Quantum Efficiency and Polarization Effects in NbN Superconducting Single Photon Detectors

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Abstract—Superconducting Single Photon Detectors based on niobium nitride (NbN) nanowires have been optimized in regards to the quality of the epitaxial layer grown on M-plane 3-inch Sapphire wafer, leading to $T_c \approx 13 \text{ K}$ and $J_c \approx 5 \text{ MA/cm}^2$ for a 5 nm thick layer patterned down to 80 nm stripe width using an e-beam writer. Using those films, 7% of quantum efficiency at 4.2 K for 100 nm linewidth nanowires detectors has been achieved. We measured the kinetic inductance of our SSPD by 2 different ways. Clear effects of light polarization on Detection Efficiency (DE) dependent has also been observed and quantified. DE varies by a factor 2 to 4 for a great number of tested SSPDs, meander width varying from 100 nm to 300 nm. The SSPD has been modeled as a detector with 2 different linear DEs as incident light can be polarized parallel or normal to the linewidth. This model is in good agreement with experimental data and roughly corresponds to the calculated absorption of the 5 nm thick NbN layer. However polarization effects also observed in multi-photon regime raise new issues.

Index Terms—NbN, superconducting single photon detector, thin films, light polarization, quantum optics, FDTD simulation

I. INTRODUCTION

SSPD offers great opportunity to single photon detection [1]. Very high Detection Efficiencies (DE) have already been realized [2] as well as the photon-counting ability [3]. This type of detector should bring major achievements in quantum optics [4] and applications in astronomy [5], especially in near infrared wavelengths. However, DE, which corresponds to the whole system efficiency, is still below semiconductor’s state-of-art detectors, such as Avalanche PhotoDiode, justifying ongoing efforts to enhance it by improving the coupling of the incoming signal to the detector, the absorption probability of photons by a very thin NbN nanowire and the quality and geometry of the latter nanowire. Attention was however lower with respect to other drawbacks of those detectors such as polarization effects. For example, it has been recently pointed out that the DE is rather different whether the incoming light polarization is perpendicular or parallel to the nanowire axis [6], which could be detrimental for some applications. Noteworthingly, the authors’ explanation for this assertion involves some internal efficiency of hot spot generation after the optical absorption event took place. In this article, we tackle this issue of polarization dependence by investigating it in the multi-photon detection regime, and stress the importance of a careful determination of the optical index of NbN ultrathin films into the determination of the polarization ratio of DE. This study was made possible by the development of an electro-optical characterization set-up that is also detailed.

II. EXPERIMENT

A. Fabrication

Superconductive ultrathin NbN films are DC-magnetron sputtered using a Ar/N$_2$ plasma and typically have a critical supercurrent of $5.5 \text{ MA/cm}^2$ and critical temperature of about 13 K for a 5 nm thick film. More details about thin film growth and characterization are given in Ref. [7]. The best transport properties are obtained after untwinned growth on M-plane sapphire substrate [8]. A 100-kV e-beam writer then allows patterning of SSPD’s NbN nanowire, using Sumitomo NEB-22A2 negative resist, forming typical meander shape that can be observed by SEM in Fig. 1 (a) and (b). The following process is shown on Fig. 1 (c) and developed in Ref. [9].

With this process, SSPDs with 7% DE were achived with a 90 nm linewidth and $3 \mu \text{m} \times 3 \mu \text{m}$. This is not too far from the state-of-the-art raw detectors because the measurements were done at 4.2 K with a $1.55 \mu \text{m}$ light wavelength.
needs to know where the fiber is. First, we used the spectral properties of the reflected laser excitation in order to determine the distance \( d \) between the fiber and the detector in the \( z \) direction. This distance, \( d \), is then directly given by the inter fringe, \( \Delta \lambda (d = \Delta \lambda /2\lambda^2) \), with an uncertainty below 1%. Fig 4 (a) shows a SSPD DE as a function of the distance \( d \). As expected, DE increases when \( d \) decreases.

Moreover, the light going out is quite accurately modeled by a gaussian waveform with its waist (5 \( \mu \text{m} \) for a 1550 nm single mode fiber) at the end of the fiber. Taking into account the SSPD size, the expected dependence of DE versus \( d \) and \( \rho \) (lines on Fig 4 (a) and (b)) is calculated, thus proving that all the expected light actually hits the SSPD. In the \( \rho \) direction (normal to the fiber), the center of the light waveform is obviously at the position where counts rate is at its maximum. Then position is directly calculated knowing this maximum count rate and \( d \).

