3. Timing jitter. This parameter specifies how well the arrival time of the photon is known. It can be important when the detector is used in coincidence experiments. Most of the superconducting detectors can be very efficiently electronically triggered with about 1 ps jitter time, and 100 GHz bandwidth superconducting sampling oscilloscopes have already been demonstrated at Hypres Inc. [19, 20].

1.2.4. Maximum count rate. Providing the counting electronics does not set the limitation, the maximum count rate is the inverse of the dead time. The latter is the time during which the
detection is inhibited after the detection of a photon. The electronic limitation is typically around 200 MHz, but this frequency has been increased to several GHz in fast detectors coupled with superconducting digitizers [15, 20].

1.2.5. Ability to resolve the photon number. Commercially available avalanche photodiodes and photomultiplier tubes are not able to distinguish between one and more than one photon if all of the photons land within the dead time of the detector. However, some specifically designed avalanche photodiodes offer this feature [8, 21] and, as shown below, superconducting detectors exhibit photon energy resolution that enables the photon number resolution.

2. Overview of superconducting photon counting detectors

The binding energy of Cooper pairs in a superconductor is of order of a few meV. The absorption of a single optical photon (energy of 1.2 eV at a wavelength of 1 µm) can therefore break a large number of Cooper pairs and create quasiparticles. This absorption alters, therefore, significantly the electrical properties of a superconducting material.

Different mechanisms and different configurations can be used in order to detect the absorption of a single photon in a superconductor. We present below the main types of superconducting detectors.

2.1. Superconducting tunnel junction (‘STJ’)

The photon absorption in a ‘STJ’ electrode generates a packet of quasiparticles at the energy edge of its superconducting gap. Before recombination, the quasiparticles are drained by the electrical field of the tunnel junction and collected by a charge amplifier resolving the number of quasiparticles and therefore the photon energy with a good accuracy \( E/\Delta E \geq 10 \) [11]. Quantum efficiency of such STJ detectors, which required low operating temperature (≈ 0.2 K), is found to be high (see table 1). The dead time of STJ is about 10 µs. A matrix of 120 STJ pixel arrays has been successfully achieved by the European Space Agency (ESA-ESTEC lab) and application to astronomy is in progress [16]. Proper STJ process improvements have been also realized in the recent years [22, 23] leading to better detector sensitivity in the infrared and visible wavelengths. These developments should lead to the design of competitive astronomical instruments based on STJs.

2.2. Resonant circuit detectors

The short lifetime quasiparticle population generated by the photon absorption in a single superconducting layer can also be detected when the pixel is coupled with a high Q microwave resonator: the quasiparticle population generates both a transient damping that reduces the resonator quality factor and a small shift in the resonant frequency position which can be recorded as it has been recently described by Day et al [12] in the x-ray domain. The advantages of such detectors reside probably both in the easy frequency division multiplexing possibility for large pixel arrays readout and in a good filling factor of the pixel area. Future work on these very promising detectors should allow, in principle, single-photon detection in the visible.
2.3. Superconducting single-photon bolometers

The third type of superconducting single-photon detectors (SSPD) is based on the bolometer principle, i.e. on the large change of the device resistance when a small amount of energy is deposited in the superconducting layer. There are two main types of superconducting bolometers, namely transition edge sensors (TES) and hot electron bolometers (HEB). HEB is the main topic of this paper and will be described in great detail below.

2.3.1. TES. Superconducting TES are biased close to the superconducting-normal metal transition edge to detect the large increase in resistance as the photon energy is absorbed. TES are preferably constant dc voltage biased to obtain the electrothermal feedback process which reduces the time constant of the detector [24]. When the photon energy is deposited, the resistance $R$ of the TES increases, and the Joule heating ($U^2/R$, where $U$ is the dc bias voltage) is reduced, bringing the system back into its working point. DC-SQUID amplifiers are very well adapted for this current readout scheme and TES detector arrays with time division multiplexing readout have been successfully developed at NIST with very good sensitivity [25]. However, there is a tradeoff between sensitivity level and time constant owing to the degree of thermal decoupling of the detector with the substrate and with the thermal bath. Recently, the best results obtained with TES in near-infrared single-photon detection have been demonstrated at very low temperature (0.1 K) on tungsten film transition and are rather slow ($>20$ µs) [17]. This latter work has exhibited an excellent photon number resolution. In contrast, YBaCuO TES epitaxially grown on self-suspended structures are properly operating at 85 K and can be relatively fast ($\approx 6$ µs) when deposited on a silicon membrane [26].

