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To cite this article: E Smirnov *et al* 2018 *J. Phys.: Conf. Ser.* **1124** 051025

Superconducting nanowire single-photon detector on lithium niobate

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Abstract. We demonstrate superconducting niobium nitride nanowires folded on top of lithium niobate substrate. We report of 6% system detection efficiency at 20 s^{-1} dark count rate at telecommunication wavelength (1550 nm). Our results shown great potential for the use of NbN nanowires in the field of linear and nonlinear integrated quantum photonics.

1. Introduction

It was shown that for optical quantum computations it is necessary to have a photon source, a single-photon detector and only linear optical elements (phase shifters and splitters) [1]. The most promising method for implementing optical calculation is the use of quantum-photonic integrated circuits (QPICs) that combine all the necessary components on a single chip [2]. To date, there are several main platforms used for the QPICs: silicon, silicon nitride, gallium arsenide, diamond, silicon carbide and lithium niobate (LN). Each platform has its advantages and disadvantages for quantum information protocols. therefore, work on QPICs is going in parallel [3]. Unlike other materials, LN has a strong $\chi^{(2)}$ nonlinearity, birefringence, high electro-optic effect and can be used not only for linear optical elements, but also for high efficient on-chip single-photon sources, active phase shifters and modulators. Here we show our recent results on the fabrication of one of the key QPIC element – superconducting nanowire single-photon detector (SNSPD or SSPD) [4] on a lithium LN substrate.

2. Device fabrication and experimental results

For SNSPD fabrication we used commercially available Z-cut LN substrate (from Gooch and Housego). After cleaning the surface of the 12x12 mm^2 LN substrate we deposit an ultra-thin niobium nitride (NbN) film with a nominal thickness of 7 nm ± 0.5 nm by a reactive magnetron sputtering in Ar and N_2 gases atmosphere. We reached a maximum critical temperature T_c = 11.3 K for the films deposited at a substrate temperature T_S = 800°C with partial pressures of Ar and N_2 of 6×10^{-3} and 2.5×10^{-4} mbar, respectively (Figure 1a). The sheet resistance of the deposited NbN film measured at room temperature was 471 Ω/sq. We used photolithography and standard lift-off technique for preparing Au-contact pads and alignment marks as well as e-beam lithography and reactive ion etching (RIE) in SF_6 for meander type NbN nanowire formation.

Dependency of the system detection efficiency on the bias current, measured at a telecommunication wavelength λ=1550 nm is shown in Figure1b. We found efficiency at the level of 6 % at 20 s^{-1} dark count rate (DCR). Unlike amorphous superconducting detectors, such as recently demonstrated WSi on lithium niobate [5], NbN detectors have a higher operating temperature, which significantly reduces the cryogenic equipment cost, as well as a higher bias current, which improves jitter due to better signal-to-noise ratio.

