SUBMILLIMETER SIS MIXERS USING HIGH CURRENT DENSITY Nb/AlN/Nb TUNNEL JUNCTIONS AND NbTiN FILMS

J. Kawamura, D. Miller, J. Chen, J. Kooi and J. Zmuidzinas
California Institute of Technology, 320-47, Pasadena, CA 91125

B. Bumble, H. G. LeDuc, and J. A. Stern
Center for Space Microelectronics Technology,
Jet Propulsion Laboratory, Pasadena, CA 91108

Abstract—We are currently exploring ways to improve the performance of SIS mixers above 700 GHz. One approach is to use NbTiN in place of Nb for all or some of the mixer circuitry. With its high gap frequency and low losses demonstrated up to 800 GHz, it should be possible to fabricate an all-NbTiN SIS mixer with near quantum-limited noise performance up to 1.2 THz. Using a quasioptical twin-slot two-junction mixer with NbTiN ground plane and wiring and hybrid Nb/AlN/NbTiN junctions, we measured an uncorrected receiver noise temperature of $T_{RX} \approx 500\,\mathrm{K}$ across 790–850 GHz at 4.2 K bath temperature.

Our second approach is to reduce the RC product of the mixer by employing very high current density Nb/AlN/Nb junctions. By using these we will greatly relax the requirement on tuning circuits, which is where substantial losses occur in mixers operating above the Nb gap frequency. These junctions have resistance-area products of $R_N A \approx 5.6\,\Omega\,\mu\mathrm{m}^2$, good subgap to normal resistance ratios, $R_{sg}/R_N \approx 10$, and good run-to-run reproducibility. From FTS measurements we infer that $\omega R_N C = 1$ at 270 GHz in these junctions. This is a substantial improvement over that available using Nb/AlO$_x$/Nb technology. The sensitivity of a receiver incorporating these high current density mixers is $T_{RX} = 110\,\mathrm{K}$ at 533 GHz using a design for lower J_c mixers, which is close to the best we have measured with lower J_c Nb/AlO$_x$/Nb mixers.

I. INTRODUCTION

SIS mixers have now developed to the point where their noise performance under 700 GHz (the gap frequency of niobium) is nearly quantum-limited, and near 1 THz their sensitivity is still better than those of competing technologies. Though it is clear that SIS mixers using Nb junctions can work efficiently above 700 GHz, resistive loss in the tuning circuit ultimately limits their performance. Indeed, the best results at 1 THz were achieved by using tuning circuits made with good normal metal conductors; however, even in this case the power coupled to the junctions is only about 20% [1]. There are two major ways to improve the performance of SIS mixers above 700 GHz: 1) Use low-loss superconducting films with T_c higher than Nb, and 2) reduce the RC product of the junctions. We are pursuing both of these options.

We recently began an effort to use NbTiN film in our quasioptical SIS mixers. Our previous work with these mixers has convincingly demonstrated that NbTiN films can have very low loss at frequencies as high as 800 GHz, and thus may be suitable for use in mixers operating up to its gap frequency, $2\Delta/h \approx 1.2$ THz. For example, a mixer with

Nb/AlO$_x$/Nb junctions, Nb wiring and NbTiN ground plane gave very impressive performance: $T_{RX} = 110\,\mathrm{K}$ at 638 GHz [2]. This measurement showed that the loss in the ground plane near 650 GHz is at least as low as in a Nb ground plane. Fourier transform spectrometer (FTS) characterization of a mixer made entirely from NbTiN film indicated that the surface resistance of the mixer wiring was $R_S < 0.03\,\Omega$ at 500 GHz, and had an upper limit of roughly $R_S < 0.1\,\Omega$ at 800 GHz [3]. These measurements support the claim that NbTiN films are not as lossy at submillimeter wavelengths as NbN films. In the past year considerable progress has been made in the fabrication process [4],[5], and we presently report on measurements made near 800 GHz on a mixer with NbTiN ground plane, NbTiN wiring, and Nb/AlN/NbTiN junctions.

Kleinsasser et al [6] studied the use of AlN as a barrier material for extremely high current density Josephson junctions. The practical difficulty in fabricating AlO$_x$ junctions with high current densities, say $J_c \gg 10\,\mathrm{kA\,cm^{-1}}$, is that the quality of the junctions, as indicated by the subgap to normal resistance ratio, degrades rapidly with increasing J_c. Using AlN as the barrier material, however, it is now possible to reliably produce very high current density junctions while maintaining their quality. In addition, the material parameters for AlN and AlO$_x$ are similar, so AlN-based junctions are amenable for incorporation into existing designs based on AlO$_x$ barriers in contrast to using MgO, which has a much higher specific capacitance for the same current density. We presently demonstrate the operation of a low-noise receiver incorporating high current density Nb/AlN/Nb junctions with an input bandwidth of about 300 GHz.

