Bandwidth Limitations of Nb/AlN/Nb SIS Mixers Around 700 GHz

Chris F. J. Lodewijk, T. Zijlstra, Shaojiang Zhu, F. Patricio Mena, Andrey M. Baryshev, and T. M. Klapwijk

Abstract—We study, using niobium-technology, the bandwidth of SIS mixers operating at frequencies close to the energy-gap frequency. Microstriplines of niobium—silicon dioxide—niobium have different properties for the top and bottom superconductor, which we find to depend on the used fabrication process. Replacing the AlO_x tunnel barrier by AlN, the bandwidth increases by 53%. The measurements, using a Fourier Transform Spectrometer (FTS) and performed in ambient air, demonstrate that the bandwidth is no longer limited by the tuning circuit but by the atmospheric absorption of radiation. Excellent noise temperatures are found over a full band of 600 to 720 GHz.

I. INTRODUCTION

THE Atacama Large Millimeter Array (ALMA) [1], [2] is one of the most challenging astronomical enterprises of this decade. Europe, USA and Japan are jointly building 64 telescopes on a 5000 m high altitude plateau in Chile, equipped with superconducting sensors. Astronomical observations will be performed in the frequency range of 30 to 950 GHz, divided into 10 bands, set by the atmospheric transmission.

In the superconducting technology of Band 9 (602 to 720 GHz), we have chosen to work with the robust Nb SIS mixers and a Nb/SiO₂/Nb tuning circuit. The latter is needed to match the antenna impedance (Z_{ant}) to the SIS junction impedance [3], which is characterized by the junction's normal state resistance R_n in parallel with its capacitance C .

Although the specifications for Band 9 can be met with aluminum oxide tunnel barriers, an intrinsically wider band coverage would be beneficial. The noise temperature (T_n) results for eight prototype Band 9 SIS mixers are shown in Fig. 1. The horizontal lines indicate the required and the hoped for noise temperatures. The results are obviously within the specifications. However, a flat response over the full band width is desirable. Also, the location of minimum noise temperature depends

Fig. 1. Uncorrected double sideband (DSB) noise temperature as a function of local oscillator (LO) frequency for 8 prototype cartridges of ALMA Band 9. Different symbols represent different cartridges and polarizations; all devices are based on Nb/AlO_x/Nb SIS mixers. Specifications (full horizontal lines) of 80% of Band 9 below 168 K and below 250 K at all frequencies are met for all devices, in spite of a clear degradation of T_n at the lower end of the band. (Inset: six completed Band 9 cartridges in our laboratories.).

on unavoidable variations in the device-technology. High critical current density aluminum nitride devices have a low $R_n C$ time constant, which would enable a desirable larger bandwidth, provided the matching circuit is not limiting [3].

II. PROPERTIES OF Nb MICROSTRIPLINES

For superconducting niobium with an energy gap 2Δ of 2.8 meV, the gap-frequency is 680 GHz. Hence, losses appear stronger in the range of Band 9, which is particularly important for the tuning circuit. This circuit, used to match Z_{ant} with the junction impedance, is realized with a Nb/SiO₂/Nb microstripline. Information about the quality of the niobium is partially derived from the tunneling current-voltage (I - V) characteristics, but it does not provide information about the niobium on both sides of the dielectric. In particular, 2Δ and the normal conductivity σ_n are essential parameters in the evaluation of the frequency-dependent behavior of the microstripline. In our case, the bottom superconductor consists of a multilayer of 200 nm DC magnetron sputtered Nb, a 6 nm DC sputtered thin layer of Al, and the tunnel barrier (1 nm AlO_x or AlN). For the completed microstripline, there is a 250 nm layer of RF sputtered SiO₂ and a top Nb layer of 500 nm.

