Development of Low Subgap Current Nb/Al STJ Detectors

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Abstract. We have developed a fabrication process for Nb-based STJ detectors which allows to fabricate junctions with subgap currents close to 20 pA at 300 mK, more than six orders of magnitude less than the subgap current at 4.2 K. The junctions are diamond-shaped devices, with areas between 20 × 20 and 100 × 100 μm². We report the details of the fabrication process, together with an analysis of the grain structure of the films by AFM and XRD. We show the measured I–V curves at 300 mK and the temperature dependence of the subgap current between 300 and 1100 mK. We also report preliminary results on x-ray measurements at 300 mK with a 5 mC ⁵⁵Fe source.

1. Introduction

Superconducting tunnel junctions (STJ) are extensively studied as high resolution photon-counting detectors from x-ray to visible wavelengths. Photons absorbed in the STJ break Cooper pairs into quasiparticles which tunnel through the insulating barrier of the STJ. The intrinsic energy resolution of this detector is limited only by fluctuations in the number of quasiparticles. For Nb, the intrinsic energy resolution is about 4 eV for a 6 keV x-ray. Several factors degrade this limit, resulting in an expected energy resolution of about 10–15 eV [1, 2]. Energy resolutions twice than this limit have been obtained experimentally at 6 keV [3].

At optical and ultraviolet wavelengths, STJ can be used as photon-counting detectors, with a minimum energy resolution for a Nb-based device of ~ 0.3 eV for 3 eV photons, limited by tunneling noise. Noise depends on the subgap current and capacitance of the junction and decreases in high-quality junctions with low subgap (or leakage) currents.

In this paper we report the development of a Nb/Al-AlOₓ/Nb fabrication process capable to produce STJ devices with subgap currents of the order of tens of pA. Al-oxide is used for the tunneling structure. To tune the fabrication parameters, much attention has been paid to the morphological and structural characterization of the films and of the whole junctions.

To keep the process as simple as possible and to test the limits of the technology involved, we have avoided to fabricate a trapping layer, and this is reflected in the low detection efficiency of our devices to x-ray radiation. Nevertheless, events coming from x-ray absorption in each the electrode could be clearly detected.
2. Junction fabrication

The Nb/Al-AlO\textsubscript{x}/Nb STJ detectors are fabricated in an uhv dc magnetron sputtering system on elettropolished R-plane sapphire substrates. The base pressure of system is below $5 \times 10^{-9}$ mbar. The Nb base layer, 150 – 200 nm thick, is sputtered at 0.6 nm/s at an Ar pressure of $8 \times 10^{-3}$ mbar. After Nb deposition, the Nb film is allowed to cool down to relax its internal stress for about 30 minutes. Subsequently, Al is deposited at 0.1 nm/s at the same Ar pressure of Nb. Its thickness, 5 – 6 nm, is the minimum thickness required to reliably cover the Nb film. The thermal oxidation of the Al film is carried out at a fixed oxygen exposure, $E = 18000$ Pa·s [4]. The Nb counter-electrode is sputtered using the same fabrication parameters of the base layer. To reduce the stress of the trilayer structure, lift-off of the whole Nb/Al-AlO\textsubscript{x}/Nb sandwich is used to define the base electrode geometry, while the Nb counter-electrode, which defines the areas of the junctions, is patterned by reactive ion-etching (RIE) in CF\textsubscript{4} plasma at a pressure of $5 \times 10^{-1}$ mbar. All the junctions have a diamond-shaped geometry with areas ranging from 20 x 20 to 100 x 100 μm\textsuperscript{2}.

The insulation between the Nb/Al-AlO\textsubscript{x}/Nb structure and the Nb wiring layer is ensured by liquid anodization in constant-current mode and by an evaporated SiO\textsubscript{2} film, deposited in two steps, separated by an interval of about 1 hour of exposure to air. Each SiO\textsubscript{2} film is 150 nm thick. The last step in the fabrication process is the sputtering of Nb wiring film, deposited with the same deposition parameters used for other Nb films. The thickness of this film is between 250 and 300 nm.

3. Film characterization

In this Section we summarize some of the measurements we have done to characterize the crystalline structure of the samples. We focus here on measurements done on single Nb films, deposited with the same parameters of the Nb base films of the STJ detectors, as the quality of these films strongly influences the final performance of the whole devices.

AFM measurements have been done on 200 nm thick dc-sputtered Nb films, deposited on (1T02) R-plane sapphire substrates (Fig. 1 (left)). The substrates have been kept at room temperature or heated at 700 °C during deposition to improve the epitaxial growth of the films. The Nb surfaces of the films deposited on the heated substrates appear flat with long filamentary

![Figure 1](image1.png)

*Figure 1.* (left) 3D AFM image of a 200 nm thick Nb film on R-plane sapphire substrate. The maximum vertical peak-to-peak roughness is 6.4 nm. (right) 3D polefigure of a 200 nm thick Nb film for 2Θ corresponding to the main (110) diffraction peak.
grains, showing a clear orientation on the plane. The maximum vertical peak-to-peak roughness is 6.4 nm. The rms roughness is $\rho = 1.2$ nm on $500 \times 500 \text{ nm}^2$ scan areas. The average grain size $D$ is about $85 \times 20 \text{ nm}^2$. The repeatability of the measurements is ensured by sampling the film surface at several different locations.