In order to control the light polarization incoming on the SSPD, we inserted a polarization controller. It classically consists of a polarizer, a quarter-wave and a half-wave plates. Each of these elements can have any angle with respect to the others, thus generating any possible polarization state from the diode unpolarized light. Note that the fiber in-between the polarization controller and the sample may be birefringent, but it is kept constant during one measurement. With this optical set-up, polarization effects for our SSPDs are characterized with reproducible results thanks to our highly controlled of fiber position.

### III. Polarization effects

#### A. Polarization dependency and simulation

We found out that SSPD’s DE is strongly light polarization dependent, as already stated in [6]. This dependency can be characterized by \( R \), ratio of highest DE for a given polarization to the lowest. Detectors with lines between 90 and 300 nm and filling factor around 50% were polarization characterized. \( R \) was measured between 2 and 4 at 4.2 K, with no clear dependency on the aforementioned parameters. Though, a dependence on the fiber position was observed: \( R \) decreases when fiber is far (more than 1 \( \mu \text{m} \)), probably due to light unpolarized reflections incoming on the SSPD.
More surprisingly, $R$ decreases when $\rho$ increases, which is not understood.

Figure 5 shows a typical graph of DE dependency with respect to wave-plate angles. Zones with high DE correspond to a linear polarization, parallel to the meander lines ($x$ direction in Fig. 1), as discussed later. On the opposite, the lowest DE is observed when electric field is orthogonal to the meander lines, that is for the half-wave plate rotated by 45° from the previous described position. This exactly corresponds to what we obtain on Fig. 5.

Moreover, we can simulate this effect by considering 2 different DE for each polarization: $DE_x$ and $DE_y$. Experimental data are well reproduced by adjusting the last optical fiber birefringence, which is usually quite low if the fiber is not twisted (dephasing below $\Pi/12$). This effect can be understood if we consider that absorption of NbN is very different for an electric field parallel or perpendicular to the nanowires. To explain this DE difference, Finite Difference Time Domain calculations were performed and proved that absorption is more efficient when electric field is parallel to the wires. Quantitatively, simulations give an absorption of 21% for polarized light along $x$ compared to 10% along $y$ for a 100 nm SSPD and filling factor of 50%. However, the uncertainty of NbN ultrathin film optical index makes it hard to clearly quantify this difference.

B. Polarization in multi-photon regime

If we current-bias SSPD in multiphoton regime, say $N$-photon regime, we observe an increasing ratio, $R_N$. Quite impressively, one can almost switch off the DE in the $y$ polarization, when $N$ is high enough. For instance, Fig. 6 (b) shows a totally extincted signal for $y$ polarization in a regime with many photons. This is almost a polarization detector even though this regime is quite unstable and rapidly saturates as observed in the center of $x$ polarization.

Fig. 6 shows the ratio dependence with decreasing bias current. The ratio is increased for decreased currents simply because the photon regime is increased. However, if we estimate the number of photons by the traditional mean [12] (see Fig. 6 (a)), the experimental ratio is not as high as expected.

IV. CONCLUSION

As a conclusion, we showed our capability to fabricate and characterize SSPDs on R-plane or more interesting M-plane sapphire substrates. The whole process finally gives DE of 7% at 4.2 K (on R-plane). The whole electro-optical setup allows to measure SSPD’s kinetic inductances and optical properties. High light polarization dependence of SSPD were demonstrated. This effect is most probably due to different absorption of incoming light polarization of the NbN films, as checked by numerical calculations. This effect needs to be taken into account for further applications, where the incoming light usually have an unknown polarization. Further integration of SSPD with other devices [5] or enhancement of NbN optical absorption will be adressed, taking into account this polarization issue.
Fig. 6. (a) Photon regime determined by plotting the count rate vs incoming laser power. The slope of the graph indicates the regime, which depends on laser power and current polarization. This figure is obtained with a 200-nm and 50% filling factor SSPD. (b) Photon regime determined by polarization dependence. Here the ratio $R$ is enhanced because of multi-photon regime.

Fig. 7. Experimental polarization ratio, $R$, dependent on the DC bias current. For low bias current, $R$ is enhanced due to multi-photon counting regime.

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REFERENCES