The importance of the quality of the niobium of the microstriplines became more strongly apparent in a series of batches of Nb/AlO_x/Nb SIS devices in which a previously assumed innocent anodization step was added after the reactive ion etching process to define the junctions. Unfortunately, these devices showed a deteriorated performance at the higher

Manuscript received August 17, 2008. First published June 30, 2009; current version published July 10, 2009. This work was funded in part by NanoImpuls, the Dutch Research School for Astronomy (NOVA), the Dutch Organisation for Scientific Research (NWO), Radionet, and the European Southern Observatory (ESO).

C. F. J. Lodewijk, T. Zijlstra, S. Zhu, and T. M. Klapwijk are with the Kavli Institute of Nanoscience, Faculty of Applied Sciences, Delft University of Technology, Lorentzweg 1, 2628 CJ Delft, The Netherlands (e-mail: c.f.j.lodewijk@tudelft.nl).

F. P. Mena was with the SRON Netherlands Institute for Space Research and Kapteyn Astronomical Institute, Landleven 12, 9747 AD Groningen, The Netherlands. He is now with the Universidad de Chile, Santiago, Chile.

A. M. Baryshev is with the SRON Netherlands Institute for Space Research and Kapteyn Astronomical Institute, Landleven 12, 9747 AD Groningen, The Netherlands.

Color versions of one or more of the figures in this paper are available online at <http://ieeexplore.ieee.org>.

Digital Object Identifier 10.1109/TASC.2009.2018231

Fig. 2. Effect of anodization on the frequency response of an SIS device. Normalized photoresponse of a device without anodization (squares) and with anodization (open diamonds), measured with a Fourier Transform Spectrometer (FTS).

frequency end, demonstrated in Fig. 2, although the DC IV characteristics revealed no sign of degraded niobium properties.

The anodization process, carried out up to a voltage of 10 V, leads to a full oxidation of the Al layer, used to make the tunnel barrier. Consequently, the bottom Nb layer is also chemically reacting with oxygen atoms. As a result, the microstripline will be a multilayer of Nb/NbO_y/AlO_x/SiO₂/Nb, where the index y may vary as a function of height. In other words, the dielectric has become a complicated package and the interface between the dielectric layer and the superconducting metal is quite different.

In tunneling experiments with anodized tunnel barriers it has been shown [4] that the energy gap of the Nb is lower than the bulk value. This finding is in line with the fact, known from tunnel junctions based on a standard niobium-oxidation process [5], [6] that the insulating niobium-oxide evolves into the niobium through a poorly conducting layer of suboxides of niobium, which become superconducting through the proximity-effect. Hence, it is justified to assume a lower 2Δ between 2.8 to 2.5 meV for the bottom Nb layer when we apply anodization in our processing. Note that this occurs without deterioration of the tunneling IV curve, because the Al and bottom Nb layer below the junction area are not anodized.

Furthermore, it is known that the normal resistivity (ρ_n) and critical temperature (T_c) of NbO_y depend strongly on y [7]. For $y > 1$, ρ_n increases rapidly from $2 \mu\Omega\text{cm}$ to $65 \mu\Omega\text{cm}$ at $y = 1.5$. Over this range T_c remains almost constant at about 1.4 K. Therefore, if anodization is used, and a layer of NbO_y is created, the bottom layer of the microstripline is likely to have a much higher ρ_n (lower σ_n).

A model that includes a lower σ_n and 2Δ for the bottom superconductor of the microstripline qualitatively explains the depressed FTS response for the anodized device in Fig. 2. We conclude that adding anodization to improve the edge-isolation of tunnel junctions may have a deteriorating effect on the microstriplines, which would in particular be harmful at frequencies around the gap-frequency of the superconductor. In addition, the microwave response of microstriplines built with a bilayer of niobium and aluminum does not necessarily comply with the standard Mattis-Bardeen theory. It has been shown, at the lower frequency of about 10 GHz, that for thick enough aluminum (tens of nanometers) the surface impedance of the Nb/Al

bilayers does not agree with that of bare Nb samples [8]. It is to be expected that at higher frequencies similar deviations should also occur for thinner aluminum layers.

