Bandwidth of Nb/AlN/Nb SIS Mixers Suitable for Frequencies around 700 GHz

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***Abstract*— We have developed a new fabrication process for AlN barriers with excellent reproducibility and control compared to previous work, enabling the use of these barriers in SIS mixers. We report results with niobium-aluminum nitride-niobium superconductor-isolator-superconductor (SIS) mixers for 700 GHz, demonstrating a wide bandwidth behavior with Fourier Transform Spectrometer (FTS) measurements. These measurements have been performed in air and reveal that the bandwidth is no longer limited by the tuning circuit but by the atmospheric absorption of radiation. We also present noise temperature measurements of AlN SIS mixers that complement the FTS results.**

I. INTRODUCTION

Although the specifications for Band 9 (602 to 720 GHz) of the atmospheric window at the Atacama Large Millimeter Array (ALMA) [1], [2] can be met with aluminum oxide [3], an intrinsically wider band coverage would be beneficial. In particular a flat response over the full band width is desirable. High critical current density aluminum nitride devices have a low *RC* time constant, enabling such a desirable larger bandwidth, provided a suitable matching circuit is realized [4].

II. BANDWIDTH OF SIS MIXERS

The bandwidth of SIS mixers for Band 9 is limited by several critical parameters. First, the superconducting gap energy 2Δ of the used superconductor is important. In this work, the electrodes of the SIS junction as well as the microstriplines are made of niobium. Its $2\Delta = 2.8$ meV translates into a gap frequency f_{gap} of about 690 GHz, implying that resistive losses will reduce the transmission at the high end of the band.

Second, other material parameters that play a role are the high frequency resistivity of the niobium microstriplines and the permittivity of the dielectric layer of silicon dioxide. The normal state resistivity can vary over the thickness of the superconducting film, whereas the effective resistivity of a superconducting bilayer (niobium-aluminium) used in the process is poorly defined.

Furthermore, the position of the SIS device in the waveguide, determined by both the mounting of the chip and the thickness of the substrate, has to be carefully monitored. It determines the antenna impedance, which is crucial for the device performance [4].

Finally, the *RC* time constant fundamentally limits the bandwidth of a device matched to a source impedance by [5]:

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

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 the critical current density J_c [6]:

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

with e the charge of an electron and R_nA the normal resistance times area of an SIS junction.

Increasing the critical current density of AlO_x barriers leads to SIS junctions with poor quality current-voltage (*IV*) characteristics for J_c above 20 kA/cm^2 [7]. 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 tunnelling terms, i.e. contains parts with transparencies close to unity. First results on AlN tunnel barriers have been published by Shiota *et al.* [8], with the attractive feature of offering a much higher critical current density. Mixing devices based on AlN barriers have recently been used by Kooi *et al.* [9] at frequencies from 275 to 425 GHz.

III. ALN GROWTH AND FABRICATION PROCESS

Compared to the growth of AlO_x, in which oxygen molecules decompose on the aluminium into reactive atomic oxygen, for AlN tunnel barrier growth, a plasma is needed to split N_2 molecules into N radicals, which subsequently react with Al. We have used an inductively coupled plasma source [10] to generate a nitrogen plasma containing N radicals which diffuse to the aluminium. This approach is different from most previous work with parallel plate reactors, where reproducibility and control were difficult to achieve [8], [11]-[13].

The devices are fabricated on a 2 inch fused quartz substrate. All metal layers are deposited by magnetron sputtering in the process chamber of a Kurt Lesker system. First, a 100 nm Nb monitor layer is deposited, after which a ground plane pattern is optically defined. Subsequently, a bilayer of 100 nm Nb and about 7 nm Al is deposited. Without breaking the vacuum, the substrate is then transferred to a nitridation chamber, where the Al is exposed to the nitrogen plasma for several minutes, producing a layer of AlN. The substrate is then again *in vacuo* transferred to the process chamber, where a top electrode of 200 nm Nb is deposited. The lateral dimensions of the multilayer of Nb/Al/AlN/Nb are patterned by lift-off. Junctions are defined by e-beam lithography with a negative e-beam resist (SAL-601) layer and reactively ion etched (RIE) with a SF_6/O_2 plasma using the AlN as an etch-stop, followed by a mild anodization (5 V). The junction resist pattern is used as a self-aligned lift off mask for a dielectric layer of 250 nm SiO_2. A 500 nm Nb/50 nm Au top layer is deposited and Au is etched with a wet etch in a KI/I_2 solution using an optically defined mask. Finally, using an e-beam defined top wire mask pattern, the layer of Nb is etched with a SF_6/O_2 RIE, which finishes the fabrication process.

