Nb/Al-AlN/Nb superconducting tunnel junctions: fabrication process and characterization results

Alexey Pavolotsky[1,*], Vincent Desmaris[1], and Victor Belitsky[1]
[1] *Chalmers University of Technology, Group for Advanced Receiver Development, Department of Space, Earth and Environment, Göteborg, 412 96, Sweden*
*Contact: Alexey.Pavolotsky@chalmers.se

Abstract—**Modern radio astronomy demands for broadband receiver systems. For SIS mixers, this translates into objective to employsuperconducting tunnel junctions with 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 instrumentation for radio astronomy. In manuscript we present results of developing a fabrication process for high quality Nb/Al-AlN/Nb junctions and characterization the junctions' DC electric properties and their aging and annealing stability, as well as the junctions' specific capacitance.**

I. Introduction

Modern radio astronomy instrumentation projects, e.g. ALMA 2030 Roadmap [1], call for twofold o threefold enhancement of the RF and IF bandwidths of the SIS mixers. Wider RF band requires lower Q-factor and consequently, lower R_nA-product of the SIS junctions. Al-oxide, traditionally used as tunnel barrier material of SIS junctions approaches its physical limit: by using SIS junctions with higher current density and thus thinner tunnel layer, 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·µm^2 for AlO_x tunnel barrier junctions. 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 and may lead to spreading of junction parameters [2].

An alternative SIS tunnel barrier material, aluminum nitride, AlN, present a reduced tunnel barrier height as compared to the Al-oxide tunnel barrier. Consequently, for the same current density (or R_nA), the physical thickness of the tunnel barrier is substantially larger for AlN than for Al-oxide material. This opens up two possibilities: **i**. for the given current density, the junctions with AlN barrier will have lower capacitance giving the immediate advantage of operating the junctions over much wider RF and IF bands as compared to today's junctions using Al-oxide barrier; **ii**. the junctions with AlN barrier can have much higher current density without degrading of their quality.

We have developed a process for high-quality junction fabrication based on microwave plasma nitridation. The Nb/Al-AlN/Nb junctions with $R_nA \sim 15$ Ohm·µm^2 demonstrate excellent quality, $R_j/R_n > 25$.

During the fabricating process and in the course of mounting/packaging, the mixer chip is exposed to the elevated temperatures. The upper temperature limit that 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. For this reason, we have carried out the study of aging and annealing behavior of Nb/AlN/Nb junctions by exposing junction samples to the aging/annealing temperature profile between room temperature and 200^{o}C.

Finally, we measured specific capacitance of the Nb/AlN/Nb junctions using approach similar to one reported in the paper [3] and compared those with the data for Nb/AlO_x/Nb junctions.

II. Nb/Al-AlN/Nb junctions fabrication process

The developed process for fabricating of Nb/Al-AlN/Nb junctions is based on the standard Nb/Al-AlOx/Nb process supported by GARD [2], [4]–[7] but with plasma nitridation of Al instead of thermal oxidation.

The earlier developed Nb/Al-AlN/Nb junctions fabrication processes first relied on either glow discharge nitridation [8]–[10]. Later, it was understood that nitrogen ion bombardment causes structure damage in the formed ultra-thin AlN layer and by that, limits the low end of accessible R_nA range. The solutions to the problem were found later [11]–[14] either in spacial separation of the sample and the plasma cathode volume (often referred as anodic plasma or remote plasma nitridation) optionally combined with active controlling of the substrate potential [15] to avoid ion bombardment in unwanted extent. Among the remote plasma sources, there were various kinds used: RF biased cathode [11] or magnetron [14], either inductively coupled plasma source [12], [13].

