Specific capacitance of Nb/Al-AlN/Nb superconducting tunnel junctions

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***Abstract*— Modern radio astronomy demands for broadband receiver systems. For SIS mixers, this translates into objective to employ superconducting tunnel junctions with a very low R_nA and low specific capacitance. The traditionally used Nb/AlOx/Nb junctions have largely approached their physical limit of minimizing those parameters. It is commonly recognized that it is AlN-barrier junctions, which are needed for further progressing of the broadband SIS mixer instrumentation for radio astronomy. In this work, we present the progress in fabrication of high quality Nb/Al-AlN/Nb superconducting tunnel (SIS) junctions and their characterization in terms DC electric properties junctions' specific capacitance.**

I. Introduction

Modern radio astronomy instrumentation projects call for twice or triple enhancement of the RF and IF bandwidths of the SIS mixers [1]. A wider RF band requires lower Q-factor and consequently, lower R_nA-product of the SIS junctions. The traditionally used Al-oxide material of SIS junction tunnel barrier approaches its physical limit: by using SIS junctions with higher current density and thus thinner tunnel layer that gets close to the situation when the tunnel barrier quality becomes hardly predictable. It is widely recognized by the SIS community that in general, the quality of the Al-oxide SIS junctions degrades and becomes unreliable, once R_nA decreases below probably 15 Ohm·µm². Simultaneously, a wider IF band of SIS mixer needs the junction capacitance be lower, in turn forcing shrinking the junction size, which may cause production yield problems.

As an alternative SIS tunnel barrier material, aluminum nitride, AlN, has reduced electrical barrier height as compared to the Al-oxide tunnel barrier and thus would need a thicker tunnel barrier for the same current density as compared to the AlO_x tunnel barrier junctions. Consequently, with physically thicker tunnel barrier, there is more possibility to obtain R_nA well below 10.

We have earlier reported on the process development for high-quality junction fabrication based on microwave plasma nitridation [2]. We show that the Nb/Al-AlN/Nb junctions with R_nA product down to ~5 Ohm·µm² demonstrate excellent quality. Moreover, even junctions with R_nA~3 Ohm·µm² can be fabricated having $R_j/R_n > 12$. Also, we show that the produced junctions are quite stable against the thermal annealing, at least up to 200°C, thus allowing for thermal impact during almost any possible fabricating or packaging technology processes.

In this manuscript, we present results of the Nb/Al-AlN/Nb junction specific capacitance measurements following the approach similar to reported in the paper [3]. The measurement result confirms that specific capacitance of the Nb/Al-AlN/Nb junction is noticeably lower than that reported for the Nb/AlO_x/Nb junctions [4], [5].

II. Nb/Al-AlN/Nb junctions fabrication

The developed process [2] for fabricating of Nb/Al-AlN/Nb junctions is based on the Nb/Al-AlO_x/Nb process supported by GARD [6]–[10] but instead of thermal oxidation, nitridation of Al with the plasma excited by electron-cyclotron resonance (ECR) plasma source [11] is applied.

A number of batches of Nb/Al-AlN/Nb junctions had been fabricated with a demonstrated range of R_nA product varying between 3 to 120 Ohm·µm², all with a low subgap current. The examples of the junctions' current-voltage characteristics are presented at the Fig. 1. All the measured junction in the fabricated batches showed uniform quality independently on the junction size (between 2 to 8 µm²).

During the fabricating process and in the course of mounting/packaging, the SIS mixer chip can be exposed to the elevated temperatures. How high temperatures can be accepted during junction fabricating (baking of resists, or heating during deposition of the layers) and packaging (curing of glues or epoxies, or heating for wire bonding) is defined by the stability of the junction properties at the elevated temperatures.

To make sure that the fabricated Nb/Al-AlN/Nb junctions safely survive elevated temperatures during fabrication and handling, we have earlier carried out the study of aging and annealing behavior of Nb/AlN/Nb junctions [2]. In course of that study, the junction wafers were exposed to the aging/annealing temperature profile between room temperature and 200°C, as shown at the Fig. 2. Current-voltage characteristics at 4K temperature were recorded directly after the fabrication of the junctions and after each step of the aging/annealing temperature profile showed only minor variation of the junctions' parameters (normal resistance (R_n) and quality factor (R_j/R_n ratio), superconducting gap (V_g) and its width (ΔV_g)). Example of the current-voltage characteristics of the junctions experienced the whole aging and annealing sequence up to 200°C is shown on the Fig. 3.