II. Receiver setup

The mixer configuration we use is a quasioptical planar twin-slot antenna coupled to a two junction tuning circuit [7]. The antenna and junctions are fabricated simultaneously on the same Si substrate. This substrate is attached to a hyperhemispherical Si lens, which is anti-reflection coated with Al_2O_3-loaded epoxy. The lens/substrate combination is clamped into a mixer block assembly, which is mounted in a liquid helium-cooled cryostat. The beam passes through a high-density polyethylene lens at 4.2 K, and several layers of porous Teflon on the 77 K radiation shield. A 25 μm mylar film serves as the vacuum window. This receiver setup is nearly identical to that used for prior measurements and is known to give excellent receiver performance up to 1 THz [1],[8].

III. Mixers with NbTiN ground plane and wire, Nb/AlN/NbTiN junctions

The NbTiN film used for the ground plane is deposited on unheated Si and has $T_c \approx 15\,\mathrm{K}$, $\rho(T_c) = 80\,\mu\Omega\,\mathrm{cm}$ and $\lambda_L \approx 230\,\mathrm{nm}$. The mixer layout was designed using these as nominal values. The wiring layer NbTiN film is deposited on SiO, and has slightly lower T_c and higher resistivity, which together imply a larger penetration depth. The junctions are defined to dimensions of $2.6 \times 0.25\,\mu\mathrm{m}$, and are made to stretch across the width of the tuning inductor while preserving an area of $0.65\,\mu\mathrm{m}^2$. This junction geometry is used instead of square junctions to lessen the impact of non-ideal behavior stemming from spreading inductance.

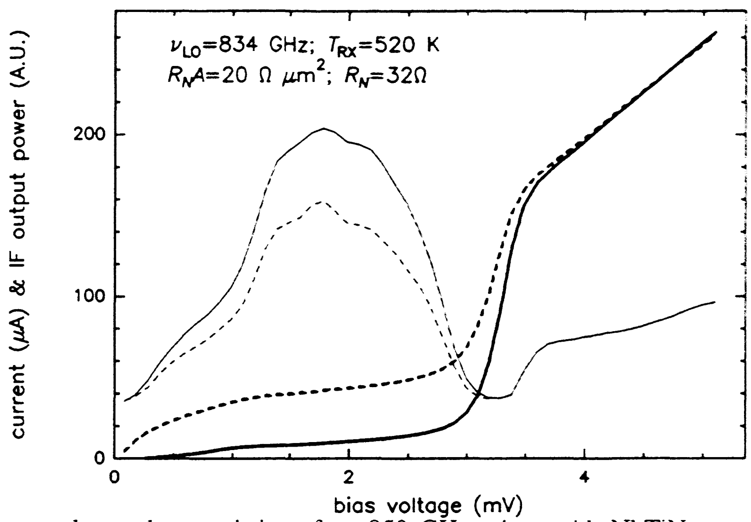

Figure 1: Current-voltage characteristics of an 850 GHz mixer with NbTiN ground plane and wiring and Nb/AlN/NbTiN junctions. Shown are the IV curve traced with (dashed heavy) and without (solid heavy) LO power applied at 4.2 K bath temperature. The IF power in response to 295 K (solid light) and 77 K (dashed light) loads are shown as a function of changing bias. The mixer is normally biased at 2.0 mV. For this particular measurement, a 25 μm Mylar beam splitter was used to couple the optimum amount of LO power to the mixer, and $T_{RX} = 520\,\mathrm{K}$.

The current-voltage curve of an 850 GHz mixer with is shown in Fig. 1. The junction's quality is good, $R_{sg}/R_N \approx 12$, but for the mixers in this batch, the gap voltage is only $V_g \approx 3.2\,\mathrm{mV}$. This is about 0.3 mV lower than seen in mixers produced in other batches. These are still significantly lower than the 4.0 mV gap we expect from this hybrid junction. We do not presently understand why the gap in these junctions is so much smaller than the sum gap value. Note that the gap is further reduced under LO pumping. We speculate that this is caused by LO-injected quasipartilces trapped near the junction.

The spectral response of an 850 GHz mixer was measured with an FTS, and is shown in Fig. 2. The response agrees reasonably well with a model that assumes that there is no loss in the ground plane and that there is an excess surface resistance in the wiring layer, $R_S \approx 0.1\,\Omega$ at 900 GHz. This value tolerable, but further measurements are needed to better quantify this value. Nevertheless, the width of the resonance indicates that the excess surface resistance cannot exceed $R_S < 0.3\,\Omega$, which is still better than the surface resistance of polycrystalline NbN film [9].