IV. DC TEST RESULTS AND BARRIER UNIFORMITY

The quality factor Q, defined as $Q=R_j/R_n$, where R_j is the resistance of an SIS junction below the gap voltage $V_{gap} = 2\Delta/e$, gives a measure for the amount of subgap current through a tunnel barrier. A low subgap current is a signature of a good quality tunnel barrier provided only first order tunnelling processes. In Fig. 1, Q for the new fabrication method is compared with Q for AlO_x devices, as reported in [7].

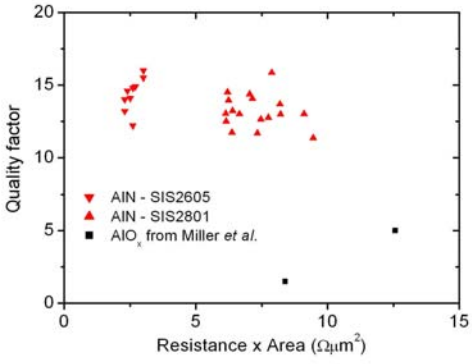

Fig. 1. Quality factor as a function of resistance times area product for different batches of SIS devices. Red triangles, pointing up and down, represent two batches of AlN barrier devices made with the new fabrication method [10]; black squares indicate data from [7].

Evidently, whereas the best values for AlO_x are below 5 for R_nA around 10 $\Omega\mu m^2$, with AlN much higher values of 15 and up are achieved down to R_nA=3 $\Omega\mu m^2$. We have also realized (not shown in this Figure) AlN SIS devices with Jc=120 kA/cm^2 (1.7 $\Omega\mu m^2$), with Q=10, and with Jc=420 kA/cm^2 (0.43 $\Omega\mu m^2$) still having Q=5. In the latter devices we observe non-equilibrium-effects causing back-bending of the *IV* characteristics. This indicates that with these low R_nA-values, high current densities, it becomes more difficult to maintain thermal equilibrium in the tunnelling electrodes.

The better quality of the AlN tunnel barriers at high critical current densities is related to their better tunnel-uniformity. They have apparently a lower fraction of the tunnel area with high tunnel transmissivity. The better uniformity is probably related to the materials quality of the AlN compared to AlOx. With high resolution Transmission Electron Microscopy we have found that the AlN barrier is crystalline [10], rather than amorphous, as is the case with AlO_x.

V. FTS EVALUATION

AlN tunnel barriers grown with the new method have been incorporated in SIS mixing-devices, designed for ALMA Band 9. All devices incorporate a multisection Nb/SiO2/Al-Nb microstripline, which tunes out the capacitance of the SIS junction. The transmission efficiency of a device is evaluated using a Fourier Transform Spectrometer (FTS) by measuring the changes in the DC current produced by the incoming light for a bias voltage of 2.5 mV, selected to be close to the gap voltage.

An AlN-based SIS device is mounted onto a waveguide backpiece. The device has the following parameters: R_n = 7.1 Ω, A_j = 0.52 μm^2, Q = 14.9, V_{gap} = 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. 2 (red 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 [3], is shown (black squares).

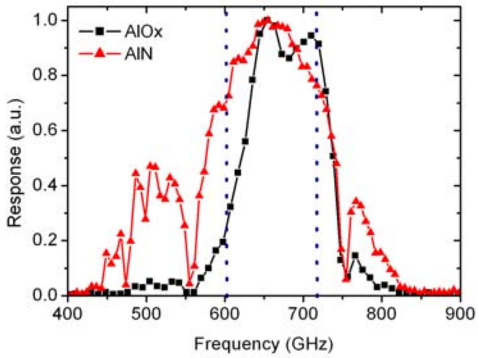

Fig. 2. Normalized photoresponse of two devices, measured with a Fourier Transform Spectrometer (FTS). The red triangles are for a device with an AlN tunnel barrier, whereas the black squares show the best achievable result for a device with an AlO_x tunnel barrier. The dashed blue lines indicate ALMA Band 9. Minima in the response are due to water absorption.

