SIS Mixers for ALMA Band-10: Comparison of Epitaxial and Hybrid Circuits

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***Abstract*— To provide a basis for optimum choice of a SIS mixer for ALMA Band-10 (787-950 GHz), numerical simulations on performance of receiver are made using properties of both SIS junction and possible design of its tuning/coupling circuit. "Traditional" Nb-AlO$_X$-Nb and epitaxial NbN-AlN-NbN junctions are studied being integrated with either NbN(NbTiN)/Al or all-epitaxial NbN circuit. Calculations are based on Tucker's theory using 3-port approximation. The extra noise associated with MAR effect in NbN junctions is taken into account. Numerical simulations are finally fitted to best experimental data demonstrating good agreement.**

I. Introduction

The Band-10 (787-950 GHz) is the most difficult band of the whole ALMA project. This is not only due to small mechanical tolerances allowed at these high frequencies. The essential part of difficulties is originated from limited choice of conductors to be used in the tuning circuit of the Band-10 SIS mixer along with lacking of well-established processing for a number of available materials. For example, such popular material as Nb is good for producing suitable SIS junctions, but it cannot be used efficiently as a part of their tuning circuit for Band-10. This situation suggests more difficult process of implementation of Nb-based SIS trilayer into a waveguiding sandwich made from low-loss normal metals or from higher-T$_c$ superconductors (NbN, NbTiN). However, the use of mentioned higher-T$_c$ superconductors for wiring of Nb trilayer was not successful since now; the wiring has to be made from relatively lossy normal metals (Al, Au). The epitaxial NbN structures fabricated at NiCT (Japan) are a good exception [1].

The NbN epitaxial films can be treated as perfect conductors with magnetic penetration depth that is quite similar to performance of Nb films below 700 GHz. The fully epitaxial SIS junction (ex. NbN/AlN/NbN) has advantages of higher gap energy and lower RF loss in electrodes. The higher gap voltage allows for higher frequency limit (up to 2 THz) yet for better response, dI_{IF}/dV_{RF}, of the mixer at about 1 THz, if compare with all-Nb devices. However, two serious drawbacks are known for epitaxial NbN SIS junctions: i) lower than for Nb quality of IV-curve and ii) extra noise associated with multiple Andreev reflection (MAR) [2, 3].

The primary goal of this paper is to analyze numerically a few most promising configuration of terahertz-band SIS mixers in respect to available experimental data. The calculations are based on Tucker's theory, which simplest 3-port approximation, according to M. Feldman, fits the terahertz-range SIS mixers [4, 5]. Authors hope that this work can facilitate the hard choice of a mixer for ALMA Band-10.

II. Modeling of IV-curves and Tuning Circuit

To calculate performance of a real SIS mixer, an appropriate model of its IV-curves is necessary. This model will be then input in most of equations of Tucker's theory on quantum mixing with SIS junctions [4]. We have synthesized IV-curves of Nb junctions using a sum of exponential functions with adjustable parameters. All functions are smooth and can be treated as a *basic functions*.

$$I(V) = I_{LEAK}(V) + I_{KNEE}(V) + I_N(V) \tag{1}$$

$$I_{LEAK}(V) = \frac{V}{R2} \cdot \left(1 + \exp\left(\frac{V - Vg}{\Delta Vg \cdot 10}\right)\right) + I0 \cdot \frac{V}{V + Vexcess \cdot 0.5} \tag{2}$$

$$I_{KNEE}(V) = I_{MAX\_KNEE} \cdot \exp\left(-\left(V - V_{KNEE}\right)^2 \cdot Q_{KNEE}\right) \tag{3}$$

$$IN(V) = \frac{\exp\left[\dfrac{V - Vg}{\Delta Vg}\right]}{\exp\left[\dfrac{V - Vg}{\Delta Vg}\right] + 1} \cdot \left(\frac{V - V_e}{Rn} - I_{LEAK}(V)\right) \tag{4}$$

IV-curves for epitaxial NbN junctions are also synthesized in fine details using its *generalized expansion* with (1)-(4). The results of modeling are presented in Fig. 1 and Fig. 2. To analyze the effect of quality of SIS junction on the final performance of a whole receiver, the IV-curves with different Q-factor from Fig. 3 are used. The Q-factor is controlled by parameter *R2*. Since the leakage current of a perfect SIS junction is fundamentally depends on the physical temperature only, the model leak current, I_{LEAK}, is presenting both the voltage independent thermal current, *I0*, and current of micro-shorts as the shunting resistor *R2* (see eq.2).