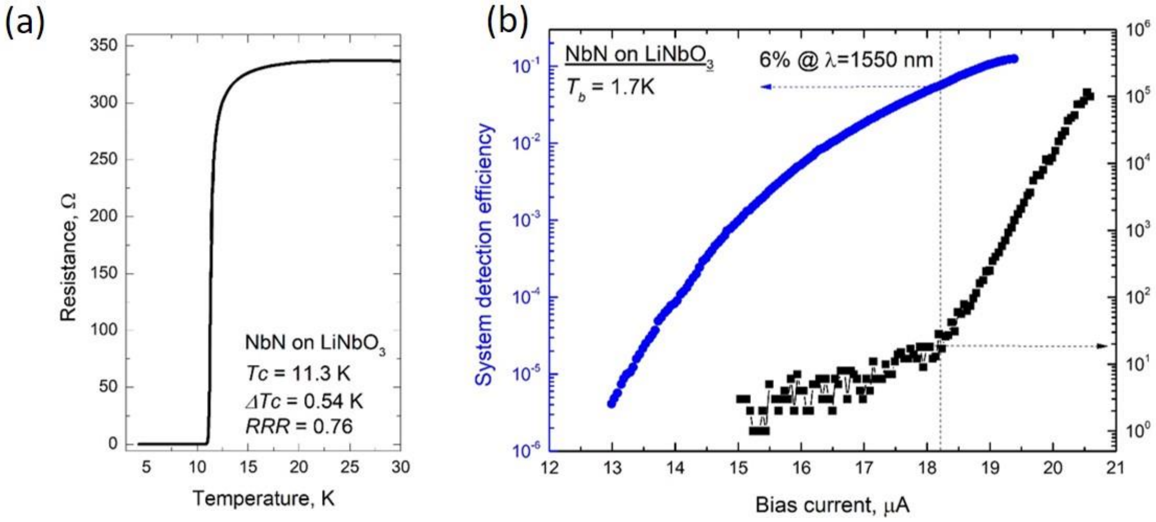

Figure 1 (a-b). (a) Measured dependence of the resistance on temperature for NbN film on LN substrate and **(b)** system detection efficiency (blue circles) and dark count rate (black squares) of SNSPD vs bias current.

Additionally to the successful implementation of classical SNSPDs for the fabrication of integrated devices on a LN substrate, it is necessary to realize waveguide integrated detectors, which are usually performed as U- or W-shaped NbN nanowire on other photonic platforms [3]. Waveguide integrated superconducting single photon detectors (WSSPDs) allow to detect radiation, which spreads within waveguide absorbing of evanescent waveguide field. For the properly designed WSSPDs, combining high absorption and internal detection efficiency it is possible to achieve close to 100% on-chip detection efficiency.

There is a serious obstacle associated with the sequence of the fabrication steps in WSSPD technology. If you first fabricated the integrated detectors, then the ultrathin NbN film degrades during the manufacture of waveguides. In contrast, if first to make waveguides, then by heating the substrate up to 800°C during the NbN film deposition, waveguides are destroyed. For this reason, NbN deposition temperature should be decreased and high quality superconducting films should be produced at room temperature or at a low heating.

We investigated the surface roughness of LN by atomic force microscopy, which is a very important characteristic for thin NbN superconducting films (4 - 10 nm). In Figure 2 shown an AFM scan of the LN surface showing a roughness R_a = 0.15 nm, suitable for NbN film deposition.

Index number	Sheet resistance, Ω/sq
1	386
2	473
3	602
4	285

Table 1. List of sheet resistance values of NbN thin films.

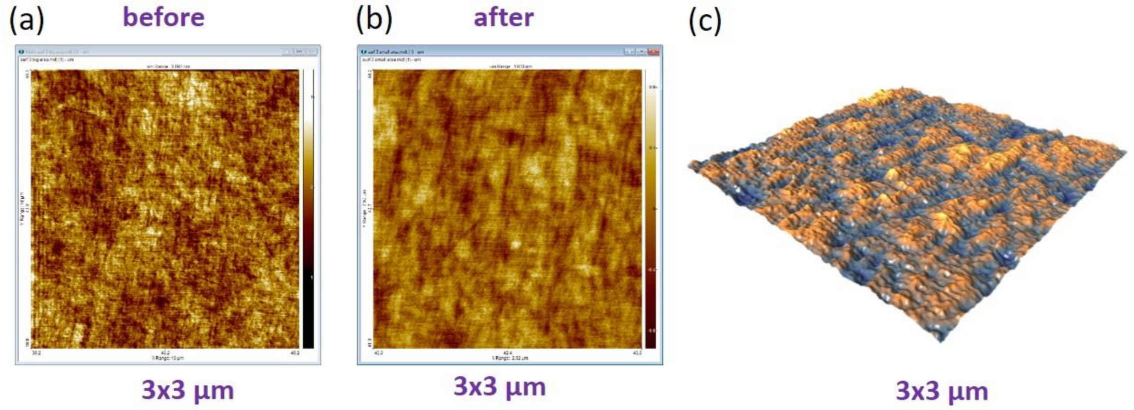

Figure 2 (a -b). AFM scan (3×3 μm) of the LN surface **(a)** before and **(b)** after NbN thin film deposition; **(c)** 3D plot of the LN surface after NbN thin film deposition.

