# High Quality Nb-based Tunnel Junctions for High Frequency and Digital Applications

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***Abstract*—A number of new fabrication techniques are developed and optimized in order to fit the requirements of contemporary superconducting electronics. To achieve ultimate performance of integrated submm receivers with operational frequency of 1 THz, tunnel junctions with AlN tunnel barrier having a $R_nS$ value as low as 1 $\Omega\mu m^2$ have been developed. High quality characteristics of Nb/AlN/Nb tunnel junctions with $R_j/R_n = 16$ and $R_nS = 10\ \Omega\mu m^2$ have been demonstrated. Electron Beam Lithography (EBL) in combination with Chemical Mechanical Polishing (CMP) has been incorporated to produce Nb/AlN/Nb junctions with 0.03 $\mu m^2$ area. A new approach to get overdamped Nb/$AlO_x$/Nb tunnel junction has been proposed and realized. The dependencies of the main parameters of novel junctions on the currents density and circuits geometry have been studied. These junctions may have a good potential in Josephson Junction Arrays and Single-Flux-Quantum applications (RSFQ).**

***Index Terms*—Aluminum nitride, Josephson tunnel junctions, SIS mixers, superconductivity.**

## I. INTRODUCTION

THE idea of utilizing SIS tunnel junctions for heterodyne mixing at THz frequencies has received remarkable support due to recent developments of Nb-Al-AlN-Nb tunnel junctions with low $R_nS$ values (where $R_n$, $S$ are junction normal-state resistance and area respectively) down to 1 $\Omega\mu m^2$ [1]–[4]. Use of sub-micrometer size Nb-Al-AlN-Nb tunnel junctions in combination with low loss NbN or NbTiN tuning circuits will result in significant improvement of 1 THz receiver sensitivity.

Apart from high critical current density, the absence of oxidation is another important advantage of Nb-Al-AlN-Nb junctions. It is well known that atomic oxygen absorbed on the surface of $AlO_x$ causes degradation of Nb-$AlO_x$-Nb(NbN) junction characteristics due to diffusion into the superconducting electrode and suppression of the superconducting gap [1], [5]. This is especially important in the case of small-coherence-length materials like NbN (NbTiN) [1]. Thus the characteristics of SIS mixers that use AlN tunnel barriers in combination with NbN(NbTiN) top superconducting electrodes can be optimized for THz frequencies.

Some processing problems must be addressed for reliable fabrication of THz SIS mixers. As the frequency of mixer operation increases to 1 THz the size of the SIS junction decreases to less than 1 $\mu$m. For reliable fabrication of sub-micrometer junction conventional technology utilizing lift-off and optical lithography cannot be used. A combination of electron beam lithography (EBL) and chemical mechanical polishing (CMP) seems to be the relevant tool [6] for sub-micrometer Nb-$AlO_x$-Nb junction fabrication. This technology is of special interest for fabrication of superconducting VLSI integrated circuits for RSFQ digital application as well.

A problem of major importance in digital applications is necessity of damping of Josephson Junctions. The Mc-Cumber – Stewart parameter, $\beta_c = 2eI_cR_n^2C/\hbar$ (where $C$ is the junction capacitance, $I_c$ the critical current) even for highly transparent junctions with $R_nS = 1\ \Omega\mu m^2$ is still above unity. As a result the junctions have a hysteretic IV curve. To get a single-valued characteristic normally an external shunt made of normal metal thin films is applied. These shunts seriously limit performance of RSFQ circuits because of their size. A better way to solve a damping problem is to use intrinsically shunted junctions based on the superconductor – insulator – normal metal – insulator-superconductor (SINIS) technology [9], [11]. However the state-of-the-art characteristic voltage $V_c = I_cR_n$ realized by this technology is just of the order of 200–300 $\mu$V. Thus a technology that allows fabrication of nonhysteretic Josephson junctions with high characteristic voltage is still desirable.

## II. NB-ALN-NB TUNNEL JUNCTIONS

We produce our junctions in an oil free UHV sputtering system with a base pressure of $10^{-6}$ Pa, which is provided by a combination of turbo-molecular and cryogenic pumps. This system is equipped with 5-inch dc and rf magnetron sources, ion gun and a grounded water-cooled substrate table. Wafers are fixed to the copper chucks using vacuum grease and attached to the substrate table.