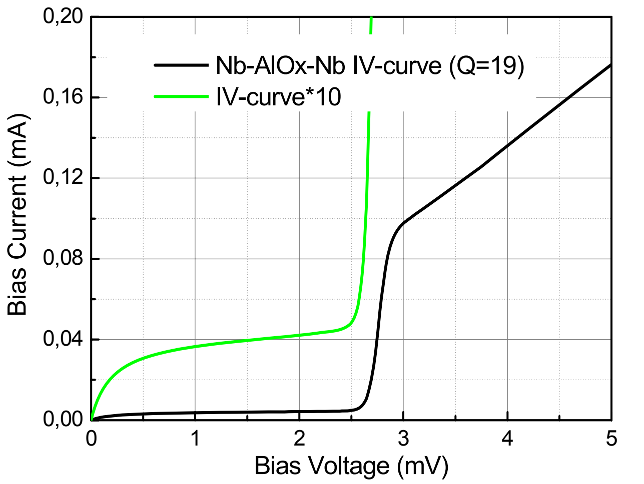

Fig. 1 Model IV-curve for high-quality high current density (J_c = 12 kA/cm^2) micron-size all-Nb SIS junction.

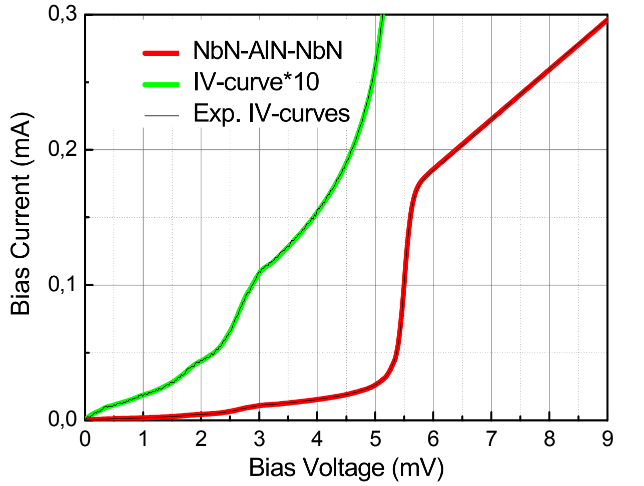

Fig. 2 Model IV-curve for epitaxial all-NbN SIS junction. Four curves are presented. Note that experimental IV-curves are almost indistinguishable from modeled IV-curves. Parameter R_NA = 34 of experimental mixer is equivalent to J_c = 6 kA/cm^2 of a "traditional" all-Nb SIS junction.

To develop a practicable model of a SIS mixer tuning circuit, the specific materials are used. Table 1 summarizes parameters used in our calculations. Since it is known of extremely good RF properties of epitaxial NbN films, they are assumed being perfect RF conductors with the magnetic field penetration depth λ = 250 nm. Note that NbN epitaxial tuning circuit is employing also epitaxial insulation of MgO (ε≈9.6) while NbTiN is usually covered with SiO_X (ε≈4.2).

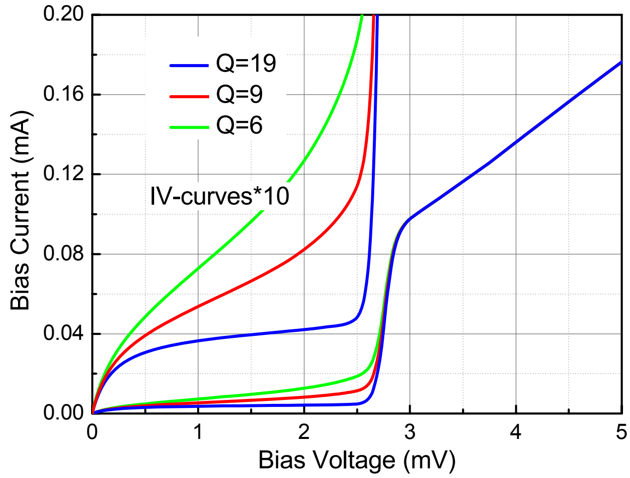

Fig. 3 Model IV-curves for Nb/AlO_X/Nb junctions of different quality, Q, which is defined by parameter *R2* of eq.(2).