2.3.2. HEB. The class of superconducting HEB detectors is based on the out-of-thermal-equilibrium hotspot mechanisms occurring in very thin (a few nm thick) superconducting bolometer films [27, 28]. In a picosecond time scale, the photon energy is locally converted into a resistive hotspot (typical diameter 10 nm), the effective temperature of quasiparticles is higher than that of the lattice and bath [29, 30]. The deposited single-photon energy can be removed from the HEB in tenths of picoseconds. This time scale depends on the material electron–electron and electron–phonon interactions, on relaxation characteristic times and on the quasiparticles and phonons heat diffusivity to the substrate [31].

In HEB SSPD, the superconducting layer is made of an ultra-thin ($\approx 5$ nm) and narrow ($\approx 200$ nm) stripe of superconductor that is operated at a temperature well below $T_c$ under a dc current bias just below $I_c$. The absorption of a photon leads to a resistive hotspot that spreads out before relaxing. This hotspot forces the current to concentrate on the sidewalks. Current density exceeds then the critical value $J_c$, and a short voltage pulse of about 20 ps is generated [32]. The dead time is of about 50 ps allowing very large counting rates. The very short timing jitter of 18 ps [15] also allows very accurate correlation experiments.3

HEB detectors made of thin superconducting films ($\approx 5$ nm thick) of niobium nitride (NbN) have been found to present the best figures of merits for detecting single visible optical photons

3 Note that the integrated circuit industry makes use of the very short timing jitter featured by HEB photodetectors to debug new devices and diagnose chip failures [33]. Indeed, HEB detectors allow the detection of the light emitted by CMOS with a very accurate time resolution revealing a very useful timing information from the circuit.
Figure 1. Picture (500 × 500 µm^2) of a NbN HEB meander pixel and of its coplanar microwave readout circuit (left); detailed observation by transmission optical microscopy of the meander covering a 10 × 10 µm^2 area (right).

at a temperature of 4 K [32, 34]. This material features a short electron–phonon scattering time constant and a convenient critical temperature (T_c ≈ 11 K ≫ 4 K).

It has also been found that characteristic times of high-T_c cuprate superconductors (HTS) such as YBaCuO are even shorter than in NbN, making HTS-HEB operating at or above liquid nitrogen temperature (77 K) attractive for future fast photon detectors [35, 36].

Figure 1 shows the structure of HEB SSPD. The NbN HEB is formed of a single layer meander patterned in a very thin layer (about 4 nm thick) of superconducting NbN of suitable composition and crystalline properties. Gold connections are used for dc electrical biasing and for extracting the fast (>10 GHz) transient electrical photovoltage from the HEB.

The quantum efficiency of the HEB SSPD should then depend on the following parameters: (i) the filling factor of the meander structure in the pixel, (ii) the photoabsorption coefficient in such a very thin layer, and (iii) the electronic signal to noise ratio of the detector [15, 24].

3. Fabrication and material characterization of the NbN HEBs

We describe here the fabrication and characterization of thin NbN films and meanders suitable for HEB-SSPD operating in the near-infrared and visible wavelengths. It should be mentioned that the constraints for fabricating good-quality NbN HEB devices used as THz mixers or for other analogue and digital high-frequency superconducting electronic circuits are rather similar [37, 38].

3.1. Importance of the substrate

R-plane sapphire (1102) and MgO (100) oriented are the most frequently used substrates for elaborating very thin superconducting NbN HEB applied to SSPD and to other high-frequency devices. Such large electronic gap and chemically stable oxide substrates are transparent in the visible and infrared wavelength. These substrates also present a very low tangent loss in the microwave regime up to THz frequencies. They are correctly adapted (crystalline lattice matched) for epitaxy of very thin NbN films in the superconducting cubic-B1 phase.
Epitaxial NbN film quality, or at least large grain size and good electrical coupling between NbN grains, is required in such thin films (few nm thick) for preventing the detrimental effect of NbN grain boundaries. Indeed, these boundaries behave as tunnel barriers leading to the insulating state in granular NbN below 10 nm [39]. For polycrystalline NbN layers thicker than 10 nm, the superconducting behaviour of the granular film is controlled by a Josephson junction network array inducing a broad superconducting transition in temperature and small superconducting critical current density at low temperature, associated with an excess of low-frequency electrical noise [40, 41]. To get good HEB detector properties, NbN epitaxial film quality is required across the whole wafer size. Good uniformity and reproducibility in the electrical and superconducting properties of the NbN layers thinner than 8 nm is also required on film areas higher than 20 cm². Particular care has, thus, to be taken both on the substrate cleanliness and on its surface steps regularity as well as on the substrate heater uniformity and the precise control of the most critical deposition parameters.