Generally speaking the Nb-AlN-Nb junction fabrication procedure follows the well-known recipe for conventional Nb-$AlO_x$-Nb junction production and is described elsewhere [7]. The only difference is substitution of an oxidation step by a nitridation one. As in the case of the conventional Al oxide process we deposit Nb and Al thin films by DC magnetron sputtering in an Ar atmosphere with a working gas pressure of 1 Pa. The dielectric layer for junction insulation consists of 250 nm $SiO_2$, defined in a self-aligned lift-off procedure. The wiring layer is defined by lift-off.

It is well known that using a simple exposure of sputtered Al surface into $N_2$ atmosphere one cannot get a continuous

Manuscript received August 5, 2002. This work was supported in part by the Russian SSP "Superconductivity," the RFBR projects 00-02-16270, INTAS project 01-0367, ISTC project 2445, and IFTI-SRON under Grant 0003/007.

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Digital Object Identifier 10.1109/TASC.2003.813657

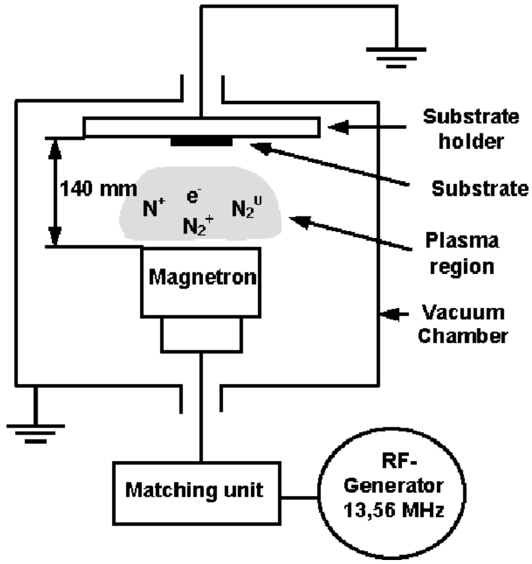


Fig. 1. The electrical scheme of the nitridation process.

AlN layer of sufficient thickness to be used as a tunnel barrier [1]. Several successful attempts of Al nitridation have been made using a glow discharge in nitrogen atmosphere [1]–[4]. Following this idea we grow an AlN tunnel barrier just after Al deposition using rf magnetron discharge. Technical details of our method are as follows. Samples are attached to the grounded substrate table and maintained at 20°C. To get a density of nitrogen ions capable of producing AlN tunnel barrier the sample holder is positioned directly above 5 inch Al magnetron rf source having holder-source distance of 14 cm. The electrical scheme of the nitridation process is presented in Fig. 1. We initiate a plasma discharge using very small power density of 0.5–0.75 $W/cm^2$. The nitrogen pressure was kept constant of 4.5 Pa. The total duration of the nitridation process was varied in the range 100 – 300 sec. Use of such conditions, small power, large source-sample distance and dense plasma, permitted us to avoid both exposure of the samples to energetic flux of ions and significant sputtering of Al target during AlN growth.

A set of Nb-AlN-Nb junction IV characteristics is presented in Fig. 2. The critical current is suppressed by a magnetic field. The $R_nS$ value changes from 0.9 $\Omega\mu m^2$ for the curve (a) to 24 $\Omega\mu m^2$ for the curve (d). The increase of the sub-gap leakage follows the increase of the critical current density. Moreover a self-heating in the junctions can be clearly seen in this figure. It causes both the gap voltage reduction and back bending of the gap singularity.

Fig. 2(c) presents the IV characteristic of the Nb-AlN-Nb junction exposed to the nitrogen plasma for 300 sec at 60 W of rf power. This junction with low RnS of 10 $\Omega\mu m^2$ demonstrates excellent tunnel characteristics with $R_j/R_n = 16$. From other IV curves presented in Fig. 2 it is clear that RnS value can be easily lowered down to 5–7 without significant degradation of sharpness. An over-heating problem, seen in Fig. 2(b), possibly can be overcome by decreasing junction area.

The dependencies of the $R_nS$ value versus nitridation time taken at different discharge power are presented in Fig. 3. Unlike previous work [4], $R_nS$ does not saturate as a function of time and power. However, for ion power of 60 W, the $R_nS$ value is a regular and slowly varying function of exposure time and thus can be easily controlled in the range of major interest: $R_nS < 10\ \Omega\mu m^2$.