In the present work, a remote plasma source based on electron cyclotron resonance (ECR) was used. ECR sources are characterized by relatively high plasma density

($\sim 10^{-11} \ldots 10^{-12}$ cm^{-3}), low plasma potential (ca. 15…30V) and consequently, low ion energy; high density of neutrals (about 2 orders of magnitude higher than that of ions) and their high temperature (~0.2 eV) [16]. On our view, these features of ECR plasma makes is especially suitable for nitridation of AlN tunnel layer. A high concentration of hot neutrals suggests an effective nitridation of the Al, once the low energy of ionized components ensures low radiation damage to the formed AlN ultra-thin layer. Additionally, the magnetic field in the plasma source is strongly diverging, and because of that, it is only over a very limited spacial region, where the frequency of the electron cyclotron oscillations appeared in resonance with the microwave excitation frequency. That additionally guarantees a spacial separation between plasma region and the sample surface being nitridized. Also, importantly, the ECR source is quite compact, thus facilitating its integration into the deposition system.

A schematic view of the plasma nitridation arrangement is shown on the Fig. 1. The plasma source is placed relatively far from the substrate, ensuring the spacial separation between the plasma region and the sample under nitridation. There is a shutter between the plasma source and the sample, which is kept closed during transient upon plasma ignition and the parameters settling process. The sample holder is grounded through the ammeter. The current to ground during nitridation was always within +1…+3 mA confirming very low ion bombardment current density.

Facilitating the initial phase of the Nb/Al-AlN/Al multilayer process development, we used anodization profiling of the tunnel structure similar to the approach suggested in [17]. We targeted obtaining the sharp profile at the Nb/Al interface. The anodization profile of Nb/Al interface was considered "sharp enough" if it was about the same shape and sharpness as that of the known high quality Nb/Al-AO_x/Nb junctions, e.g. those used for ALMA Band 5 mixer production [5]–[7], shown on the Fig. 2 (green curve). Additionally, the height of the peak at the profiles corresponding to the AlN tunnel layer was taken as a rough indication of the layer thickness, which allowed quick converging to the nitridation process parameters providing the junction's R_nA numbers within the range of interest (the blue and red curves on the Fig. 2).

III. Electrical characterization of Nb/Al-AlN/Nb junctions

A. Current-Voltage characteristics

The fabricated junctions demonstrated current-voltage characteristics typical for high quality junctions: low subgap leakage current quantified by R_j/R_n ratio larger than 25 and high and vertical superconducting gap current onset. The junctions with lowest R_nA demonstrated the signs of overheating while recording the current-voltage characteristic. Plots at the Fig. 3 demonstrate typical characteristics for the junctions with high (ca. 120 Ohm·μm^2) and low (ca. 15 Ohm·μm^2).

B. Aging and annealing stability of Nb/Al-AlN/Nb junctions

The upper temperature limit that 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. For this reason, we have carried out the study of aging and annealing behavior of Nb/AlN/Nb junctions.

