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Fabrication of High-Speed Single Photon Detectors in NbN for Quantum Information Processing

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Abstract. We describe the collective fabrication and characterization of superconducting single photon detectors (SSPD) made of a superconducting NbN meander, suitable for near-infrared applications. The NbN layer acting as the photon absorber is deposited epitaxially on a three inch diameter R-plane Sapphire heated substrate by DC-Magnetron sputtering from a Nb target in a reactive mixture of nitrogen and argon gas. Very thin NbN (~4 nm) films superconducting up to 12 K with a rather large critical current density are in-situ covered by a 1.4 nm thick room temperature sputtered AlN layer protecting NbN from oxidation. Two reliable patterning processes has been developed successfully, one based on electron beam lithography, the second based on selective NbN film anodization under an AFM tip. The filling factor obtained with 150 nm wide stripes in the meander pixel is about 0.5 with e-beam lithography and improved up to 0.8 with AFM patterning. In order to achieve an improved optical coupling of the SSPD by using wafers integrating ion implanted IR waveguides, growth studies of NbN layers have been focused on R-plane Sapphire and silicon substrates. We present optical and superconducting properties of NbN layers by FTIR, ellipsometry and STM.

1. Introduction

Superconducting single photon detectors (SSPD) based on hot electron bolometer (HEB) made of niobium nitride ultra-thin meander films have been proved to combine high sensitivity combined with some energy resolution, high speed, low jitter and potentially high quantum efficiency [1-4]. However photon absorption yield and detection efficiency of the NbN SSPD has to be is to be significantly improved in the near infrared (1.3-1.5µm) in order to make feasible telecoms and quantum cryptography applications. In such a meander type HEB SSPD, the superconducting layer is required to be ultra-thin (< 5 nm) and the strip narrow (< 200 nm) in order to make the area were the photon impacts sensitive to the energy deposited by a single infrared photon when operated at a temperature well below critical temperature *Tc* under a dc current bias just below *Ic*. The absorption of a photon leads to a resistive hotspot that spreads out leading to the formation of a phase-slip line across the strip before relaxing. Current density exceeds then the critical value *Jc*, and a short voltage pulse of about 100 ps duration and 2 mV in amplitude, is generated and detected [1-4]. In this paper we focus on NbN ultra-thin films and dense meander devices processing for improving further the SSPD performances such as the quantum efficiency and the reliability of arrays of SSPDs.

2. Elaboration and patterning of NbN ultra-thin layers epitaxied on R-plane Sapphire

2.1. *Optimization of highly textured NbN thin film deposition.* To get good SSPD properties, 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 [5]. Highly (100) textured NbN thin films (2.5-30 nm) with 9K<Tc<16K and Jc ~ 10^7 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 [6, 7]. 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_XO_Y 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 Tc above 6K and sharp superconducting transition, making possible the realization of NbN SSPD on top of buried optical wave guides.

2.2. *SSPD meander patterning*

The process consists to optimize the patterning and filling factor of the meander acting as the pixel.

2.2.1. E-beam lithography: The difficulty is to get the small dimension meander stripe as homogeneous as possible. We use a direct method to etch narrow stripes in the thin epitaxial NbN film: the deposition of a 0.08 µm thick PMMA 950K 2% electron resist layer is followed by electron beam lithography with these exposition parameters: U= 30 kV and the dose 230 µC/cm². The developer used is MIBK/isopropanol 1:3 solution and isopropanol. Then we directly etch the NbN layer using Reactive Ion Etching (RIE) with SF_6 for defining the stripes (see Fig. 1).