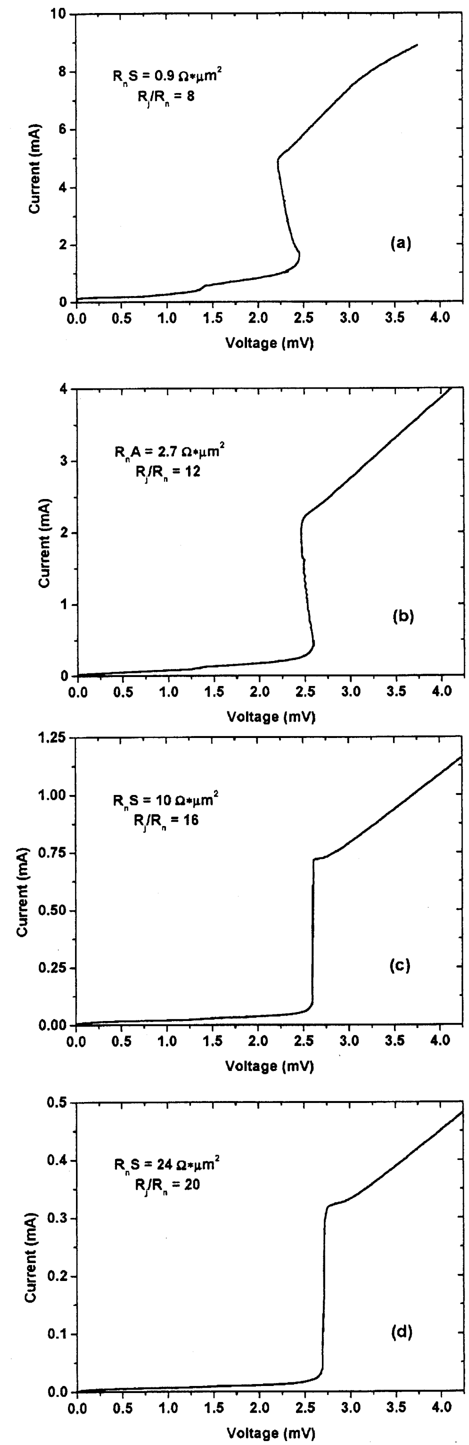


Fig. 2. IV characteristics of Nb-AlN-Nb junctions with (a) $R_nS = 0.9\ \Omega\mu m^2$, (b) 2.7 $\Omega\mu m^2$, (c) 10 $\Omega\mu m^2$, (d) 24 $\Omega\mu m^2$.

The implementation of AlN tunnel barrier in combination with NbN top superconducting electrode is expected to give a significant improvement in SIS THz mixer performance. To explore this idea we produced a Nb-AlN-NbN tunnel junction.

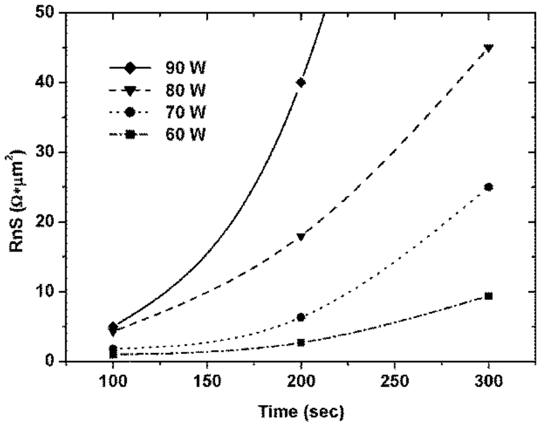


Fig. 3. The dependencies of the $R_nS$ value versus nitridation time taken at different discharge power.