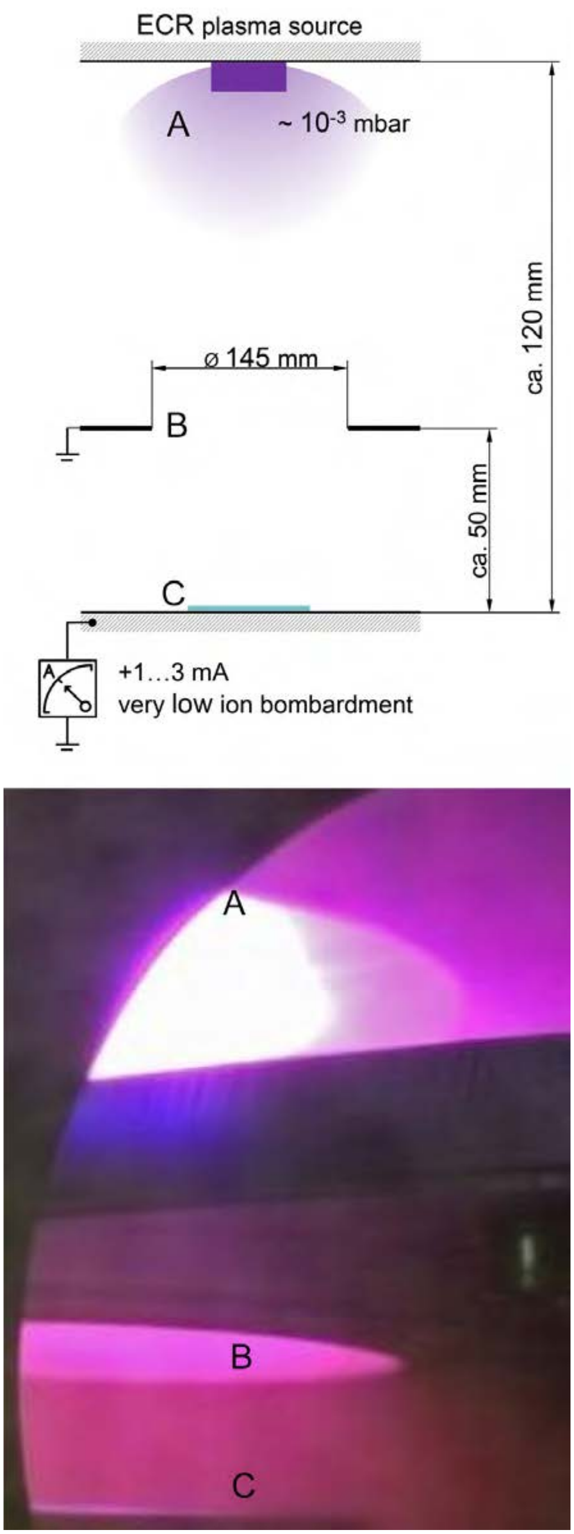

Fig. 1. Plasma nitridation arrangement: A – plasma source, B – opening in the shutter plate, C – sample holder with sample.

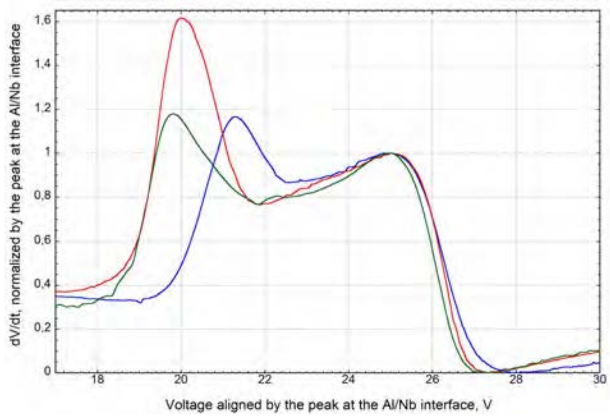

Fig. 2. Anodization profiles of the tunnel structures: green line: - Nb/AlOx/Nb, (R_nA ~ 30 Ohm·µm^2), same as those used for ALMA Band5 mixers [5]–[7]; red line - Nb/AlN/Nb, R_nA ~ 120 Ohm·µm^2; blue line - R_nA ~ 15 Ohm·µm^2.