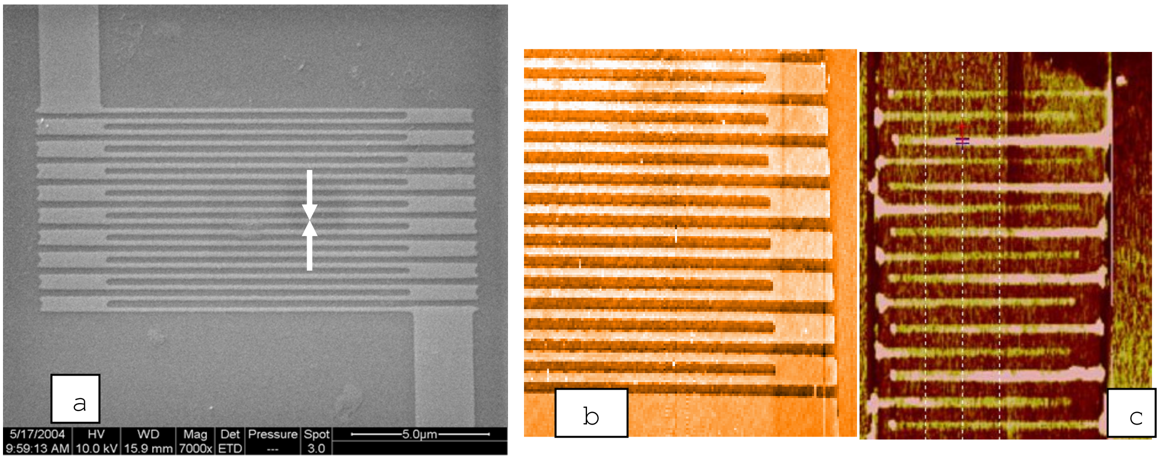

Figure 1: a: Observation of the e-beam patterned NbN meander pixel area using scanning electron microscope; b: Part of the same meander area observed by AFM; c: AFM picture of a NbN SSPD fabricated using anodization technique achieved by the AFM tip; the tracks are only about 60 nm wide which indicate an improvement of the pixel filling factor in comparison with a, b.

The electron resist is finally removed with O_2 RIE. The next step is the lift-off of the Ti/Au contact pads. 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. Figure 2-a, b shows a 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.

2.2.2. *AFM Lithography*

As shown on figure 1-c, the patterning of the tracks in the NbN meander can be minimized in area by using a complete anodization of the NbN layer achieved under a scanning AFM conducting tip. The process described previously [8] has been successfully applied to the same AlN-NbN layers grown on R-plane Sapphire without any detrimental effect on the NbN superconducting properties. Filling factor observed in the figure for 150 nm wide stripes and about 60 nm tracks is about 70% and up to 80% in other devices making this process flexible and very attractive.

3. Optical properties of the epitaxial ultra-thin NbN films on Sapphire

Optical characterization of superconducting NbN layers have been done previously by optical ellipsometry [9], and for our highly textured 30 nm thick NbN films on MgO and Si by Far Infrared transmission spectroscopy [10], indicating that like other metallic nitrides, can be described by a Drude model together with added discrete infrared modes. We measured at low temperature a collision frequency of about 350 cm^{-1} and plasma frequency of 12 600 cm^{-1} for epi-NbN on MgO and lower values for polycrystalline NbN on silicon (respectively 210 and 8000 cm^{-1}). We observed ultra-thin NbN films on Sapphire by ellipsometric spectroscopy in the UV-visible and infrared wavelengths as shown on Figure 2. Qualitatively the same behavior is found indicating that a 4 nm thick NbN layer covered by 1 nm of AlN do not differ significantly from a thicker NbN layer. It is noted that the higher value of the imaginary constant k than n value down to the visible wavelength make surface plasmons of infrared energy propagation possible in such nitride layers. We have also measured by IR spectroscopy between 1 and 2 µm, about 20% of absorption (60% transmitted and 20% reflected) for 4 nm thick un-patterned NbN films deposited on Sapphire and on Si. We work presently on new detector materials and designs using for instance optical waveguides buried in the substrates in order to better couple optically such semi-transparent NbN layers.

