Study of SNS and SIS NbN Josephson junctions coupled to a microwave band-pass filter

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Abstract. We have fabricated both NbN/Ta\textsubscript{x}N/NbN SN*S-type, NbN/MgO/NbN SIS-type Josephson junctions and microwave band-pass filters on different substrates (Si, Sapphire, MgO). NbN films have been deposited on both sides of (100) oriented, 250 \( \mu m \) thick, MgO substrates with a high crystalline texture quality. The aim was to investigate the performances and the maximum achievable operating frequency in an NbN based RSFQ modulator front-end of an ADC in the 4 K-10 K temperature range. We observed that Ta\textsubscript{x}N thin films can be tuned from an insulating phase to a superconducting phase (\( T_c \sim 4K \)) by varying the nitrogen content during sputter deposition while the barrier height of MgO can also be controlled by deposition conditions and by tri-layer postdeposition annealing. Junction properties (\( J_c \sim 10^{-25} \) kA/cm\(^2\)), Mac Cumber parameter and \( R_nI_c \) product measured up to 1 mV are shown to be controlled by the reactive sputtering conditions. We have designed three pole band-pass filters and resonators in a micro-strip configuration and studied the junction coupling with the filters. We will show that a sigma-delta NbN technology is a suitable solution for analogue-to-digital conversion in the future generations of telecommunication satellites to achieve high sampling frequency and large bandwidth at high carrier frequency signal.

1. Introduction
Superconducting Rapid Single Flux Quantum (RSFQ) circuits are considered a new alternative to silicon electronics [1]. Significant effort is spent on developing the materials which give the best junction and integrated circuit performance. The generation of Josephson junctions based on niobium as electrode material is still matter of interest worldwide thanks to its high degree of reliability, associated to the use since 1983 of alumina tunnel barriers, and thanks to a trilayer-based processing technology [2]. Some registers, demultiplexers, analogue-to-digital converters and more other devices based in Nb technology are already fabricated and tested operating at high frequencies. Although requiring a cryogenic environment these circuits show low power consumption and picosecond time response in logic operation, but Nb junction performance is constrained at high frequencies. Nb logic circuits, which require damped junctions, are limited to switching frequencies of about 250 GHz. In order to damp a Nb junction, the alumina barrier capacitance has to be externally shunted by a resistor or substituted by a suitable self-shunted normal metal barrier. However metal barrier Nb junctions with a suitable high frequency cutoff have not yet been realized. Finally, Nb circuits can not operate at temperature higher than 4K. This last constraint increases the cost, the weight, and the power consumption of the required cooling system, thus representing a handicap for space applications. Niobium nitride (NbN) is a reliable conventional BCS material, and a medium temperature superconductor (MTS) in
its cubic phase. We believe that this material constitutes a more appropriate choice than Nb both for analogue SIS and for digital technologies. NbN junctions with a large energy gap (gap frequency of about 1.45 THz) allow circuits operations up to 800 GHz at temperatures up to 12 K, twice higher than Nb [3].

In order to employ this technology for a sigma-delta ADC working at 200 GHz for an input signal of 10 or 30 GHz, we have studied the film deposition and the Josephson junctions fabrication, we have measured a SIS and SNS Josephson junctions and we have coupled the SNS junction to a 10 GHz resonator in order to analyse the Shapiro steps and the resonator frequency response.

2. NbN/MgO/NbN and NbN/Ta\textsubscript{x}N/NbN Josephson junctions

NbN layers are deposited via DC-magnetron sputtering in an argon-nitrogen controlled atmosphere [4]. NbN films have been deposited on both sides of (100) oriented, 250 \( \mu \)m thick, MgO substrates with a high crystalline texture quality. The film quality is strongly influenced by the choice of the substrate and the chamber temperature during deposition. Several substrates have been employed: sapphire, MgO, silicon and SOI. When NbN sufficiently thick films were deposited on a substrate heated above 350 °C, X-ray diffraction studies highlighted the concurrence of two different crystalline film textures: a hexagonal and a cubic phase, the last one being addressed as essential to the superconductive transition. Films grown at high temperature (~ 600 °C) show a better epitaxy compared with those realized at ambient temperature. Moreover a thin MgO (100) buffer placed right before the NbN layer has been found to favour a correct epitaxial growth of the film. SOI and Si/SiO\textsubscript{2} substrates need such MgO buffer to be suitable for superconducting applications.

2.1. MgO and Ta\textsubscript{x}N barriers

Ultra thin MgO barrier layers (~ 0.6 nm thick) have been RF-magnetron sputtered with a good uniformity by applying substrate rotation. MgO has been grown in-situ in the same chamber where NbN electrodes are deposited in a sequential controlled process. The MgO dielectric barrier tunnel transparency can be decreased in a controllable way, and improved in terms of quality factor by a defined thermal annealing at about 250 °C [5].