In the frequency range studied here the conclusion is that in evaluating the microstripline, the normal state conductivity and the energy gap of the top and bottom superconductors should be assumed to be different and dependent on the growth specifics and possibly the post-processing of the material.

III. BANDWIDTH OF SIS MIXERS

Apart from the quality of the materials used for the microstripline and the position of the SIS device in the waveguide, determined by both the mounting of the chip and the thickness of the substrate [3], the critical current density J_c of the tunnel barrier itself is the dominant parameter in the bandwidth.

The tunnel barrier defines the RC time constant, which limits the bandwidth of a device matched to a source impedance by [9]:

$$\ln\left(\frac{1}{\Gamma_{\max}}\right) \Delta f = \frac{1}{2RC}, \quad (1)$$

where $\Gamma_{\max}$ is the maximum reflection coefficient over a bandwidth Δf . A wide Δf is achieved by a low RC product of the SIS junction, which in its turn is set by the tunnel barrier transparency. This transparency can be characterized by J_c [10]:

$$J_c = \frac{\pi}{2} \frac{\Delta}{eR_nA}, \quad (2)$$

with e the charge of an electron and A the area of the SIS junction.

Increasing the critical current density of AlO_x barriers leads to SIS junctions with poor quality IV characteristics for J_c above 20 kA/cm^2 [11]. At this relatively low critical current density, or relatively high R_nA value the subgap current increases rapidly indicating that a substantial fraction of the tunnel barrier area carries higher order tunneling terms, i.e. contains parts with transmissivities close to unity.

A route towards higher critical current densities, achieved by replacing AlO_x with AlN, was first identified by Shiota *et al.* [12] and subsequently explored by others [13], [14]. We have recently developed a technological route to AlN devices suitable for SIS mixers [15] using an ICP approach, which was also proposed in [16] and identified that in comparison to AlO_x the AlN tunnel barriers have much more uniform tunneling properties. Mixing devices based on AlN barriers, using a different technological process, have recently been reported at frequencies from 275 to 425 GHz [17].

In order to test the sensitivity to variations in fabrication parameters, we have studied the transmission efficiency of SIS devices using a model reported before [3]. Unless indicated, we use the following parameters for our simulations: $R_nA = 25 \Omega\mu\text{m}^2$, $A = 1.0 \mu\text{m}^2$, specific capacitance $C_s = 65 \text{ fF}/\mu\text{m}^2$ for AlO_x, and $R_nA = 6.0 \Omega\mu\text{m}^2$, $A = 0.50 \mu\text{m}^2$, and specific capacitance $C_s = 60 \text{ fF}/\mu\text{m}^2$ for AlN tunnel barriers (see Section IV). The parameters of the microstripline are $\sigma_{n,b} = 0.8 \times 10^7 \text{ S/m}$ for the bottom Nb and $\sigma_{n,t} = 0.9 \times 10^7 \text{ S/m}$ for the top Nb, with the energy gaps set at the optimal value of 2.8 meV, unless indicated otherwise.

Fig. 3. Substrate thickness dependence of the frequency response of SIS devices (calculated). Curves are for a substrate thickness of 35 μm (dotted lines), 40 μm (nominal, full lines), and 45 μm (dashed lines). The curves for AlO_x and AlN tunnel barriers are indicated. The frequency range of ALMA Band 9 (602 to 720 GHz) is indicated with dash-dotted lines.

Fig. 4. Junction area dependence of the frequency response of SIS devices (calculated). Curves are for a nominal junction area (A_n , full lines), a 20% reduced junction area (dotted lines), and a 20% increased junction area (dashed lines). For AlO_x , the A_n is 1.0 μm^2 , for AlN , A_n is 0.50 μm^2 . The frequency range of ALMA Band 9 (602 to 720 GHz) is indicated with dash-dotted lines.

In Fig. 3, the influence of a variation of the substrate thickness is shown, for SIS junctions with an AlO_x and with an AlN tunnel barrier. Clearly, the substrate thickness plays an important role for the AlO_x devices, but has less an effect on the much wider bandwidth of the AlN devices.