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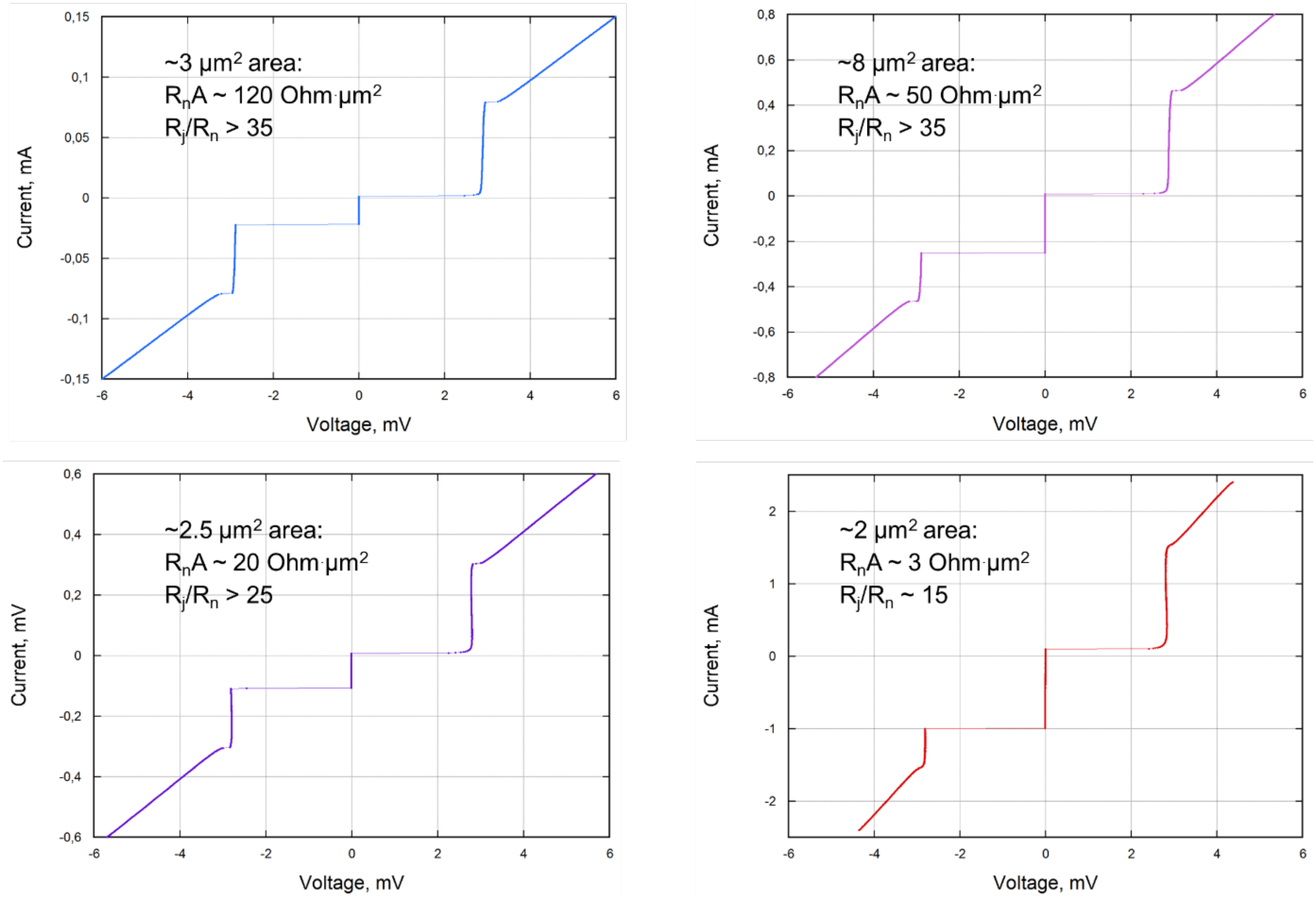

Fig. 1. Examples of Nb/Al-AlN/Nb junctions' current voltage characteristics with R_nA ranging between 3 and 120 Ω·μm². The legend inside each plot panel shows junction's size, R_nA and R_j/R_n values.

It can be concluded that the Nb/AlN/Nb junctions are probably somewhat more temperature stable than high-quality Nb/AlO_x/Nb junctions (see e.g. for comparison the evolution of Nb/AlO_x/Nb junctions due to aging and annealing summarized in [6] vs. that for Nb/AlN/Nb junctions [2]). That is consistent also with the earlier reported results, e.g. [12].

Further post-annealing aging of the Nb/AlN/Nb junctions at room temperature for ca. 8 months after their exposure to annealing experiments shown on the Fig. 2 demonstrated only minor (<5%) drop of R_n and no measurable change of R_j/R_n, ΔV_g and ΔV_g.

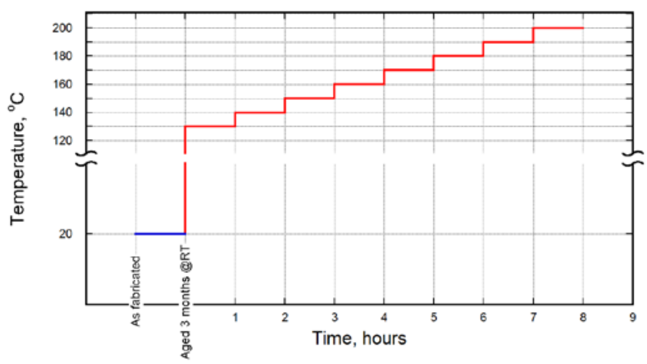

Fig. 2. Temperature profile of aging/annealing of AlN-barrier junctions [2].

