High-Speed Superconducting Single Photon Detectors for innovative astronomical applications

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\textbf{Abstract.} Superconducting Single Photon Detectors (SSPD) are now mature enough to provide extremely interesting detector performances in term of sensitivity, speed, and geometry in the visible and near infrared wavelengths. Taking advantage of recent results obtained in the Sinphonia project, the goal of our research is to demonstrate the feasibility of a new family of micro-spectrometers, called SWIFTS (Stationary Wave Integrated Fourier Transform Spectrometer), associated to an array of SSPD, the whole assembly being integrated on a monolithic sapphire substrate coupling the detectors array to a waveguide injecting the light. This unique association will create a major breakthrough in the domain of visible and infrared spectroscopy for all applications where the space and weight of the instrument is limited. SWIFTS is an innovative way to achieve very compact spectro-detectors using nano-detectors coupled to evanescent field of dielectric integrated optics. The system is sensitive to the interferogram inside the dielectric waveguide along the propagation path. Astronomical instruments will be the first application of such SSPD spectrometers. In this paper, we describes in details the fabrication process of our SSPD built at CEA/DRFMC using ultra-thin NbN epitaxial films deposited on different orientations of Sapphire substrates having state of the art superconducting characteristics. Electron beam lithography is routinely used for patterning the devices having line widths below 200 nm and down to 70 nm. An experimental set-up has been built and used to test these SSPD devices and evaluate their photon counting performances. Photon counting performances of our devices have been demonstrated with extremely low dark counts giving excellent signal to noise ratios. The extreme compactness of this concept is interesting for space spectroscopic applications. Some new astronomical applications of such concept are proposed in this paper.

1. Introduction

We started to investigate possible applications of Superconducting Single Photon Detectors (SSPD) by the beginning of 2001, attracted by the amazing performances promised by these superconducting performances. Since this date, progress of our technology and achieved performances were regularly reported ([1], [2], [3], [4], [5]).

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We report in this paper a new application of micro-spectrometers, called SWITS, which associates the light from a waveguide to an array of SSPD nanowires $\lambda/4$ distributed across the waveguide. If the waveguide is ended by a mirror, one can show that we can reconstruct the spectrum of the light with SWIFTS. This is mainly based on the Lippman principle. This paper reports on the progress of the fabrication of all the elements needed to build this kind of micro-spectrometer.

2. SSPD device fabrication

The first step was to fabricate SSPD with a classical geometry, i.e. a 10 $\mu$m x 10 $\mu$m meander with a filling factor of 50% (see Figure 1). This type of devices is fabricated to develop the SSPD technology and verify their photon counting performances. The final application of this paper will require a different geometry with an array of linear nanowires deposited across a light waveguide (see section 5.).

With the meander geometry of the Figure 1, the difficulty is to get the small dimension stripe as homogeneous as possible. Thickness of the NbN layer used to fabricate the SSPD is routinely ~ 4 to 5 nm. We use a direct method to etch narrow stripes in the thin epitaxial NbN film: the deposition of a 150 nm NEB22A2 negative tone resist layer from Sumitomo is followed by electron beam lithography with these exposition parameters optimized for 100 nm lines with 50% fill factor: $U= 100$ kV and the dose 105 $\mu$C/cm². The lines were developed after post exposure bake in Rohm & Hass MF702 for 45s. Then we directly etch the NbN layer using Reactive Ion Etching (RIE) with SF₆/O₂ to define the stripes used for connexion to the fast amplifier by a coaxial cable. The patterning issues for the SSPD fabrication is fully described in [5].

Then the remaining resist is stripped. The only successful stripping process, with respect to the conservation of the NbN transport properties, is the one using wet etching with EKC-LE (see [6]). The next step is the lift-off of the Ti/Au contact pads. The Figure 1 shows the SEM image of a meander realized. The width of the stripes and the distance between them are the same: 150 nm corresponding to a filling factor of 50% which can be increased to 70% by e-beam improvements of the patterning definition. The Figure 2 shows the gold coplanar line used for the device biasing and coupling to the fast amplifier to be used for photon detection. The Figure 3 shows the different steps of the SSPD fabrication detailed above.