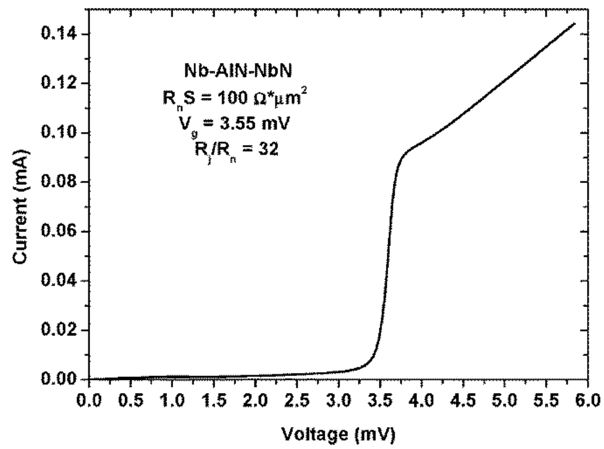


Fig. 4. IV characteristic of Nb-AlN-NbN junction, with $R_nS = 100\ \Omega\mu\mathrm{m}^2$.

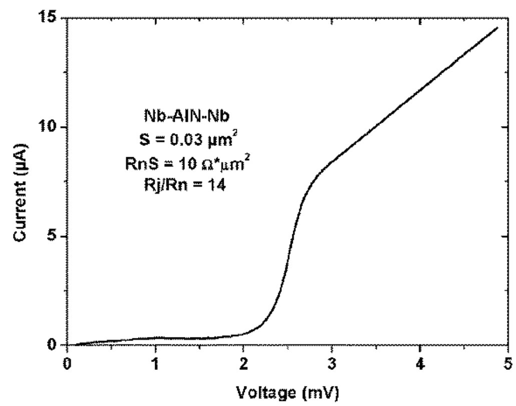


Fig. 5. IV characteristic of sub-micrometer Nb-AlN-Nb junction with $R_nS = 10\ \Omega\mu\mathrm{m}^2$, $S = 0.03\ \mu\mathrm{m}^2$.

NbN was deposited by DC reactive magnetron sputtering at ambient temperature with 1.8 $\mathrm{W/cm}^2$ power density using Ar $+$ $9\%\mathrm{N}_2$ gas mixture. Otherwise the fabrication procedure was the same as described above for Nb-AlN-Nb junctions.

The IV characteristic of this junction is presented in Fig. 4. The $R_nS = 100\ \Omega\mu\mathrm{m}^2$, $R_j/R_n = 32$ and gap voltage is 3.53 mV. It is worthy to note that the $R_nS$ value for these junctions appear to be much higher than for Nb-AlN-Nb junctions assuming the same nitridation procedure is applied. A possible explanation of this is an erosion of the AlN layer during Nb top electrode deposition. It can be caused by the plasma bombardment and thermally stimulated diffusion of nitrogen into Nb.

To take advantage of the high transparency of an AlN tunnel barrier it is important to fabricate sub-micrometer sized junctions. Toward that end we have put in place reliable Chemical-Mechanical Polishing (CMP) processing using a Tech. Prep 8 polishing machine from Allied High Tech Products Inc. Electron Beam Lithography (EBL) has been incorporated to reduce junction area down to 0.1 $\mu\mathrm{m}^2$.

In our CMP process, after definition of individual junctions, the resist pattern is removed and 300 nm of $\mathrm{SiO}_2$ is deposited. We do CMP planarization in two steps. A hard lapping film with $\mathrm{Al}_2\mathrm{O}_3$ is used for fast removal of 250 nm of the insulation layer that covers the small areas (typical planar size is 100 $\mu$m) of the trilayer pattern. A soft dense low napped silk pad is used for slow uniform polishing of the remaining 50 nm of $\mathrm{SiO}_2$ to reach the junction surface. At the moment a number of test structures have been successfully fabricated and measured. The IV characteristic of Nb-AlN-Nb junction of 0.03 $\mu\mathrm{m}^2$ area is presented in Fig. 5.

## III. Non-Hysteretic Nb-AlO$_x$-Nb Tunnel Junctions

Hysteresis in Josephson tunnel junctions is related to the amount of damping [8] as indicated by the value of the McCumber-Stewart parameter, $\beta_c = 2eI_cR_n^2C/\hbar$. The $I$-$V$ characteristic of a junction becomes nonhysteretic for $\beta_c < 1$. As follows from [8] in the case of tunnel junctions, the $R_n$ in $\beta_c$ should be substituted by $R_j$, the sub-gap resistance.

Using external shunts made of sputtered Mo thin films we have fabricated nonhysteretic Nb-AlO$_x$-Nb tunnel junctions with $R_nS = 20\ \Omega\mu\mathrm{m}^2$ and characteristic voltage as much as 420 $\mu$V. These junctions have been successfully employed for a high performance SQUID Amplifier [12].