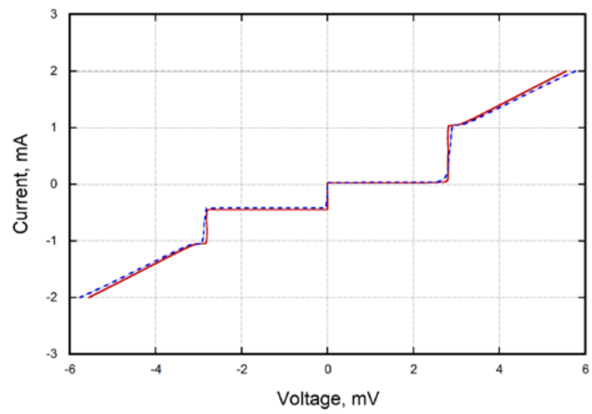

Fig. 3. Comparison of an Nb/Al-AlN/Nb junction as fabricated (red) and after annealing sequence up to 200ºC (Fig. 2).

III. Characterization of Junction Specific Capacitance

For the measurements of the Nb/Al-AlN/Nb junctions specific capacitance, we followed the approach similar to that communicated in the paper [3], using cryogenic S-parameter measurements [13].

For extracting the C_s versus R_nA data for Nb/Al-AlN/Nb junctions, we used the test sample layout (Fig. 4), which allowed dc-testing of the junctions with the sizes 3, 4, 5, 6 and

8 µm^2 on the wafer, before its dicing into the individual chips. That permitted extracting information about the junctions' R_nA value. After dicing into 6 pieces, each chip contained a full set of junction sizes that allowed characterization of both R_nA and C_s on the single mounted sample (only re-bonding of the individual junctions was needed).

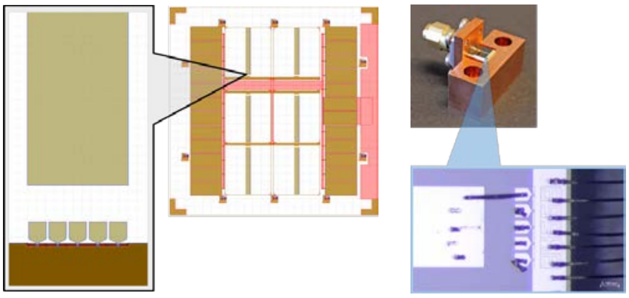

Fig. 4. The test junction wafer containing 20 single junctions of the sizes 3, 4, 5, 6 and 8 um^2 connected to the external contact pads. The six chips for measurement of specific capacitance each have 50Ω line and single junctions of the sizes 3, 4, 5, 6 and 8 μm^2 to be connected by bonding.

Specific capacitance numbers of the junctions with R_nA ~ 20 and 50 Ohm·µm^2 and nominal area of 3 – 8 µm^2 were measured. For lower R_nA product value and bigger area junctions, the extracting of a reliable value of the junctions' specific capacitance is problematic because of domination of real conductivity due to a very low R_n over the imaginary conductivity, which includes the junction capacitance contribution.

On the Fig. 5, the comparison between measured specific capacitance numbers of superconducting tunnel junctions with AlN and AlO_x tunnel barriers is presented. For the so far measured, the specific capacitance of the junctions with AlN barrier is significantly (about 20%) lower than that of the junctions with AlO_x barrier.

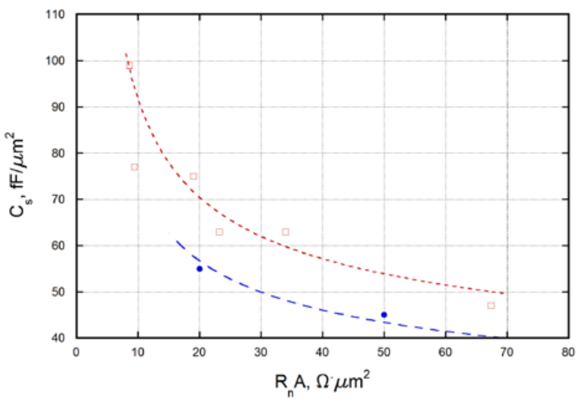

Fig. 5. Specific capacitance of Nb/Al-AlN/Nb junction (*red*) as compared with that of Nb/Al-AlOx/Nb junctions [5] (*blue*). The capacitance data for the junctions are approximated with empirical relation $C_s = a/ln(R_nA)$ [14], where *a* is equal to 211 [5] for the Nb/Al-AlOx/Nb junctions and to 170 for the measured Nb/Al-AlN/Nb junctions.

IV. Conclusions

In this work, we presented the progress in fabrication of high quality Nb/Al-AlN/Nb junctions. The fabricated junctions were characterized in terms of their DC electric properties and specific capacitance. The specific capacitance of the studied Nb/Al-AlN/Nb junctions is noticeably lower than that reported for the Nb/AlO_x/Nb junctions.

Acknowledgement

This work was partially supported by the European Organisation for Astronomical Research in the Southern Hemisphere (ESO) in the frame of the Collaboration Agreement No. 73301/16/78225/OSZ and Radionet within the frame of the AETHRA JRA.

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