![Figure 1: 10µm x 10 µm SSPD detector fabricated at CEA Grenoble/DRFMC with 150 nm width NbN lines.](image1)

![Figure 2: Coplanar line for biasing and fast signal measurement.](image2)
3. SSPD characterisation

3.1. NbN films characteristics

To get good SSPD photon detection performances, one needs good uniformity and reproducibility in the electrical and superconducting properties of the NbN layers thinner than 5 nm across the whole wafer size. Thus due to the high specific resistance of NbN grain boundaries, epitaxial film quality is required or at least large grain size and good electrical coupling between NbN grains (see [2]). Highly textured NbN thin films (3.5-5 nm) with $9K < T_c < 14K$ and $J_c \sim 10^6 A/cm^2$ at 4K have been achieved by dc magnetron sputtering from a 6-inch 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 ([4], [6]). The surface of the NbN layer is passivated in-situ, after substrate cooling at room temperature, by reactively RF-sputter deposition of a very thin (1.4 nm) aluminum nitride layer in pure nitrogen from an aluminum target. This prevents native NbN oxide formation on top of the NbN film and subsequent degradation of the thin NbN layers under ambient atmosphere. The AlN layer has been found by X-ray diffraction and ellipsometry to be composed of nanometer size grains. This leads to an atomically flat NbN-AlN surface only showing the replica of substrate surface atomic terraces. Recently about 1-2 nm thick MgO, Nb or Ta, sputtered buffer layers have been used to growth textured NbN nano-layers on silicon wafers with $T_c$ above 6K and sharp superconducting transition, making possible the realization of NbN SSPD on top of buried optical wave guides made on silicon wafers.

3.2. I/V curves of SSPD

Typical I/V curves obtained at 4.2 K with our devices are shown in the Figure 4 and in the Figure 5. The Figure 4 shows the I/V curve, the detector bias point and the 50 $\Omega$ source impedance of the biasing circuit. Also shown in this figure is the “hot spot” plateau: in this region, the “hot spot” is induced by Joule heating. The resistance seen at low current in the superconducting state is the resistance of the coaxial cable due to the 2 points DC wiring. The Figure 5 shows the same I/V curve, but for higher voltages/currents. This figure shows the transition of the different branches of the meander mainly due to cross-heating effects between meander nearest branches and in-homogeneity of the meander width. An e-beam patterning having more precise definition allows to decrease this effect.
and allows to obtain higher biasing currents, this shows the importance of the NbN patterning definition.

4. Photon counting experiments

Photon counting experiments were performed with SSPD meander geometry showed above. The test set-up consists in a cryostat head system plunged in a liquid helium tank allowing to achieve a temperature of 1.8 K by pumping the cold head. The SSPD is illuminated by an optic fiber linked to a pulsed Ti laser providing 1 ps light pulses with 80 MHz rate of ~1 μm photons. In the cryostat head, the fiber position can be tuned by an XYZ stage of cryogenic piezzo-movements (see Figure 6). The SSPD is biased using a filtered current source and a bias Te. The connexion between the cryogenic probe and the outside of the cryostat is made using an RF coaxial cable. Electrical pulses due to the photon detection are amplified by an RF detection chain having a 20 GHz bandwidth. This allows to detect the 20 ps pulses from the SSPD. After amplification, the pulses are counted using a discriminator and a pulses counter. In general, SSPD are biased at 90% of their critical current for the best trade off between photon counting performances and dark counts minimization.