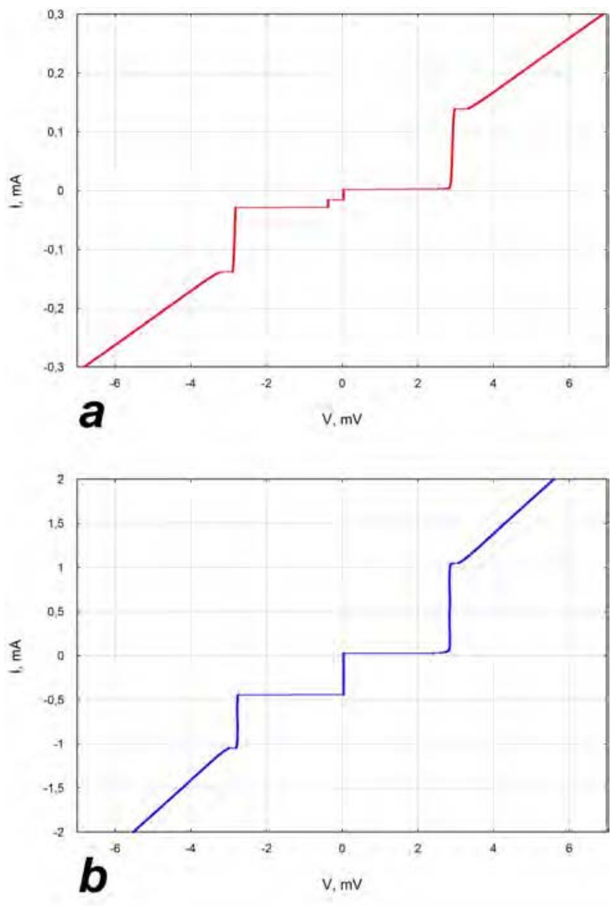

Fig. 3. Typical current-voltage characteristics of Nb/AlN/Nb junctions with ~6 mm^2 area: (a) R_nA ~ 120 Ohm·mm^2, R_j/R_n > 35; (b) R_nA ~ 15 Ohm·mm^2, R_j/R_n > 25

The wafers of junction with R_nA ~ 15 and 120 Ohm·mm^2 respectively had been exposed to the aging/annealing temperature profile between room temperature and 200°C, as shown at the Fig. 4a. Current-voltage characteristics at 4K temperature were recorded directly after the junctions fabrication and after each step of the aging/annealing temperature point. Values of normal resistance (R_n) and quality factor (R_j/R_n ratio) were extracted from all recorded current-voltage characteristics Fig. 4b and Fig. 4c present the evolution of the normal resistance and quality factor values in course of the aging/annealing.

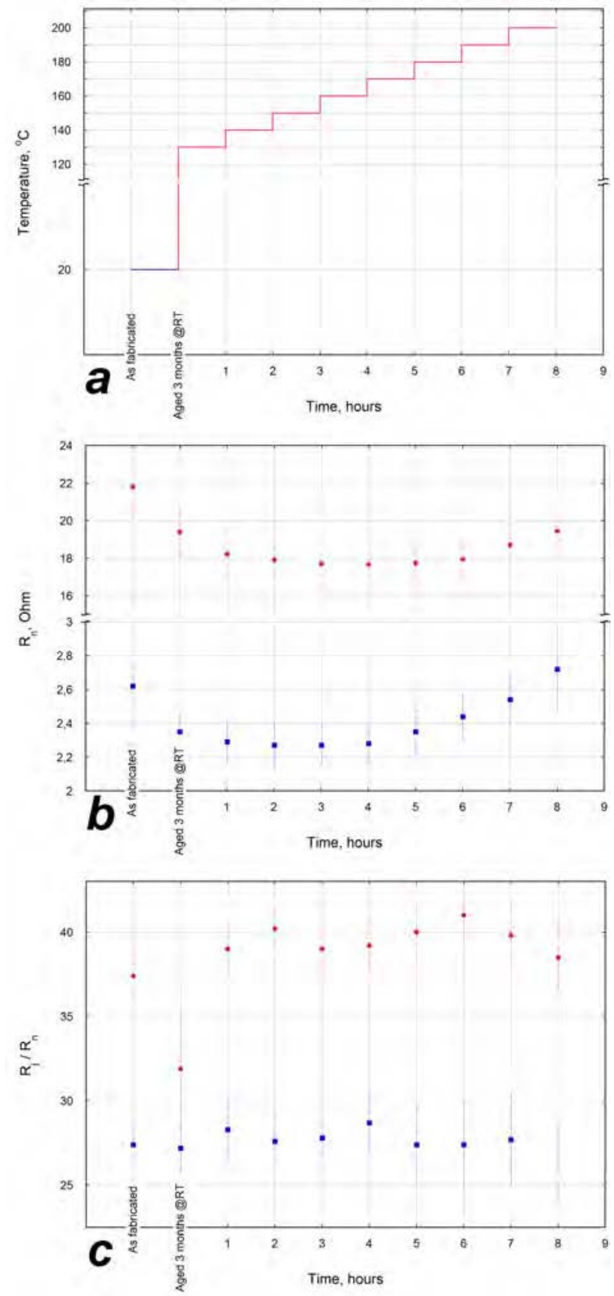

Fig. 4. Temperature profile (a) of aging/annealing of AlN-barrier junctions and evolution of R_n (b) and R_j/R_n ratio (c) for the junctions with R_nA ~ 120 Ohm·mm^2 (red) R_nA ~ 15 Ohm·mm^2 (blue).