X-ray diffraction (XRD) measurements on base Nb films show that the films grow along the (110) plane and have a slight compressive stress (with a lattice spacing $d = 0.33066$ nm for the film of Fig. 1, to be compared to the bulk value of Nb, $d_0 = 0.33007$ nm). From these measurements, an average crystalline size $D \approx 25$ nm is evaluated, in fair agreement with the value found by AFM. The difference can be ascribed to the effect of the instrumentation characteristics on the broadening of the XRD diffraction peaks and hence on $D$.

XRD measurements give useful information about the texturing of the film along the growth direction. However, each grain may have a random orientation on the plane normal to the growth direction. The determination of the preferred orientation of the grains is obtained by measuring the diffraction intensity of a given reflection, at constant $2\Theta$, for a large number of different angular orientations $\Phi$ and $\Psi$ of the sample, thus assembling a 3D representation of the scattered x-ray (polefigure).

Fig. 1 (right) shows the polefigure obtained by fixing $2\Theta$ at the value corresponding to the (110) diffraction peak of Nb. On the vertical scale, the diffraction intensity is plotted as $\sqrt{I}$, to enhance the visibility of the background features. The central peak corresponds to the main diffraction peak in the (110) direction. The presence of a ring for $\Psi = 60^\circ$ around the central peak, without any other visible structure, indicates the presence of constructive diffraction only for the lattice planes of the bcc cell of Nb. Therefore, all the grains composing the film appear well oriented on the plane parallel to the substrate.

4. Low temperature measurements

All measurements have been performed in a pumped $^3$He cryostat at the European Space Agency (ESA), Noordwijk, The Netherlands. Details of the measurement setup can be found in [5].

Fig. 2 (left) shows the $I-V$ characteristics in the subgap region of a $20 \times 20 \mu\text{m}^2$ STJ detector. A small external magnetic field of 0.1996 G has been applied to suppress the critical current. From top to bottom, the current scale has been progressively expanded to show the junction leakage current. Between 0 and 0.8 mV, the leakage current is below 100 pA peak-to-peak, with the measurement limited by the intrinsic noise of the measuring system.

Fig. 2 (right) shows the temperature dependence of the leakage current between 300 and 1100 mK. The leakage current increases with $T$, in particular around $V = 0.25 - 0.5$ mV, where a clear bump appears. At $V = 0.5$ mV, the leakage current is less than 20 pA at $T = 300$ mK, increasing to 0.5 nA at 1100 mK and up to 100 $\mu$A at 4.2 K, a factor of $5 \times 10^6$ from 300 mK to 4.2 K.

The critical current density is 40 A/cm$^2$, while the normal resistance is $R_N = 0.08$ $\Omega$ and the dynamical resistance in the subgap region is $R_d = 85.76$ k$\Omega$, with a junction quality factor $R_d/R_N = 10.75 \times 10^5$.

The voltage gap $V_G$ measured at half rise of the superconducting transition is about 2.2 mV, while the transition width evaluated between 10% and 90% of the transition is about 0.4 mV. These values are much worse than those measured at 4.2 K on the same device, being the voltage gap lower and the transition larger. With decreasing temperature, in fact, one would expect the superconducting transition to become sharper due to the suppression of the thermal population. A possible explanation for such result, which was found in all the measured junctions, is that the AlO$_x$ barrier has somewhat been degraded due to excessive heating during the bonding of the sample to the chip holder.

Some preliminary measurement of our STJ irradiated by x-ray has been performed [5]. The x-ray source is a 5 mC $^{55}$Fe radioactive source, which decays to $^{55}$Mn by emitting 5.89 keV
Figure 2. $I - V$ curves of a $20 \times 20 \, \mu m^2$ STJ detector: (left) $I - V$ curves with the current scale progressively expanded from top to bottom, (right) subgap current at $T$ between 300 and 1100 mK. In both cases, the critical current has been suppressed by a small magnetic field.

Mn-K$_\alpha$ (88%) and 6.49 keV Mn-K$_\beta$ (12%) photons.

The measurements shows that the count rate is higher in the lower charge output part of the spectrum. These events are referred to those absorbed in the substrate, which is coupled to the detector through phonons and gives rise to a typical absorption structure. The responsivity of the device is extremely low, as can be noted from the low count-rate in the charge spectrum. Therefore, the peaks relative to the top and to the bottom electrodes are hidden from the events absorbed in the substrate.

No typical “islands” of events relative to the superconducting electrodes can be seen in this measure: although about $10^6$ quasiparticles are created in the junction by an incident x-ray, a large fraction of them are lost because of recombination and diffusion out of the junction area.

In order to reduce this loss and to enhance the quantum efficiency of the detector, trapping of quasiparticles has been successfully employed. A device fabricated with suitable Al trapping layer has therefore been measured with the same $^{55}$Fe radioactive source, with encouraging results.

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