The Figure 8 demonstrates the photon counting capability of our SSPD and of our detection setup. This figure shows the number of counted pulses as a function of the bias current for 2 light wavelengths: 0.93 μm and 1.55 μm. Also shown are the dark counts (number of detected pulses without illumination). The Quantum Efficiency (QE) was also evaluated and is showed on the figure. When the bias current increases, the efficiency of the photon detection increases but the number of dark count increases also. So a trade off has to be found between the detector efficiency and the dark count. In this figure, a good trade off could be obtained with a bias current of ~17 μA (Ib/Ic=0.9 where Ib is the bias current and Ic is the critical current), in that case the ratio between dark counts and counted photons is 10^-4. When the photon wavelength increases, the detector is less efficient because the photon has less energy to create the hot spot on the SSPD and to induce the pulse when the bias current is close to the critical current. By plotting the number of counts as a function of the light power, we obtained a linear curve, which demonstrates that the detector works in the single photon counting regime.
**Figure 6**: picture of the cryogenic head experimental set-up showing the 50 GHz probe (allowing to detect very fast signals), the optical fiber for the device illumination, the SSPD and the motors which allow a 3D scan of the fiber in front of the detector.

**Figure 7**: photon counting demonstration of CEA Grenoble SSPD at 4.2 K (120 nm width) characterized at the Institut Néel. Left square points correspond to measured QE’s as a function of the bias current for 0.93µm photons and middle square points to 1.55 µm photons. Black plain square points on right side correspond to dark counts.
5. The SWIFTS micro-spectrometer based on SSPD nanowires

SWIFTS (Stationary Wave Integrated Fourier Transform Spectrometer) is an innovative way to achieve very compact spectro-detectors using nano-detectors coupled to evanescent field of dielectric integrated optics. The principle of SWIFTS in fully described in [7] and is based on the Lippman concept. In 1891, at the “Académie des Sciences” in Paris, Gabriel Lippmann presented a beautiful colour photograph of the sun’s spectrum obtained with his new photographic plate. Later, in 1894, he published an article (see [8]) on how his plate was able to record colour information in the depth of photographic grainless gelatine and how the same plate after processing (development) could restore the original colour image merely through light reflection. He was thus the inventor of true interferential colour photography and received the Nobel Prize in 1908 for this breakthrough. Unfortunately, this principle was too complex to use for colour photography, but Lippman concept remains nonetheless extremely interesting for spectroscopic applications.

In the SWIFTS configuration, light to be detected is coupled into a single mode waveguide terminated with a mirror. The Figure 8 shows the principle of SWIFTS. When reflected onto the mirror, waves become stationary (see Figure 8-a). If the light is polychromatic, the sum of the stationary waves forms an interferogram called “Lippman interferogram” (see Figure 8-b). Miniature localized nano-detectors are placed in the evanescent field (see Figure 8-c) of the waveguide mode in order to extract only a small fraction of the guided energy. This peripheral detection approach allows proper sampling of the standing wave using relatively small size detectors in comparison with the quarter wavelength of the guided light. Unlike a classical Fourier interferogram, Lippmann’s interferogram starts at the surface of the mirror with a black null optical path difference fringe such that only one side of the fringe packet is detected. In this way the whole energy is recovered using a minimum number of detectors. This principle thus acts like a spectrometer with simultaneous recorded Fourier transforms, i.e. no moveable part is required to record the information needed to restore the spectrum. The first validation of the SWIFTS concept is fully described in [7] and uses gold nanowires diffracting the light of the waveguide. Light was sensed using a scattering-type scanning near field optical microscope (s-SNOM) which allows probing of the optical near-field of waveguides with nanometre resolution. This replaced the array of SSPD in the preliminary demonstration.

To take fully advantage of the SWIFTS efficiency, development of nanodetectors is therefore needed. SSPD is one of the good candidates for achieving this kind of detection. The ultimate application of this concept would require a number of SSPD nanowires between ~ 100 and 1000, linearly distributed with $\lambda/4$ steps.

While making spectroscopic instruments more robust and cheaper through the use of integrated technologies, SWIFTS is a general concept that can be used in a large number of applications and especially in optics where micro-spectrometers are essential. These applications would be space-borne spectrometry, metrology, endoscopy, gas and chemical sensors, colour photography and parallel spectral imaging.
Figure 8: Stationary Wave Integrated Fourier Transform Spectrometer (SWIFTS) principle. a) The forward propagating wave coupled in the waveguide is reflected on the mirror, leading to a stationary wave. b) Nanodetectors are placed in the evanescent field of the waveguide, each detector sample a small part of the flux over a distance smaller than the fringe pattern. Then, if the entrance light is polychromatic, the resulting superimpose of stationary wave gives a Fourier interferogram sampled by nanodetectors. c) 3D view of SWIFTS for three colors entrance light where the three mixed interferograms.