In this paper we present a new approach to get overdamped tunnel junctions that does not utilize external thin film shunts. In the proposed arrangement a Nb-AlO$_x$-Al-Nb SIS tunnel junction is encircled by a shunting conductance created by Nb-AlO$_x$ -Al superconductor – insulator – normal metal (SIN) junction. Topologically both junctions share the same Nb bottom electrode and AlO$_x$ tunnel barrier. The area of the Nb-AlO$_x$-Al shunting junction is designed to exceed the area of Nb-AlO$_x$ -Al-Nb junction by two to five times. Details of this structure will be presented in subsequent publications.

The shunting conductance is determined by the tunnel transparency of an AlO$_x$ layer and area of SIN junction. The specific sub-gap resistance of the Nb-AlO$_x$-Al SIN junction is much smaller compared to sub-gap resistance of the Nb-AlO$_x$-Al-Nb SIS junction, and thus for the most part determines the resistance of the whole structure in the sub-gap region. It is worth noting that reproducibility of the shunting conductance arranged in this way is expected to be much better in comparison with the usual normal metal thin films shunts.

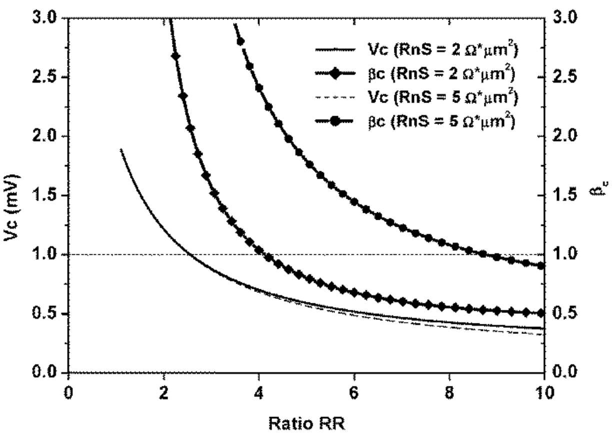


Fig. 6. Mc-Cumber-Stewart parameter $\beta_c$ and characteristic voltage $V_c$ calculated for two values of $R_nS$ : 2 and 5 $\Omega\mu\text{m}^2$ as a function of the ratio (RR) of the total area of the whole SIS-SIN structure to the area of SIS junction.

The capacitance of the whole structure increases and resistance decreases proportionally to the area of the shunting SIN junction. As it follows from the definition $\beta_c \sim R_j^2 C$, $\beta_c$ can be lowered to unity using a SIN junction of large enough area. On the other hand a characteristic voltage $V_c \sim R_j I_c$ and can be kept large enough. Our estimations show that ultimate parameters can be realized for sub-micron junctions with high current density.

Fig. 6 illustrates our calculations based on the Resistively Shunted Tunnel Junction Model. Two dependences of $V_c$ and $\beta_c$ are plotted against the ratio of the total area of the whole structure to SIS junction area. $R_nS$ of 2 and 5 $\Omega\mu\text{m}^2$ are assumed. It can be seen that a $\beta_c$ value below unity and high enough characteristic voltage $V_c \approx 0.7$ mV and 0.35 mV for $R_nS = 2$ and 5 $\Omega\mu\text{m}^2$, respectively, can be achieved simultaneously provided that the area of the whole structure exceeds the area of Nb-Al$O_x$-Nb junction by 4 and 9 times respectively.

## IV. Conclusion

We have developed a reliable and reproducible fabrication process for high quality Nb-Al-AlN-Nb tunnel junctions with $R_nS$ value as low as 1 $\Omega\mu\text{m}^2$. The dc glow discharge in a nitrogen atmosphere was employed for Al nitridation. Despite such a high tunnel barrier transparency our junctions demonstrate sharp $I$-$V$ characteristic with a high value of the quality parameter $R_j/R_n$ of about 10. The same nitridation procedure has been successfully employed for fabrication of NbN based tunnel junctions Nb-Al-AlN-NbN. These junctions in combination with NbN(NbTiN) tuning circuits are excellent candidates to be used as a high performance 1 THz mixers.

## Acknowledgment

The authors would like to thank N. Iosad and M. Khabipov for fruitful discussions, and V. Krupenin and D. Presnov for assistance in EBL processing.

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