We obtained a critical temperature of 9.4 K for a film grown at room temperature with the sheet resistance equal to 285 Ω/sq shown great potential for the use of NbN nanowires in the field of linear and nonlinear integrated quantum photonics.

In order to determine the most suitable films prepared at ambient temperature for SSPD pattering, we deposited four types of films with different sheet resistance (Table.1). Using e-beam lithography and negative resist mask (ma-N 2403), we patterned detectors, varying their sizes to determinate the most suitable geometry for detection of radiation within waveguide (Figure 2(b-d)).

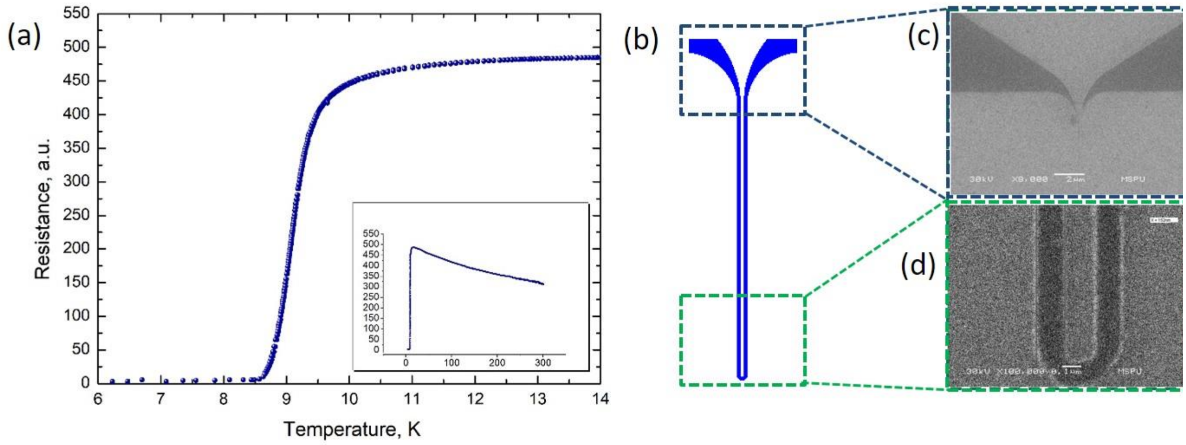

Figure 3 (a - d). (a) Measured dependence of the resistance on temperature for NbN film on LN substrate. Film grown at room temperature with the sheet resistance equal to 285 Ω/sq; **(b)** Schematic view of the U-shaped NbN nanowire pattern; **(c)** Zoom-in image of the NbN nanowire part for contact pads connection, obtained by a scanning electron microscope (SEM); **(d)** Zoom-in image of the nanowire turn obtained by SEM.

3. Conclusion

We demonstrated an SNSPD fabricated on lithium niobate substrate. We shown the system detection efficiency of 6 % at 20 s^{-1} dark count rate. According to our data, this is the highest value for SSPDs on LN that has been demonstrated to date. Direct comparison with the data presented in [6] shows significant increase of the detection efficiency of the NbN detectors. We associate this result with the better quality of the superconductor film grown at a higher substrate temperature. The second part of our work is formation of SSPD on waveguide. For this we changed parameters of NbN deposition process, including the ambient substrate temperature. Our results shown great potential for the use of NbN nanowires in the field of linear and nonlinear integrated quantum photonics on LN substrates.

Acknowledgments
G. Goltsman and V. Kovalyuk acknowledge support by Ministry of Education and Science of the Russian Federation №14.583.21.0065 (RFMEFI58317X0065).

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