From the plots, one can conclude that compared with the high-quality Nb/Al-AlOx/Nb junctions [4], the Nb/Al-AlN/Nb junctions are probably somewhat more temperature stable. It is safe and rather advisable to anneal junctions up to the modest 130 - 150°C and probably safe to expose to temperatures up to 180°C for the shorter time intervals. In the other words, any resist, glue or epoxy can safely be used in the fabricating and packaging processes involving Nb/Al-AlN/Nb junctions.

Moreover, heat treatment at the modest 130 - 150ºC could be advisable for adjusting of the junctions' normal resistance values, as well as for stabilizing of their properties. No degradation of the junction quality was observed after that treatment. Above 180ºC however, junction quality starts degrading, which also could be seen also by reducing of the superconducting gap voltage and smearing of the gap feature at the current-voltage.

C. Junction capacitance characterization

By the moment, the first measurements of the Nb/Al-AlN/Nb junctions specific capacitance have been made following the approach similar to that communicated in the paper [3], using cryogenic S-parameter measurements [18].

Specific capacitance numbers of the junctions with $R_nA \sim 6$ and 50 Ohm·mm^2 and area of 4 – 10 mm^2 were attempted to measure. So far, we have found extracting of reliable value of specific capacitance of the junctions with $R_nA \sim 6$ Ohm·mm^2 to be problematic. That is probably due to the very high conductance of the junctions. As for the junctions with $R_nA \sim 50$ Ohm·mm^2, we estimate specific capacitance to be about 45 fF/mm^2.

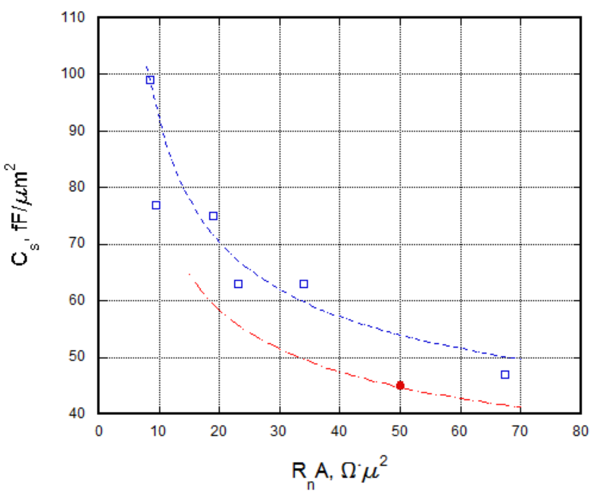

Fig. 5. Specific capacitance of Nb/Al-AlN/Nb junction (*red*) as compared with that of Nb/Al-AlOx/Nb junctions [19] (*blue*). The capacitance data for the junctions are approximated with empirical relation $C_s = a/ln(R_nA)$ [20], where a is equal to 211 [19] for the Nb/Al-AlOx/Nb junctions and to 175 for the measured Nb/Al-AlN/Nb junctions.

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 junctions with $R_nA \sim 50$ Ohm·mm^2, the specific capacitance of the junctions with AlN barrier is about 17% lower than that of the junctions with AlO_x barrier, which is consistent with usually referred values of dielectric permittivity of alumina and bulk aluminum nitride materials, i.e. 9.5 – 10 vs 7.9 – 8.3, e.g. [21].

Conclusions

In this work, we developed a fabrication process for the high quality Nb/Al-AlN/Nb junctions. We characterized the junctions' dc electric properties and their aging and annealing stability. We showed that Nb/Al-AlN/Nb junctions are probably somewhat more stable against aging and annealing than traditional Nb/Al-AlO_x/Nb junctions are. We present the early results of the Nb/Al-AlN/Nb junctions' specific capacitance measurements. The obtained data shows the specific capacitance of the Nb/Al-AlN/Nb junctions about 17% lower than that of the Nb/Al-AlO_x/Nb junctions with the same R_nA product value. That is in the agreement with the difference between dielectric constants of bulk aluminum nitride and alumina.

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