Ta\textsubscript{x}N is an interesting nitride barrier for different reasons [6]. First of all, its crystalline lattice and chemical properties are close to the one of NbN, so that the barrier can easily grow over

![Figure 1](image-url)

**Figure 1.** Resistance as a function of the temperature for the TaN samples. Films with a higher nitrogen flow rate (figure a) show an insulating behavior at low temperature, while films in figure b with a lower nitrogen contribute present a clear metal-superconductor transition.
the electrode and vice-versa. Moreover, the Ta$_x$N electrical barrier properties can be tuned by using two control parameters: the nitrogen-versus-argon gas flow rate during deposition and the film thickness. Several Ta$_x$N films have been DC-magnetron sputtered over silicon substrates and then characterized. Figure 1 shows the resistance of the various films as a function of the temperature. From sample A2045 to sample A2049 the Nitrogen rate has been successively reduced in order to obtain films with smaller resistance. The superconductor transition of the sample A2049 (Tc $\sim$ 4K) has been a positive result. Since we are looking for metallic films with higher resistance, in the sample A2051 we have further reduced the deposited thickness, increasing its resistance by a factor 10000. Meanwhile the sample is still superconductive, with a Tc lower than 1K.

2.2. SIS Junction
Figure 2 shows the I-V characteristic of a NbN/MgO/NbN junction with a 0.6 nm thick tunnel barrier. The junction is strongly hysteretic and has a current density of 15 kA/cm$^2$.

Samples are usually heated at 250 °C for about 1 hour. The MgO barrier annealing process has been clearly interpreted in the frame of a diffusion process which make MgO more dense, leading to an increase of the tunnel barrier potential height [5]. The benefit of such MgO barrier annealing has been clearly demonstrated in SIS heterodyne receivers, making possible to obtain better circuits with improved performances.

2.3. SNS Junction
SNS junctions present a naturally self-shunted I-V characteristics, and are therefore particularly suitable for RSFQ logic applications. Figure 3 shows the characteristics of a NbN/Ta$_x$N/NbN junction with a surface of 10 $\mu$m$^2$ achieved at a deposition temperature of about 450 °C. The sample is nearly nonhysteretic, with a current density of 4 kA/cm$^2$, a $\beta_c$ around 0.5 and a RnIc product around 0.7 mV at 4.2 K, which gives a maximum characteristic frequency of 340 GHz. To realize the presented sample, a 5 masks fabrication process has been developed at CEA-Grenoble, in which the base electrode constitutes also the ground-plane of the circuit.

3. Coupling the SNS junction with a filter
In order to control the best coupling of the junctions presents in the comparator of our future Sigma-Delta ADC, we have fabricated a 10 GHz resonator in microstrip technology. A circular
Josephson junction of 4 μm of diameter is located at one of the end of the resonator. A low pass filter with a cutoff frequency of 4 GHz, as figure 4 shows, allows the junction bias and a 4 point measurement. The resonator in NbN covers the counter-electrode of the Josephson junction.

![Microstrip resonator](image1)

**Figure 4.** Microstrip resonator with the Josephson junction (JJ) at one end. The low-pass filter allows to test and to bias the JJ.

![Measured transmission coefficient](image2)

**Figure 5.** Measured transmission coefficient of the resonator in figure 4. The resonant frequency is 11.3 GHz.

This junction is obtained from the NbN/Ta_xN/NbN trilayer, in which the base-electrode is used as ground plane for the microstrip resonator and low-pass filter. Figure 5 shows the measured transmission coefficient of this resonator using a Vectorial Network Analyzer (VNA) without biasing the Josephson junction. The resonant frequency is 11.3 GHz, about 1 GHz above the simulation. Because of our microwave measurement setup, two GSG (Ground-Signal-Ground) probes mounted at the end of an insert for an ordinary cryostat, it was not possible to make a good calibration of the VNA and to reduce the radiation losses. This can explain the shift of the resonant frequency and the low quality factor (about 225).

4. Conclusion

In this paper we have shown that NbN and barrier film deposition conditions are critical for good SIS and SNS Josephon junctions. Current-voltage characteristics of both hysteretic and shunted junction have high RnIc. Future work will be to fabricate and characterize more NbN/Ta_xN/NbN Josephson junctions together with RSFQ circuits and in particular a two Josephson junctions comparator coupled to a 30 GHz microwave filter, which will constitute the sigma-delta modulator of the ADC.

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