Fig. 4 shows the calculated response for SIS junctions with variations in the area A . Whereas there is a sizable difference in response for the AlO_x devices, the bandwidth performance of AlN is hardly affected.

Finally, in Fig. 5, the dependence of the transmission efficiency on 2Δ is shown. Although the response of the AlN devices remains higher than that of the AlO_x devices, a degradation at the higher end of the band is clearly visible and undesirable. This indicates that despite the intrinsically wider bandwidth of AlN devices, it is crucial to maintain high quality niobium for the microstriplines.

IV. BANDWIDTH EVALUATION

A set of SIS devices with a tuning circuit suitable for Band 9 of ALMA has been realized with AlN tunnel barriers, using our recently introduced method [15]. All devices contain a multisection Nb/ SiO_2 /Al – Nb microstripline, to tune out the capacitance of the SIS junction. The transmission efficiency of a device is evaluated using a Fourier Transform Spectrometer (FTS)

Fig. 5. Microstripline energy gap dependence of the frequency response of SIS devices (calculated). Curves are for microstriplines for which both top and bottom superconductor have an equal 2Δ of 2.8 meV (full lines), a 2Δ of 2.7 meV (dashed lines), and a 2Δ of 2.6 meV (dotted lines). Calculations corresponding to AlO_x and AlN tunnel barriers are indicated. The frequency range of ALMA Band 9 (602 to 720 GHz) is indicated with dash-dotted lines.

Fig. 6. Normalized photoresponse of two devices, measured with an FTS. The triangles are for a device with an AlN tunnel barrier, whereas the squares show the best achievable result for a device with an AlO_x tunnel barrier. The dash-dotted lines indicate ALMA Band 9. Minima in the response are due to water absorption.

by measuring the changes in the DC current produced by the incoming light for a bias voltage of 2.5 mV.

The device is mounted onto a waveguide backpiece. The device has the following parameters: $R_n = 7.1 \Omega$, $A = 0.52 \mu\text{m}^2$, the ratio of the subgap resistance to the normal resistance $Q = 15$, and the gap voltage $V_g = 2.64$ mV. J_c for this device is 56 kA/cm^2 . The FTS data, taken at a temperature of 4.2 K, are shown in Fig. 6 (triangles). The FTS setup is operated in air, leading to the water absorption lines at the edges of the band. In the same graph, one of the best available FTS results for an AlO_x based SIS device, selected for one of the prototype cartridges of Band 9, is shown (squares).

The full width half maximum (FWHM) bandwidth of the AlN device is about 168 GHz, whereas the FWHM bandwidth of the AlO_x device is around 116 GHz. Obviously, the bandwidth of the AlN device is about 45% larger than that of the AlO_x device. A good response is obtained over the full targeted band.

In Fig. 6, there are clearly minima in the response, due to the absorption of radiation by water vapor in the atmosphere, in particular at 560 and 750 GHz. In order to compare the FTS data with model calculations we subtract the atmospheric transmission from the data. Fig. 7 shows the same FTS measurement results as Fig. 6 corrected for the atmospheric transmission [18]. The triangles show the corrected response for the AlN device,

Fig. 7. FTS measurement results, corrected for the atmospheric transmission. The triangles are for an AlN device, the squares for an AlO_x device. The full line shows the simulated response for the AlN device, using real device parameters. All curves are normalized to their maximum.

Fig. 8. Uncorrected DSB noise temperature of an SIS mixer with an AlN tunnel barrier (triangles pointing up), earlier AlN results [21] (triangles pointing down) and the average of the traces of Fig. 1, for an SIS with an AlO_x tunnel barrier (squares), in the frequency range of ALMA Band 9.

the squares indicate the corrected response for the AlO_x device. The full line is the model fit for the AlN device, based on its measured device parameters. The specific capacitance of the SIS junction, used as a fitting parameter, is determined to be $60 \text{ fF}/\mu\text{m}^2$. Based on a permittivity of AlN of 8.8 [19], this corresponds to a tunnel barrier thickness of 1.3 nm, which is well within the tolerance of the Transmission Electron Microscope result in [15], which yields $1.5 \pm 0.5 \text{ nm}$.