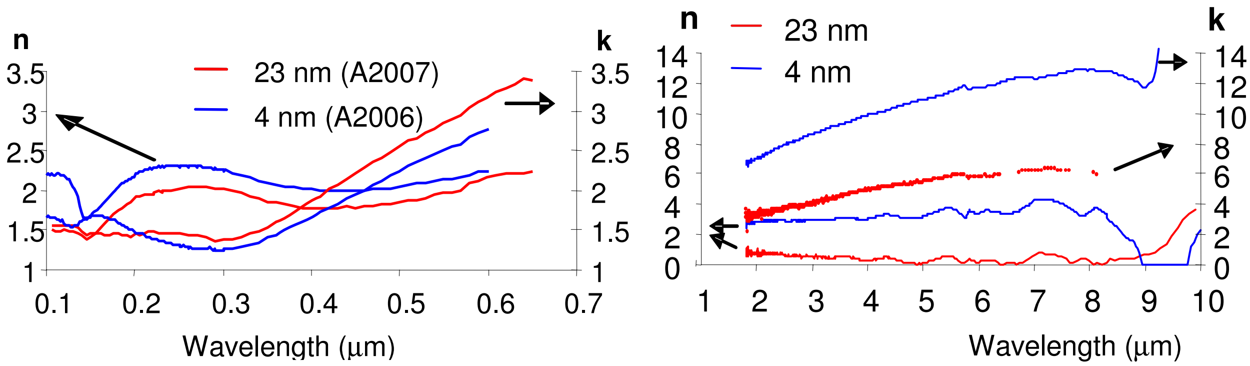

Figure 2: Spectroscopic ellipsometry characterization of the optical indices n and k, in the visible (left) and infrared (right) of two NbN films deposited on R-plane Sapphire: the first (in blue) is a 4nm thick NbN covered by 1 nm thick AlN; the second (in red) is a 23 nm thick NbN layer covered by 1 nm thick AlN. Note that the infrared spectrum is less precise due to the small size of the samples.

4. Superconducting characterization of the NbN films and meanders

NbN superconducting energy gap values measured by STM have been found uniform on the whole 3 inch wafer as well Tc and Jc values. As also shown on figure 3, the SSPD meander device is either current or voltage biased in a suitable optical set-up described elsewhere [3]. Quasi-static characteristics show a good uniformity between the critical current of the branches and low dark current values. Recently fast photo-responses have been obtained in the visible at low light intensity which will be described elsewhere. All theses data indicate that the collective processes we are using can be applied in the near future to arrays of integrated SSPD detectors.

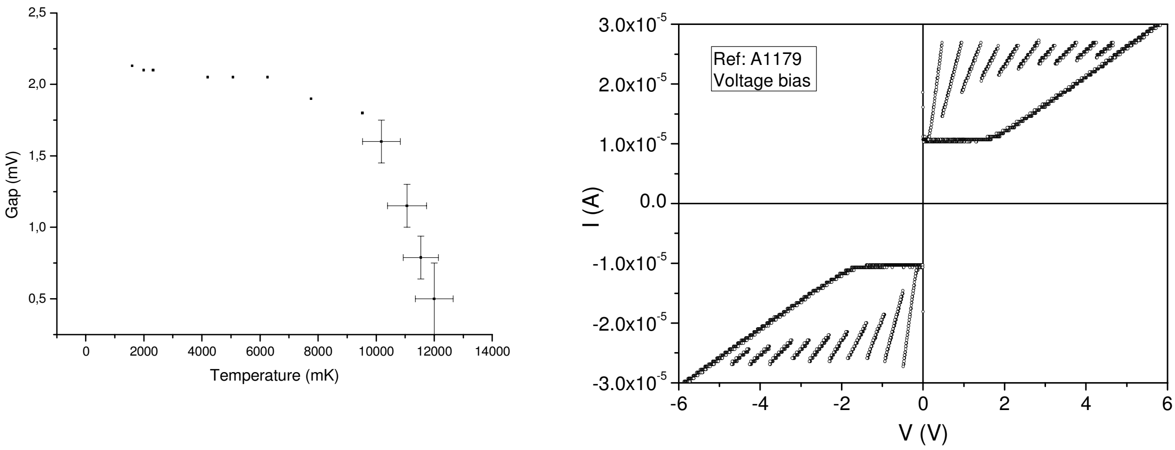

Figure 3: Superconducting energy gap versus temperature (left) observed by scanning tunneling microscopy on a 3.4 nm thick NbN film on Sapphire; electrical characteristics of a meander made of 11 stripes e-beam patterned in the same film. The meander is dc voltage biased at 2 K. One can see the stripes thermally transiting one by one to the normal state (~ 500 kΩ) with a small dispersion.

5. Conclusions

We have shown that it is possible to obtain in a reproducible way, SSPD meanders nano-structured with a large filling factor from high quality highly textured ultra-thin NbN superconducting layers grown on 3 inch Sapphire but also on other substrates like MgO or Si. Development of integrated optical coupling will open the field of SSPD applications in IC failure analysis, quantum key distribution, low light level detection in astronomy and telecoms, biomedical imaging.

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