Advanced superconducting optical detectors

D. Perez de Lara¹, M. Ejrnaes², S. Pagano¹, M. Lisitskiy¹, E. Esposito¹, C. Nappi¹, R. Cristiano¹
¹C.N.R. Istituto di Cibernetica E.R. Caianiello, I-80078 Pozzuoli, Napoli, Italy
²INFN Sezione di Napoli, I-80126 Napoli, Italy
david@fisica.cib.na.cnr.it

Abstract. We have investigated advanced superconducting optical and infrared detectors for their integration with superconductive active circuits. The detectors are based on ultra-thin NbN striplines. NbN is the material of choice for single photon optical and infrared detectors, as already demonstrated in the literature. The detectors so far proposed are based on conceptually simple, although difficult to realize, sub-micrometric meander type structures. Most applications of such detectors require some treatment of the signal generated, either as pulse shaping or signal amplification, to fully exploit the detection capabilities, such as sub-ns response time and proportional response. We have developed a room temperature process that, while preserving reasonable superconducting properties of NbN, allows a simple integration of the detectors in Nb-based circuits. Moreover we have developed a passivation technique, by using a protective AlN layer on top of the NbN one. The developed technology allows complex detector configurations, such as integrated RSFQ circuits or SQUID readout, to be relatively easily realized. The response of our NbN strip to photon irradiation will be presented.

1. Introduction

Superconducting strip detectors (SSD) are based on the transition from the superconductive to the normal state of a small biased stripline. The transition is driven by the impact of a particle or a photon to be detected. The sudden occurrence of a resistance is revealed as a voltage drop across the stripline, thus signaling the occurred impact. The small size of the strip allows the detection of a tiny amount of energy, of the order of a fraction of eV, thus giving the possibility to detect single optical or infrared photons. Moreover the small strip volume and large aspect ratio dramatically improves the heat exchange with the substrate, thus speeding up the detector recovery. The choice of NbN as strip material is due to its small coherence length. This allows the realization of few nm thick film structures showing good superconductive properties. NbN has also a nonequilibrium response which implies an extremely fast response time (few tens of ps) [1]. NbN SSDs developed so far use an high temperature (600-800°C) deposition process. We have developed a room temperature deposition process for ultra-thin NbN films that preserves good superconductive properties (Tc, Jc) and allows an easy integration with the standard fabrication processes of Nb-based superconductive electronics.

2. Fabrication Process of SSD

We have deposited at room temperature ultra thin films of NbN by using dc magnetron sputtering in reactive atmosphere (Ar + N2). The sputtering was made at a deposition power P=500W, corresponding to a deposition rate of 1.8 nm/s. The process was calibrated to obtain the highest critical temperature by depositing films with a constant thickness d=100nm by changing the total pressure, the percentage of N2 gas partial pressure and the substrate: sapphire and MgO. The results are shown in Figure 1 and 2. It can be seen that we have obtained a critical temperature as high as Tc=15.8K. The residual resistive ratio up to RRR=0.97 was obtained. Then, we have reduced the thickness down to d=2 nm obtaining Tc=13.4K. Typical values of the critical current density were Jc=2x10⁷ A/cm² at 4.2 K for 10 nm thick films. Figure 2 shows that at T=10 K a reduction in Jc of only a factor 2 has been achieved. The films quality was always good and reproducible, even after etching processes for patterning. Figure 3 shows a photograph of the fabricated structure made by conventional micrometric photolithographic processes.
We also successfully developed a passivation technique based on an AlN layer. The AlN is deposited using a reactive dc-sputtering in N₂ atmosphere, and at room temperature. The N₂ pressure is 1 mTorr and the dc power 50 W. The typical thickness of the AlN layer deposited is 40 nm, sufficient to protect the active part of the detector while featuring a good optical transparency.

3. The optical response
To demonstrate the operability of our SSD we realized a number of test detectors of the type shown in figure 1. The SSDs have a width of 4 μm and therefore cannot respond to single photon excitation. As each optical photon absorbed in a 10 nm NbN film generates a 20 nm wide hot spot [2], in order to
trigger the S/N transition of the strip a minimal photon density (pulse energy) is necessary. However, by decreasing the strip width down to about 100 nm, it has been shown that the detector sensitivity can be increased up to single photon response [3]. Although mainly aimed to optical detection, the SSD could be usefully employed also in other contexts, such as the detection of macromolecules [4].

The SSD is placed on the cold finger of a continuous flow helium cryostat, and wire-bonded to a chip-holder, where a 2.5 Ω shunt resistor is located. The chip holder is connected, through a 50 Ω coaxial cable, to room temperature dc biasing and amplification electronics (see figure 4). The generated signal is amplified using a RF amplifier (20 dB gain, 1 GHz bandwidth). The SSD can be illuminated by a focused laser beam which can be precisely aimed on the strip, though a specially designed microscope. The laser signal can be pulsed down to 1 ns width and with a power up to 200 μW. After the absorption of a laser pulse the NbN strip, if properly biased near its critical current,
undergoes an S/N transition (represented by the switch in figure 4). The transition results in the bias current being diverted to the shunting resistor and generating a finite voltage. Shortly after, the decrease in bias current and the thermalization of the strip brings the SSD again in the superconductive state, and the voltage to zero. This process generates a fast voltage pulse. In figure 5 the time evolution of one of the light-induced voltage pulses is shown. The measured rise time is 490 ps and is limited by our amplification electronics. The fall time is about 20 ns and is determined by the external shunting circuit (\(L_{\text{ext}}\) and \(R_{\text{shunt}}\)).

Figure 6 shows the dc current voltage characteristics of a test SSD, where the current induced S/N transition can be clearly seen. The curves \(a\) and \(b\) correspond to transition to the normal state of the active (4 \(\mu\)m) and the wider part of the strip respectively. In the figure is also indicated the return point where the strip goes back to the superconductive state. This bias point is important since the power dissipated at this point is strictly related to the thermal conduction properties of the interface between the NbN and the substrate.

When a continuous train of laser pulses is sent to the detector, the voltage pulses become very frequent and a non zero DC voltage can be measured across the SSD, as shown in figure 7. The curves \(b\)-\(e\) in figure 7 correspond to irradiation with laser pulses of increasing width and fixed amplitude and repetition rate (10 MHz). The SSD was externally shunted with a 2.5 \(\Omega\) resistor and the temperature was 4.89 K. In each curve is visible a branch which corresponds to a laser induced generation of one (curve \(b\)) or more (curves \(c\)-\(e\)) voltage pulse by each optical stimulation. The smooth transition of each branch toward the zero voltage for decreasing dc bias current is due to a decrease of the probability of generating a voltage pulse by each optical stimulation, underlining the intrinsic stochastic nature of the detection event.

4. Conclusions
We have demonstrated the feasibility of a room temperature fabrication process for the realization of NbN based SSD for applications in advanced optical detection. The developed technology allows complex detector configurations, such as integrated RSFQ circuits or SQUID readout, to be relatively easily realized.

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