From Fig. 7, we can correct the FWHM bandwidth for water absorption. The AlN device has a bandwidth of 187 GHz, the AlO_x device yields 122 GHz. Hence, the use of AlN has improved the bandwidth by 53%.

V. NOISE TEMPERATURE

The same AlN based device has been mounted in a standard ALMA Band 9 test cartridge. The noise temperature of the mixer, the accompanying optics and the Intermediate Frequency (IF) chain [20] has been evaluated using the standard Y-factor method. The resulting uncorrected DSB noise temperatures at different local oscillator (LO) frequencies are presented in Fig. 8 (triangles pointing upwards). In the same graph, the average of the 16 traces for the prototype cartridges in Fig. 1, obtained with AlO_x based SIS devices, are shown with squares. AlN results reported earlier, based on an unoptimized tuning circuit [21] are indicated by the triangles pointing downwards.

Evidently, the noise temperature of the newest AlN SIS mixers is much flatter over Band 9 than for the best AlO_x mixers, while practically maintaining the same low value.

VI. CONCLUSION

The optimal astronomical use of the Band 9 frequency window of the Atacama Large Millimeter Array is dependent on a few material parameters of the superconducting mixing devices. We find that the energy gaps of the bottom and the top superconductor of tuning microstriplines, which can not be inferred from DC SIS measurements, are dependent on the process route and may limit the band coverage. The normal conductivity of these superconducting layers is determined by the fabrication process as well, and is in general different for the top and the bottom layer. The use of an anodization step in the processing will deteriorate the performance of the tuning microstriplines, due to a degradation in σ_n and 2Δ .

The use of AlN tunnel barriers in SIS devices leads to a sizable gain in the FWHM bandwidth, which, after correction for the atmospheric transmission, amounts to about 53% in comparison to AlO_x devices. Heterodyne measurements reveal that the AlN SIS devices have an uncorrected DSB noise temperature which is comparably low at the optimum frequency, but much lower than the AlO_x mixers currently in the prototype Band 9 cartridges at the other frequencies of the band.

ACKNOWLEDGMENT

The authors thank G. Gerlofsma and J. Barkhof for technical assistance.

REFERENCES

- [1] The Atacama Large Millimeter/Submillimeter Array Web Site [Online]. Available: <http://www.alma.nrao.edu/>
- [2] J. Kanipe, "High and dry," *Nature*, vol. 439, pp. 526–528, Feb. 2006.
- [3] C. F. J. Lodewijk, O. Noroozian, D. N. Loudkov, T. Zijlstra, A. M. Baryshev, F. P. Mena, and T. M. Klapwijk, "Optimizing superconducting matching circuits for Nb SIS mixers operating around the gap frequency," *IEEE Trans. Appl. Superconductivity*, vol. 17, pp. 375–378, Jun. 2007.
- [4] J. Aponte, E. Rivera, A. Sa Neto, and M. Octavio, "Anodized niobium as barrier for Josephson tunnel junctions," *J. Appl. Phys.*, vol. 62, pp. 700–705, Jul. 1987.
- [5] G. B. Arnold, J. Zasadzinski, and E. L. Wolf, "A resolution of the controversy on tunneling in Nb," *Phys. Lett. A*, vol. 69, pp. 136–138, Nov. 1978.
- [6] J. M. Rowell, M. Gurvitch, and J. Geerk, "Modification of tunneling barriers on Nb by a few monolayers of Al," *Phys. Rev. B*, vol. 24, pp. 2278–2281, Aug. 1981.
- [7] J. K. Hulm, C. K. Jones, R. A. Hein, and J. W. Gibson, "Superconductivity in the TiO and NbO systems," *J. Low Temp. Phys.*, vol. 7, pp. 291–307, 1972.
- [8] M. S. Pambianchi, S. N. Mao, and S. M. Anlage, "Microwave surface impedance of proximity-coupled Nb/Al bilayer films," *Phys. Rev. B*, vol. 52, pp. 4477–4480, Aug. 1995.
- [9] H. W. Bode, *Network Analysis and Feedback Amplifier Design*. New York: Van Nostrand, 1945, sec. 16.3.
- [10] V. Ambegaokar and A. Baratoff, "Tunneling between superconductors," *Phys. Rev. Lett.*, vol. 10, pp. 486–489, Jun. 1963.
- [11] R. E. Miller, W. H. Mallison, A. W. Kleinsasser, K. A. Delin, and E. M. Macedo, "Niobium trilayer Josephson tunnel junctions with ultrahigh critical current densities," *Appl. Phys. Lett.*, vol. 63, pp. 1423–1425, Sep. 1993.
- [12] T. Shiota, T. Imamura, and S. Hasuo, "Nb Josephson junction with an AlN barrier made by plasma nitridation," *Appl. Phys. Lett.*, vol. 61, pp. 1228–1230, Sep. 1992.