### 3.2. Growth conditions and structural characterization of NbN films

Epitaxy of very thin (2.5–30 nm) NbN films with relatively high superconducting critical temperature $9 \, \text{K} < T_c < 16 \, \text{K}$ is achieved by dc magnetron sputtering from a 6-in diameter niobium target in a reactive (nitrogen/argon) gas mixture on MgO (100) unheated (or preferably heated) substrate and also on R-plane sapphire substrate (3-in in diameter) only when heated above 500 °C [42]. Deposition of NbN layers at high substrate temperature ($\approx 600 \, \text{°C}$) on R-plane sapphire requires a good degassing process of the vacuum chamber and a reproducible heat coupling between the heater and the wafer. The precise control of the nitrogen gas flow inducing Nb target nitridation and of the total pressure is extremely important. The accurate control of the NbN deposition rate (associated with Nb magnetron target current and voltage) and of the shutter controlling the deposition time are also essential.

After the growth, the surface of the thin NbN layer is passivated to prevent the native NbN$_X$O$_Y$ oxide formation and subsequently degradation of the very thin NbN layers under ambient atmosphere. This is achieved in situ, after cooling, by deposition of a very thin (1.5 nm) amorphous aluminium nitride layer reactively RF-sputtered in pure nitrogen from an aluminium target.

Structural and morphological properties of thin NbN layers have been studied and correlated to dc film resistivity and square resistance measurements to optimize both the film characteristics and its reliability with regard to SSPD detector performance. By using high resolution transmission electron microscopy (HRTEM) and x-ray diffraction methods (XRD) it has been shown previously [40]–[42] that NbN layers are (100)-epitaxially oriented with a low level of strain when deposited on cubic MgO (100) and are also (100) oriented when deposited at 600 °C on R-plane sapphire substrates. However, when deposited on R-plane sapphire, the cubic NbN layer is probably highly strained up to a critical thickness ($< 30 \, \text{nm}$), where the hexagonal NbN phase nucleation is observed with a much lower $T_c$ ($T_c$ is found below 2 K). Figure 2 shows a STM scan of the surface of a 3.5-nm-thick NbN layer performed at room temperature. One can clearly see R-plane sapphire substrate terraces ($\approx 0.4 \, \text{nm high}$) spaced by 20 nm. These terraces are replicated in the NbN layer attesting the very good two-dimensional coverage of the substrate surface by the NbN layers. The same property has been observed on MgO (100) substrates.

In summary, it has been shown [23] that good epitaxial superconducting NbN thin films in the B1 cubic phase can be routinely obtained on large-area R-plane sapphire substrates (up to
Critical current versus temperature for a 3.4-nm-thick NbN film leading to a critical current density of $4.6 \times 10^6$ A cm$^{-2}$ at 4.2 K. Inset: STM image scan of a $0.3 \times 0.3 \mu m^2$ surface area showing good uniformity and little roughness of NbN covering the vicinal surface step structure, spaced 20 nm of the sapphire surface.

4-in in diameter) under a critical thickness limit. Better NbN quality has been achieved on other cubic single crystal substrates (MgO, CaF2, YSZ, etc), which are however not available on large sizes. Silicon, silicon on insulator (SOI) and SiC substrates can also be considered for the future of SSPD devices but they are more difficult to handle with sputter deposition. The remaining amorphous silicon oxide, nitride or carbide surface layer prevents any NbN epitaxial growth possibility. It is difficult to maintain a clean oxide-free surface after ex situ substrate preparation, and the in situ oxide removal requires an ultra-high vacuum deposition chamber.