Heterodyne tests were performed following the FTS test, and their results are summarized in Table 1. For the 850 GHz mixer it was necessary to use a 25 μm mylar beam splitter, with transmission of about $t \approx 76\,\%$, to couple enough LO power for optimal noise performance. The best receiver noise temperature was $T_{RX} = 520\,\mathrm{K}$ at an LO setting of 834 GHz. Generally, using a 13 μm beam splitter ($t \approx 92\,\%$) improved the noise performance even though the mixer was LO starved. The best noise temperature thus achieved was $T_{RX} = 460\,\mathrm{K}$ at an LO frequency of 824 GHz. For the 550 GHz mixers enough LO

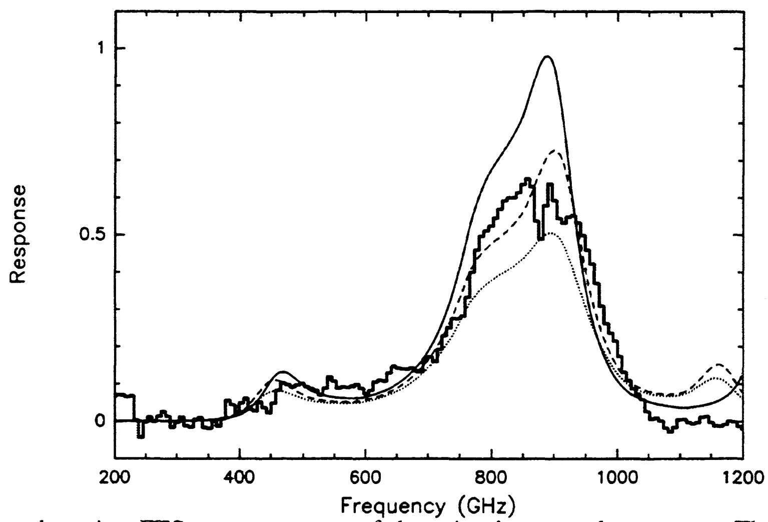

Figure 2: Direct detection FTS measurements of the mixer's spectral response. The measured response is shown as a histogram. The absorption feature near the peak of the response at 875 GHz is a measurement artifact. Model calculations are plotted as follows: a circuit model that assumes no loss in either the NbTiN ground plane or wiring is shown as a solid line; the dashed line assumes an excess surface loss in the wire layer of $R_s = 0.1\,\Omega$ at 900 GHz; and the dotted line, $R_s = 0.3\,\Omega$.

power was coupled using a 13 μm beam splitter ($t \approx 97\,\%$). Though we have some problems understanding the spectral response of the 550 GHz mixers, their noise performance is still quite respectable.

It is quite clear from our measurements that substantial improvements can be made to the receiver's sensitivity, especially for the 850 GHz mixer. For this receiver the 25 μm beam splitter accounts for approximately 200 K of the total receiver noise temperature. We forsee immediate improvement in the receiver performance by upgrading the optics to a similar configuration used in the 850 GHz CSO waveguide receiver [10]. Furthermore, since the circuit design was optimized for mixers using NbTiN ground plane and Nb wiring, we should see some improved performance with a new design.

Mixer's peak frequency response (GHz)	LO frequency (GHz)	$T_{RX,DSB}$ (K)
530	536	160
550	536	160
850	834	520
"	824	460

Table 1: Noise performance of mixer with NbTiN ground plane and wiring, and Nb/AlN/NbTiN junctions. For the measurement in the last line, a 13 μm mylar beam splitter was used.