- [13] A. W. Kleinsasser, W. H. Mallison, and R. E. Miller, "Nb/AlN/Nb Josephson junctions with high critical current density," *IEEE Trans. Appl. Superconductivity*, vol. 5, pp. 2318–2321, Jun. 1995.
- [14] B. Bumble, H. G. LeDuc, J. A. Stern, and K. G. Megerian, "Fabrication of Nb/Al-Nx/NbTiN junctions for SIS mixer applications," *IEEE Trans. Appl. Superconductivity*, vol. 11, pp. 76–79, Mar. 2001.
- [15] T. Zijlstra, C. F. J. Lodewijk, N. Vercruyssen, F. D. Tichelaar, D. N. Loudkov, and T. M. Klapwijk, "Epitaxial aluminum nitride tunnel barriers grown by nitridation with a plasma source," *Appl. Phys. Lett.*, vol. 91, pp. 233102 1–233102 3, Dec. 2007.
- [16] T. W. Cecil, R. M. Weikle, A. R. Kerr, and A. W. Lichtenberger, "Investigation of NbTiN thin films and AlN tunnel barriers with ellipsometry for superconducting device applications," *IEEE Trans. Appl. Superconductivity*, vol. 17, pp. 3525–3528, Jun. 2007.
- [17] J. W. Kooi, A. Kovács, M. C. Sumner, G. Chattopadhyay, R. Ceria, D. Miller, B. Bumble, H. G. LeDuc, J. A. Stern, and T. G. Phillips, "A 275–425-GHz tunerless waveguide receiver based on AlN-barrier SIS technology," *IEEE Trans. Microwave Theory and Techn.*, vol. 55, pp. 2086–2096, Oct. 2007.
- [18] The program that calculates the atmospheric transmission has been provided by J. R. Pardo-Carrion, Departamento de Astrofísica Molecular e Infraroja, Consejo Superior de Investigaciones Científicas, Madrid, Spain.
- [19] L. M. Sheppard, "Aluminum nitride: A versatile but challenging material," *Am. Ceram. Soc. Bull.*, vol. 69, pp. 1801–1812, 1990.
- [20] A. Baryshev, E. Lauria, R. Hesper, T. Zijlstra, and W. Wild, Fixed-Tuned Waveguide 0.6 THz SIS Mixer With Wide Band IF ALMA memo 429, Jul. 2002.
- [21] C. F. J. Lodewijk, T. Zijlstra, D. N. Loudkov, T. M. Klapwijk, F. P. Mena, and A. M. Baryshev, "Wideband AlN-based SIS devices for frequencies around 700 GHz," presented at the Proc. 18th Int. Symp. on Space THz Technology, 2007, paper 10-1, Ed. A. Karpov, pp. 256–259, unpublished.