The polycrystalline films of NbTiN are known for varying their properties dependent on condition of deposition. Since they are assumed for use in combination with relatively resistive aluminum wiring, the RF conductivity of NbTiN film is (voluntary) assumed to be about twice better than one of aluminum. This assumption makes aluminum wiring dominating with RF loss in the tuning circuit.

We modeled only the twin-SIS tuning circuit [6, 7]. The twin-type of tuning arrangement consists of two lumped SIS junctions and two sections of microstrips: one connecting them in parallel and second one – to the feed point. The GTM-method of calculating superconducting microstrips is used; the method is described elsewhere [8]. The feed-point impedance of the tuning structure is assumed to be 50 Ω. The IF chain following the mixer is estimated to have noise temperature about 10 K that includes noise of coolable amplifier and effects of loss in IF cables and wide-band (4-12 GHz) isolator.

III. Results of Calculations

The effect of quality of all-Nb SIS junction on performance of the whole receiver is presented in Fig. 4. It seems that the sensitivity of receiver is almost proportional to the quality factor of the mixing junction. This effect is possible to explain qualitatively with the experimental fact that the best noise temperature of the receiver observed at condition close to the infinite mixer gain (at extremely large R_d). Under this condition all output current is driven into the IF chain. Thus the upper limit of R_d defines the efficiency of the transfer of IF current towards the output. The maximum R_d is defined by the leakage resistance of the particular sample of SIS junction, i.e. by its Q-value.

TABLE I
Material Parameters.

Structure	R_NA	A (µm^2)	C0 (fF)	Total (Ω/sq)	Ground plane (Ω*m)$^{-1}$ / λ(nm)	Wiring (Ω*m)$^{-1}$ / λ(nm)	Insulation t(nm) / ε
NbTiN-Nb/AlO_X/Nb-Al	17	0.64	85	0.239	2.3e8 / 250	1.16e8 / 0	300 / 4.2
NbN-NbN/AlN/NbN-Al	17	0.64	120	0.165	perfect cond. / 250	1.16e8 / 0	300 / 4.2
NbN-NbN/AlN/NbN-NbN	17	0.64	120	0	perfect cond. / 250	perfect cond. / 250	300 / 9.6
Al-Nb/ AlO_X /Nb-Al	10	0.64	85	0.28	1.16e8 / 0	1.16e8 / 0	300 / 4.2

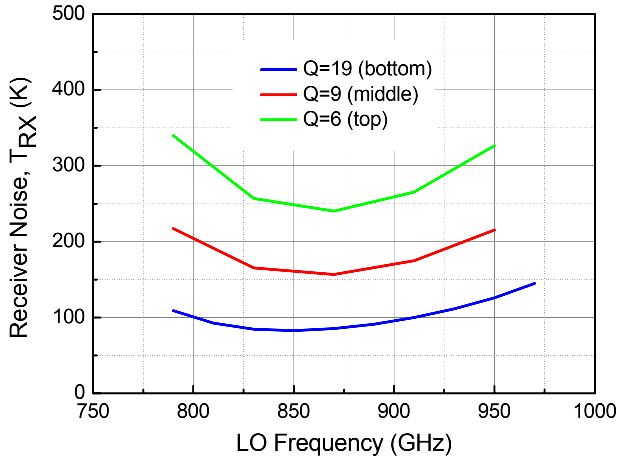

Fig. 4 Effect of quality of Nb/AlO$_X$/Nb junction on performance of the receiver using twin-type mixer. Noise temperature is referenced to the feed-point of the tuning structure, also for all graphs below.