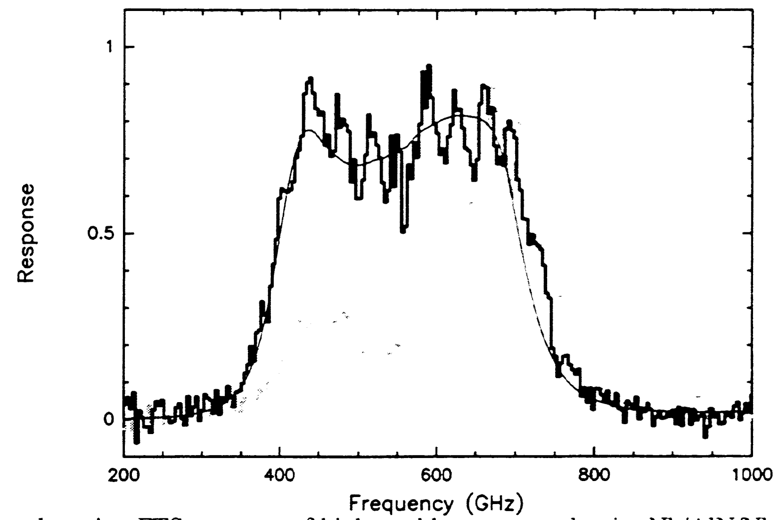

Figure 3: Direct detection FTS response of high- and low-current density Nb/AlN/Nb mixers designed for the same frequency band. The histograms are the measured receiver responses, and the lines are model fit to these. Those shown in black are the response of high current density mixer with $R_N A = 5.6\,\Omega\mu\mathrm{m}^2$; grey, the low current density mixer with $R_N A = 20\,\Omega\mu\mathrm{m}^2$. For the high current density mixer, we infer $\omega RC = 1$ at 270 GHz, whereas for the low current density mixer, $\omega RC = 1$ at 110 GHz. The rather large ripples on the response are caused by reflections between layers of new infrared filters, which have since been replaced.

IV. High-current density Nb/AlN/Nb junctions

The high current density mixers were fabricated using an existing design for low current density Nb/AlO$_x$/Nb SIS mixers which gave good performance and whose behavior was well-understood [8]. However, in place of the AlO$_x$ barriers, AlN barriers are formed by plasma nitridation following the Al deposition. The junctions are square, with a nominal area of $A = 1.7\,\mu\mathrm{m}^2$. The mixers used in our study have $J_c \approx 30\,\mathrm{kA\,cm^{-2}}$, yielding junctions with $R_N A = 5.6\,\Omega\,\mu\mathrm{m}^2$ and good quality, $R_{sg}/R_N \approx 10$. To allow a direct comparison, a batch of mixers with low current density was also fabricated, with $R_N A = 20\,\Omega\,\mu\mathrm{m}^2$. These mixers have very similar R_{sg}/R_N ratios as the high current devices.

The spectral response of 650 GHz mixers of each kind was measured with an FTS, and the results are shown in Fig. 3. The difference in response between the two types of junctions is dramatic and impressive. The response of the high current mixer spans nearly an octave! Nevertheless, the curves are well-modeled, and provide tight constraints to the value of the junction capacitance. Combined with the junction normal resistance, which is trivially determined from DC measurements, we derive that $\omega R_N C = 1$ at 270 GHz. Similarly, for the low current density mixer, we find $\omega R_N C = 1$ at 110 GHz.

Measurements of the receiver noise temperature followed the FTS experiments. The best performance was recorded for a 550 GHz mixer, where $T_{RX} = 110\,\mathrm{K}$ at 530 GHz. We stress that the mixer circuit design was optimized for a junction with $R_N A \approx 20\,\Omega\,\mu\mathrm{m}^2$, so that the coupling is not optimal at either the IF or RF. Regardless, the performance at 530 GHz is still competitive with the best receivers employing lower J_c Nb/AlO$_x$/Nb mixers.

The use of high current density mixers in SIS mixers should greatly advance the development of low-noise mixers above 1 THz. Mixers using Nb junctions and normal metal tuning circuits could see an improvement in their sensitivity by a factor of about 2. Even for millimeter-wave mixers, the the large bandwidth made possible by these mixers offers obvious advantages.

V. Conclusions

We have made conclusive measurements that show NbTiN-based mixers will work with low-noise performance up to at least 900 GHz Modest improvements to the receiver optics should allow us to demonstrate a receiver with a noise temperature near $T_{RX} \approx 300\,\mathrm{K}$ across 800–900 GHz with the existing set of mixers. Tests are on-going to determine whether or not this type of mixer will work comparably well up to 1.2 THz. The spectral response of a 1 THz mixer is shown in Fig. 4.

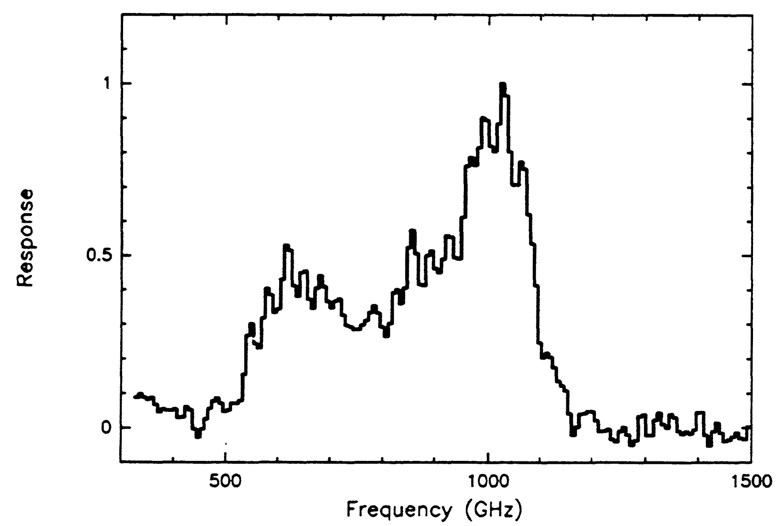

Figure 4: Spectral response of a 1 THz mixer measured with an FTS.