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 order to allow a fair comparison care has been taken to position the devices in identical positions in the waveguide.

In Fig. 2, 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. 3 shows the same FTS measurement results as Fig. 2 corrected for the atmospheric transmission [14]. The red triangles show the corrected response for the AlN device, the black squares indicate the corrected response for the AlO_x device. The full blue line is the model fit for the AlN device, based on its measured parameters, and on the following realistic microstripline parameters: RF normal conductivity of Nb is 1.0×10^7 S/m [4] and permittivity of SiO_2 is 3.8. The specific capacitance of the SIS junction, used as a fitting parameter, is determined to be 60 fF/μm^2. Based on a permittivity of AlN of 8.8 [15], this corresponds to a tunnel barrier thickness of 1.3 nm, which is well within the tolerance of the Transmission Electron Microscope analysis in [10], which yields 1.5 ± 0.5 nm.

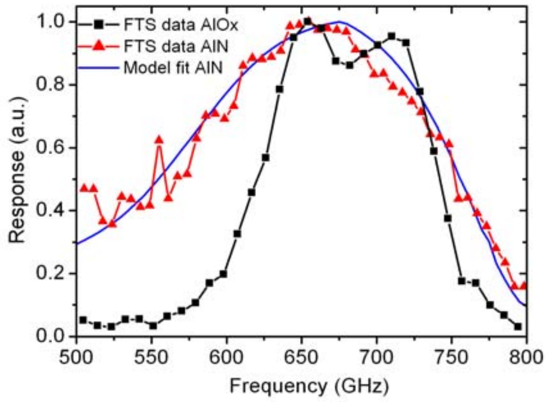

Fig. 3. FTS measurement results, corrected for the atmospheric transmission. The red triangles are for an AlN device, the black squares for an AlOx device. The full blue line shows the simulated response for the AlN device, using real device parameters. All curves are normalized to their maximum.

From Fig. 3, 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. The use of AlN has improved the bandwidth by 53 %.

VI. 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 [16] has been evaluated using the standard Y-factor method. The resulting uncorrected Double Sideband (DSB) noise temperatures at different local oscillator (LO) frequencies are presented in Fig. 4 (red triangles pointing upwards). In the same graph, the best results obtained with AlO_x based SIS devices are shown with black squares. The AlN results reported before [17] are indicated by the green triangles pointing downwards.

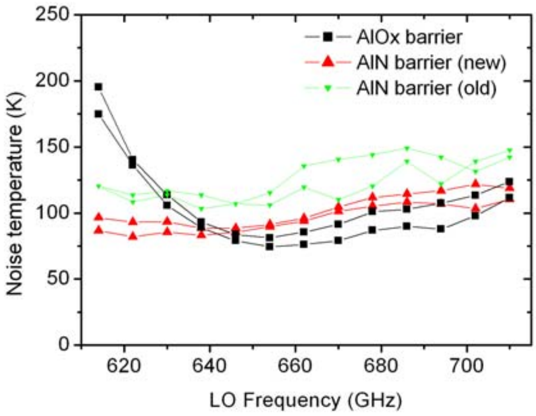

Fig. 4. Uncorrected Double Sideband (DSB) noise temperature of an SIS mixer with an AlN tunnel barrier (red triangles pointing up), earlier AlN results [17] (green triangles pointing down) and the best result obtained for an SIS with an AlO_x tunnel barrier [3] (black rectangles), in the frequency range of ALMA Band 9.

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

CONCLUSIONS

Utilizing AlN tunnel barriers, grown with a new method [10], in SIS devices for ALMA Band 9 the bandwidth has improved considerably in comparison with AlO_x devices. After correction for the atmospheric transmission, the gain in the FWHM bandwidth amounts to 53 %. Heterodyne measurements reveal that the AlN SIS devices have an uncorrected DSB noise temperature which is equally low, but flatter than the AlO_x mixers that are currently equipping the prototype ALMA Band 9 cartridges [3].

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