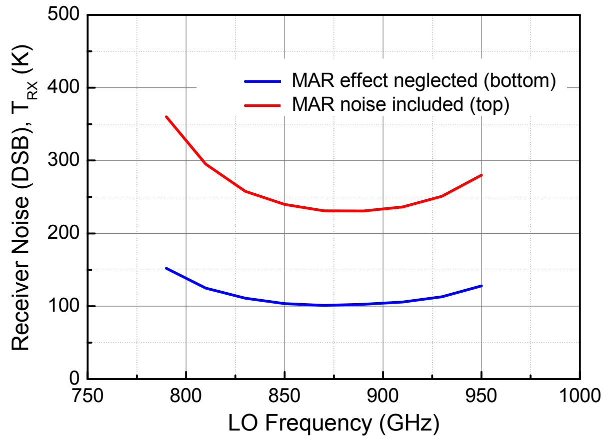

Fig. 5 Result of excessive noise in the NbN SIS mixer due to effect of multiple Andreev reflection (MAR effect) [2, 3]. IV-curve from Fig. 2 is used in calculation of twin-type mixer.

The best experimental epitaxial NbN junctions usually have Q-value about 10. According to Fig. 4 this Q-value can result in performance essentially better than 200 K, since higher responsivity, dI_{IF}/dV_{RF}, and lower loss in electrodes are that essential advantages of a NbN junction.

However, the presence of excessive noise due to MAR effect [2, 3 makes these expectations less encouraging as presented in Fig. 5.

IV. Comparison to Experimental Data

Recently we got a series of quite encouraging experiments with ALMA Band-10 mixers that allow for some preliminary comparison. Our best experimental data (at the moment of the Conference) are presents in Fig. 6 as three thick dots along with calculated performance for variety of SIS mixers presented as solid curves. (The details on the experimental study will be presented elsewhere.) The dots of experimental data are evaluated according to Table 2, which presents the break-down for known noise components of our receiver system. Estimate of optical noise is the important part of the noise breakdown as shown in Fig. 7.

Since the relatively large value of the optical noise (≈150 K) can be hardly explained with parameters of the RF and IF circuits, the effect of beam spillover is suggested. This effect has been both detected and predicted from presence of two non-compensated elliptical mirrors used for guiding the beam towards the cold load. The estimate shows that 1 dB spillover is that realistic value to characterize the experimental discxrepancy. In the near future we are going to improve the beam quality and report the resulting effect.

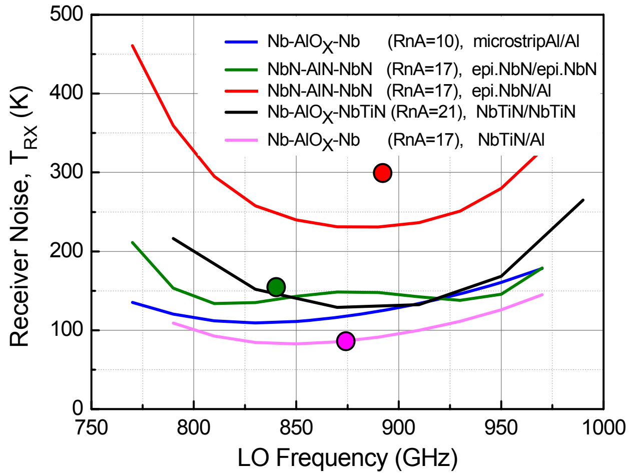

Fig. 6 Calculated performance of SIS mixers along with our best experimental data: red dot (top at 300 K) is measured for $J_c = 6$ kA/cm^2 that is reason for discrepancy from calculated red curve $J_c = 12$ kA/cm^2; green dot (middle) is for resonant λ/2 junction, while the green curve is calculated for twin-SIS mixer; magenta (lowest dot at 80 K) is calculated and measured for hybrid twin-SIS mixer.

TABLE II
Evaluation of Experimental Data.