3.3. Electronic and microwave characterization of superconducting properties of NbN nanolayers

3.3.1. Superconducting-normal transition. The critical current density of a NbN film is plotted in figure 2 as a function of temperature. Figures 3 and 4 display the resistance of a very thin NbN film (3.4 nm) epitaxially grown on R-plane sapphire as a function of temperature. It indicates a critical temperature $T_c$ of 11.3 K with a 1 K transition width, shown in the inset of figure 3. The resistance ratio ($R_{300K}/R_{20K} = 0.68$ for the sample) is less than unity as is often the case. The resistivity at room temperature is 146 $\mu \Omega$ cm and the critical current density at 4.2 K is rather high: $J_c = 4.6 \times 10^6$ A cm$^{-2}$. It is observed in figure 4 that a dc current bias above 5 $\mu$A heats the bridge only when the operating temperature is higher than 11 K and that dc current bias of 12.5 $\mu$A keeps the meander at the bottom of the resistive transition up to 9 K. Such curves are useful for the determination of the dc current biasing at the operating temperature.

Generally, transition metal nitride superconductors and specially NbN are not considered as good metals even if their superconducting energy gap and $T_c$ amplitude values are among the largest in the conventional BCS superconductors [43].

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Figure 3. Temperature variation of the resistance of a 3.4-nm-thick epi-NbN layer deposited on R-plane sapphire. Inset: film parameters and the superconducting transition.

Figure 4. Resistance of the SSPD meander (160 \( \mu \text{m} \) long and 0.3 \( \mu \text{m} \) wide) after processing and applying different static dc biasing currents.
3.3.2. Superconducting energy gap. We have performed tunnel spectroscopy at low temperatures on NbN samples with thicknesses ranging from 3.5 to 10 nm and we observed that the superconducting energy gap $\Delta(T)$ is well fitted by a BCS model with a strong coupling measured parameter indicating $2\Delta(0) = 4.15k_B T_c$ for a 10-nm-thick NbN film (cf figure 5). The $T_c$, $J_c(0)$ (critical current density at $T = 0$ K) and $\Delta(0)$ values are decreasing when the NbN thickness decreases as expected, but the quasiparticle energy gap remains empty of states down to very thin films. Experiments performed with a low-temperature scanning tunnelling microscope (LT-STM) on scans executed several times at different locations on the sample indicate a very good spatial uniformity. The dc resistivity, superconducting energy gap, superconducting transition temperature are constant over the whole sample.

Microwave surface resistance measurements in a cavity at about 10 GHz have been done on selected NbN films [40]. Transmission far-infrared (TFIR) measurements [44] give characteristic ac conductivity parameters such as plasma frequency and collision time. They show that the superconducting NbN energy gap is strongly sensitive to the crystalline properties of the substrate surface. Table 2 presents the rather large NbN energy gap observed on MgO substrates (confirmed by tunnel spectroscopy measurements) and the lower values obtained on silicon wafers even after introducing a thin MgO buffer layer. In complement, we have also measured in the visible and near-infrared wavelengths the optical transmission and reflection of our epitaxial NbN films grown on sapphire. This indicates an absorption of about 20% for a 3.5-nm-thick NbN layer.

**Figure 5.** Observation by LT-STM of the superconducting energy gap variation with temperature in a 5-nm-thick NbN epi-layer deposited on R-plane sapphire. Inset: measurement at 1.6 K of the quasiparticle density of state versus voltage (or energy) indicating completely empty electronic states below 1.5 meV and of the clear superconducting energy gap at 2.38 meV. The gap is well fitted by the ‘BCS’ model with a ‘pair-breaking parameter’ $\Gamma = 0.02$. 

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Table 2. Observation of the correlation between dc resistivity measured at 300 K, microwave surface resistance at 10 GHz and 3 K (corrected using the thickness factor) and photon absorption (or tunnel) energy gap in $\approx 20$-nm-thick NbN films deposited on various substrates; the NbN films on MgO and on sapphire are epitaxial, and those on Si are polycrystalline and textured when a MgO buffer layer is added.

| NbN/R-Al_2O_3 | NbN/MgO (100) | NbN/MgO/Si | NbN/Si (100) |
|---------------|---------------|------------|--------------|
| $\rho_{300}$ K ($\mu \Omega \text{cm}$) | 100           | 60         | 120          | 140          |
| $R_s$ at 10 GHz | $\approx 7 \mu \Omega$ | $\approx 12 \mu \Omega$ | $\approx 20 \mu \Omega$ |
| $f(\Delta_0)$ (THz) | 1.2 (tunnel) | 1.4 (TFIR) | 1.3 (TFIR) | 0.9 (tunnel) |

used in our SSPD and close to that observed by Korneev et al [15]. Sensitive ac susceptibility screening measurements [41] and inductive measurements made on patterned NbN SQUIDs indicate that very thin NbN films have a large effective London penetration depth value and present a rather large kinetic inductance effect which should be taken into account in the SSPD electrical switching mechanisms and associated time constant analysis [42, 45, 47, 48].