6. Astronomical perspective for SSPD

It is well known that astronomers are mainly interested by the detector’s sensitivity rather its speed. Contrary to that, we would set an astronomical scene for SSPD considering the following two examples. First of all, optics developed by astronomers is often based on wave description but forgets the quantum description of light, despite successful attempt by Hanbury-Brown & Twiss to measure Sirius diameter using intensity interferometry in 1956 [9]. Two decades after in 1974, they measured the diameter of 32 stars brighter than 2.5 mag [10]. This interferometric technique is based on correlation measurements on photons arriving date. This one was severely limited by the acquisition rate and the precision of photon time dating. Today, SSPD are able to be 1000 times faster that 1960 decay’s PM, that means that we could win at least this factor by both enlarging the spectral band and decreasing the double events detection time. Additional gains come from the higher quantum efficiency, the lower dark noise and finally from the use of an SSPD array installed in modern grating spectrometers. Contrary to 1994’s feeling of R. Hanburry Brown in [11], all these factors would permits astronomers to gain several magnitudes on current projects of kilometric array interferometers.
that use unaffordable and complex optical delay lines. The second very exiting application, close to the previous one, is the capability offered by very fast and noiseless detectors to reveal the quantum-optical statistics of photon arrival time: the goal in that case is to determine if the light is “bunched” as in laser emitting light or “anti-bunched” as in resonant fluorescence compared to the random photon statistic emitted by a classical black body. Astronomers have wrote proposals for that purpose, this is the main goal of the instrument QuantEYE [12] that has been proposed to the ESO Extremely Large Telescope (ESO-ELT). Performances are deeply dependant of the quality of time dating. SSPD included in SWIFTS mounting is a very innovative way to achieve simultaneously bunched events detection and spectroscopy of them. For example, to isolate laser emission in the environment of star η Car, a high spectral resolution is desirable. An another advantage of SWIFTS concept is that bunched events are spread over the entire collection of detectors, this limits the occurrence of double photons detected by the same detector at the same time.

7. Conclusion

SWIFTS is a totally new concept for building extremely compact spectrometers that can be used in a large number of applications where cost and compactness drive the choice of the technology used. This spectrometer is based on the Lipmann concept, never used this way. First demonstration of this concept has been made by using gold nanowires instead of the SSPD array, diffracting the light of the waveguide. This is the first attempt for demonstrating the SWIFTS concept and for achieving very small integrated 1D spectrometer suitable in applications where micro-spectrometers are essential.

The SWIFITS spectrometer associates an array of nanodetectors and a waveguide with a mirror at its extremity leading to a stationary wave. The evanescent field of the waveguide is sampled by the array of nanodetectors allowing to recover the light spectrum. SSPD are one of the best solutions for this kind of nanodetectors. In that case, a simple nanowire across the waveguide is sufficient to build a detector, the long NbN meander is not needed, which simplifies the difficulty to build a long meander and minimizes the stripe width variation.

We fully manage all steps of the application, from the SSPD fabrication and characterisation to the final application. We have fabricated state of the art SSPD with (100) textured NbN thin films (3.5-5 nm) having Tc between 9K and 14K and Jc ~ 4.10^6 A/cm^2 at 4K. We have demonstrated photon counting performances of our detectors at 0.93 μm and 1.55 μm.

Next step of this study is to improve the SSPD efficiency by a better control of the e-beam patterning and the NbN film quality improvement. In a second step, we will associate a small linear array of SSPD nanowires with a waveguide built in a Sapphire substrate in order to achieve the first demonstration of the SWIFITS concept with SSPD nano-detectors.

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