Mixer type	Experimental T_{RX} (beam splitter noise excluded)	Loss preceding SIS junction	T_{RX} at the mixer
Quasi optical mixer with epitaxial NbN/AlN/NbN (twin-SIS with Al wiring)	660 K @ 890 GHz	spillover 1 dB = 60 K lens loss 2 dB (no AR-coating) tuning circuit loss 3dB	300 K @ feed-point 150K @ SIS
Waveguide mixer with epitaxial NbN/AlN/NbN (resonant half-wavelength)	300 K @ 840 GHz	spillover 1 dB = 60 K mixer block loss 1 dB tuning circuit loss 0.5 dB	165 K @ feed-point 150 K @ SIS
Waveguide mixer with hybrid twin NbTiN/Nb/AlO$_X$/Nb/Al	180 K @ 875 GHz	spillover 1 dB = 60 K mixer block loss 1 dB tuning circuit loss 2.5 dB	80 K @ feed-point 45 K @ SIS

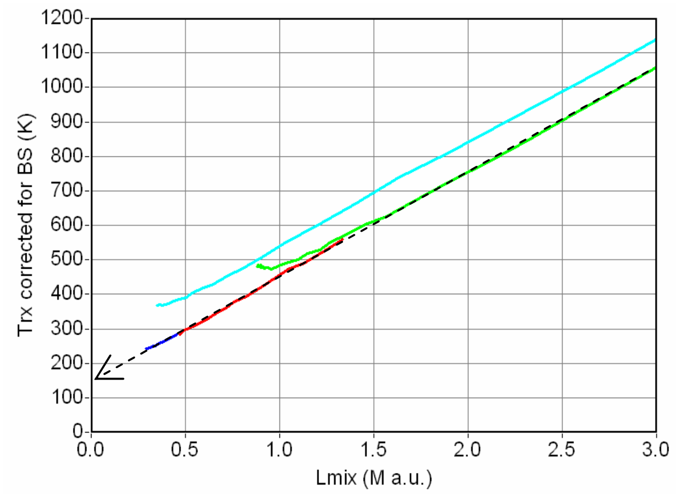

Fig. 7 Estimate for optical noise via extrapolation of measured mixer's conversion loss toward zero. The relatively high value of about 150 K is found that can be explained with presence of excessive noise (beam spillover).

Conclusions

We conclude that, in spite the relatively leaky IV-curve, the performance of an epitaxial NbN junction embedded into a low-loss epitaxial NbN tuning circuit can be close to a high-quality Nb/AlO$_X$/Nb junction embedded into a aluminum-based tuning circuit. This conclusion is now supported by our own experimental data.

- T_{RX} below 700 K (DSB) is demonstrated with epitaxial NbN/AlN/NbN twin-type mixer with Al wiring.
- T_{RX} about 300 K (DSB) is demonstrated with epitaxial NbN/AlN/NbN mixer employing resonant SIS junction.
- T_{RX} below 200 K (DSB) is demonstrated with hybrid SIS mixer NbTiN/Nb/AlO$_X$/Nb/Al cooled down to 2 K.
- Assuming presence of spillover of input beam ≈20% (1 dB of spillover loss at 300 K), the experimental results, including the optics noise of about 150 K, are in good agreement with the simulated data.

Acknowledgements

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References

[1] Y. Uzawa, Z. Wang, A. Kawakami, "Terahertz NbN/AlN/NbN mixers with Al/SiO/NbN microstrip tuning circuits," Appl. Phys. Lett., vol. 73, no. 5, pp. 680–682, 1998.

[2] Y. Uzawa, Z. Wang, "Coherent multiple charge transfer in a superconducting NbN tunnel junction," Phys. Rev. Lett. 95, 017002 (2005).

[3] P. Dieleman et al., Phys. Rev. Lett. 79, 3486 (1997).

[4] Tucker J. R., Feldman M. J. "Quantum detection at millimeter wavelengths," Rev. Mod. Phys., vol. 4. pp. 1055-1113 (1985).

[5] M. J. Feldman, Private communication (2005).

[6] T. Noguchi, K. Sunada, J. Inatani, "An SIS mixer with integrated tuning circuit (II) - A proposal of SQUID-type mixer," Proc.39th Spring Meeting of the Japanese Society Appl. Physics, Tokyo, Japan, p. 76, March 1992.

[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, Apr. 1994.

[8] S. V. Shitov, O. V. Koryukin, Y. Uzawa, T. Noguchi, A. V. Uvarov, M. A. Bukovski, I. A. Cohn, "Design of Balanced Mixers for ALMA Band-10," IEEE Trans. Appl. Supercond., 17(2), 347-350 (2007).