3.4. Nanopatterning

We have developed a nanopatterning process of the thin NbN layer based on electron beam lithography and reactive ion etching (RIE) (cf figure 6) [46]. The $10 \times 10 \mu m^2$ pixel area is covered by a 200-nm-wide meander structure, leading to a filling factor of about 0.5. The difficult processing task consists of patterning the meander structure with a rather regular shape to get the small dimension meander strip as homogeneous as possible. We use a direct e-beam written resist mask to protect NbN narrow strips during etching. In the 3.4-nm-thick epitaxial NbN film, the strip’s width can be as narrow as 200 nm. The deposition of a 0.08 $\mu$m-thick PMMA 950 K 2% electron resist layer is followed by electron beam lithography with the following parameters: $U = 30$ kV, $I = 15$ pA, dose = 230 C cm$^{-2}$. The developer used is MIBK/isopropanol (1 : 3) solution and isopropanol. Then we directly etch the NbN layer using RIE in SF_6 for defining the stripes (see figure 7). The electron resist is finally removed with RIE in pure oxygen. The next step is the lift-off of the Ti/Au contact pads; we use a high-frequency 50 $\Omega$ coplanar waveguide patterned structure to allow operation of the device in the GHz range. The last step is the definition of the pixel area: an AZ1512 photoresist layer is deposited over the stripes and all the unprotected NbN areas are etched using SF_6 + O_2 RIE, as shown in figure 6. Finally, we observe, as other authors [15] that the value of the pixel filling factor of about 50–60% induced by the nanopatterning is the main practical parameter limiting the quantum efficiency of the NbN HEB detector. It is why more precise nanopatterning tools such as AFM anodization, which has demonstrated the capability of patterning 30 nm wide tracks in our thin NbN layers [45], should be used in the future development of NbN SSPD.

4. Conclusion

In this paper, we have pointed out the capability of recent SSPD technologies to offer an interesting alternative to usual single-photon counters for applications in photonic quantum information
Figure 6. Strip detector fabrication process: (a) Patterning of 200-nm-wide strips using direct electron beam lithography with PMMA electron resist on the thin NbN film. (b) RIE of the NbN film with SF6 and removal of the resist layer in an oxygen plasma. (c) Ti/Au lift-off of the contact pads. (d) Optical lithography with AZ1512 photoresist to protect the pixel area then (e) RIE in SF6 + O2 of unprotected NbN and removal of the photoresist. The NbN meander structure appears in (f).

Figure 7. SEM image of a part of an NbN SSPD device. The width of the stripes and the distance between them are the same: 300 nm. The pixel filling factor is therefore 0.5.

processing as well as in astronomy and telecommunications. Besides the specific merits of TES and STJ devices, the focus has been made on HEB patterned in very thin single crystalline NbN films. HEB’s main feature consists in ultrafast single-photon detection. In particular, high rate (2 GHz) photon counting at the telecom wavelengths of 1.3 and 1.55 µm has been observed very recently [15]. This latter reference also reports the best quantum efficiency (10%) in the infrared for HEB. But this value is still far from the quantum cryptography and photonic quantum logic
gate requirements. We think that the quantum efficiency of NbN HEB can be further improved in the infrared through three contributing factors: (i) by lowering the electronic noise (NEP) with a more homogeneous NbN material and patterning quality facilitating the SSPD biasing conditions at a suitable operating point, (ii) by improving the photon absorption in the active NbN layer and (iii) by increasing the meander filling factor by using more efficient tools in nanolithography.

We have also shown that the NbN HEB SSPD can be collectively and reproducibly produced on rather large R-plane sapphire wafers (3 in and more in diameter) and efficiently protected from aging effects by using a thin AlN layer. Finally, we mention that achievement of small size focal plane array of NbN HEB SSPD should be possible by using a fast multiplexing readout scheme such as those based on superconducting SQUIDs and RSFQ logic gates.

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