In addition, we demonstrated low-noise performance of a mixer with a very high-current density AlN junction. Generally, this technology will allow the development of SIS mixers with very wide bandwidth operation. Most notably, reliance on tuning circuits will be relaxed; and clearly, this has important consequences for mixers with normal metal turning circuits operating near 1 THz. But it is obvious that the development of low-loss tuning circuits using NbTiN does not diminish the advantages gained by using high current density junctions: rather, we soon hope to develop a mixer that draws the benefits from each approach, a terahertz mixer with low-noise performance and wide bandwidth operation.

This work was supported in part by NASA/JPL and its Center for Space Microelectronics Technology, by NASA grants NAG5–4890, NAGW–107, and NAG2–1068, by the

NASA/USRA SOFIA instrument development program, and by the Caltech Submillimeter Observatory (NSF grant AST–9615025).

References

[1] M. Bin, M. C. Gaidis, J. Zmuidzinas, T. G. Phillips, and H. G. LeDuc, "Low-noise 1 THz niobium superconducting tunnel junction mixer with normal metal tuning circuit," *Appl. Phys. Lett.*, vol. 68, pp. 1714–1716, 1996.

[2] J. W. Kooi, J. A. Stern, G. Chattodpadhyay, H. G. LeDuc, B. Bumble, and J. Zmuidzinas, "Low–loss NbTiN films for THz SIS mixer tuning circuits," *Int. J. IR and MM Waves*, vol. 19, pp. 373–383, 1998.

[3] J. Zmuidzinas, J. Kooi, J. Kawamura, G. Chattopadhyay, B. Bumble, H. G. LeDuc, and J. A. Stern, "Development of SIS mixers for 1 THz," in *Proc. SPIE* (T. G. Phillips, ed.), vol. 3357, pp. 53–62, 1998.

[4] B. Bumble, H. G. LeDuc, and J. A. Stern, "Fabrication of Nb/Al-N_x/NbTiN junctions for SIS mixer applications above 1 THz," in *Proc. of the 9th Int. Symp. on Space THz Tech.* (W. R. McGrath, ed.), pp. 295–304, 1998.

[5] J. A. Stern, B. Bumble, H. G. LeDuc, J. W. Kooi, and J. Zmuidzinas, "Fabrication and DC-characterization of NbTiN based SIS mixers for use between 600 GHz and 1200 GHz," in *Proc. of the 9th Int. Symp. on Space THz Tech.* (W. R. McGrath, ed.), pp. 305–313, 1998.

[6] A. W. Kleinsasser, W. H. Mallison, and R. E. Milller, "Nb/AlN/Nb josephson junctions with high critical current density," *IEEE Trans. Applied Superconductivity*, vol. 5, pp. 2318–2321, 1995.

[7] J. Zmuidzinas, H. G. LeDuc, J. A. Stern, and S. R. Cypher, "Two-junction tuning circuits for submillimeter SIS mixers," *IEEE Trans. Microwave Theory Tech.*, vol. 42, pp. 698–706, 1994.

[8] M. C. Gaidis, H. G. LeDuc, M. Bin, D. Miller, J. A. Stern, and J. Zmuidzinas, "Characterization of low-noise quasi-optical SIS mixers for the submillimeter band," *IEEE Trans. Microwave Theory Tech.*, vol. 44, pp. 1130–1139, 1996.

[9] S. Kohjiro, S. Kiryu, and A. Shoji, "Surface resistance of epitaxial and polycrystalline NbCN films in the submillimeter wave region," *IEEE Trans. Applied Superconductivity*, vol. 3, pp. 1965–1767, 1993.

[10] J. W. Kooi, J. Pety, B. Bumble, C. K. Walker, H. G. LeDuc, P. L. Schaffer, and T. G. Phillips, "A 850 GHz waveguide receiver employing a niobium SIS junction fabricated on a 1 μm Si_3N_4 membrane," *IEEE Trans. Microwave Theory Tech.*, vol. 46, pp. 151–161, 1998.