Fundamental limitations of THz and Niobiumnitride SIS mixers

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Chapter 7

Shot noise beyond the Tucker theory in niobium tunnel junction mixers.

The electrical and shot noise characteristics of high current density niobium superconductor - insulator - superconductor tunnel junctions suitable for heterodyne detection of THz radiation are studied. It is found that a significant part of the current at voltages $V < 2\Delta/e$ is carried via barrier defects (pinholes). Due to the transport mechanism in these pinholes, the shot noise is considerably increased. The data presented clarify an often-observed discrepancy between measured and expected heterodyne mixer noise temperatures and predict a 25 % increase in the receiver noise temperature of Nb SIS heterodyne detectors at 1 THz.

7.1 Introduction

The standard procedure to calculate the gain and noise of Superconductor - Insulator - Superconductor (SIS) heterodyne detectors is by means of the Tucker theory[1]. A fundamental assumption of this theory is that the current transport mechanism is single - electron tunneling through the insulator. It has recently been shown that this assumption does not hold for high current density NbN SIS junctions[2]. Consequently the measured noise can be more than twice as large as theoretically predicted. This discrepancy is also of interest for Nb junctions for two reasons. First, a discrepancy of equal magnitude has often been observed in Nb junctions but has never been understood[3–6]. Second, since junctions with progressively thinner oxide barriers are used to improve the ωRC product at THz frequencies[7]. An intrinsic dependence exists between the oxide thickness and the current carried by barrier imperfections (pinholes). This is shown in Fig. 7.1 in which values for the subgap current in junctions fabricated by several groups are normalized to the theoretically expected thermal current[8]. Fig. 7.1 demonstrates that at a commonly used current density (J_c) of 10 kA/cm^2 the subgap current is at least 4 times larger than the expected thermal current, indicating that 80 % or more of the current is carried via higher order processes(1). The charge transport mechanism in these pinholes is multiple Andreev reflection (MAR)[9,10], which causes the current to flow in multiply charged quanta (Andreev clusters). Therefore, with increasing current density the generated shot noise increases as the current flowing through pinholes increases. Moreover, the shot noise associated with this current is much larger than theoretically expected[2]. To investigate the impact of this effect on the heterodyne mixing performance of Nb SIS junctions we measure the shot noise as a function of bias voltage and compare it with the theory of Ref. [2].

7.2 Junction characteristics

The tunnel junction used is fabricated by sputtering 100 nm of Nb and 8 nm of Al. The Al is oxidized *in situ*, after which a top electrode of 100 nm Nb is deposited. The junction size is defined by optical lithography. Fabrication details are described in Ref. [11]. The junction has an area of 0.8 μm^2 and a resistance of 20.5 Ω, corresponding to a critical current density of 13 kA/cm^2. The current-voltage characteristic measured at 3.6 K is plotted in Fig. 7.2(a), together with the differential conductance curve. The subharmonic gap structure indicated by the arrows is clearly visible, showing that a considerable part of the subgap current is carried by MAR.

(1) The linear dependence of the leakage current on J_c can be explained by the discrete layer thickness model discussed on page 31. An increase in J_c means a linear increase of area A_1 in which the pinholes are present and hence a linear increase in the number of pinholes. The slope of the line is most likely influenced somewhat by the fabrication techniques used, but the general trend clearly is an increase of the subgap current with increasing J_c.

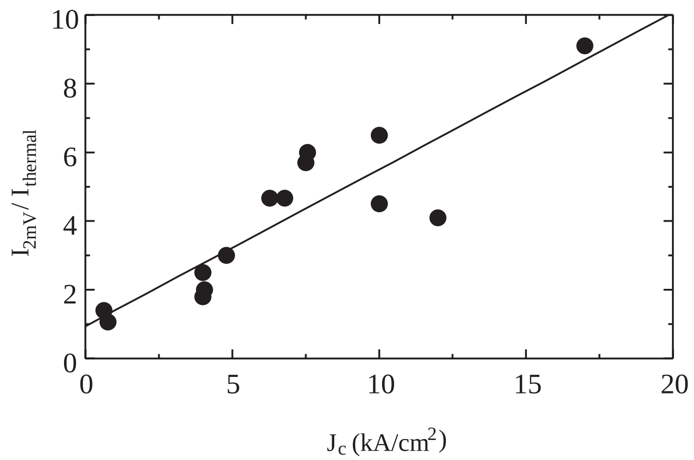

FIGURE 7.1. Subgap current at 2 mV (I_{2mV}) as a function of the current density J_c. The current is normalized to the thermal current theoretically expected at 4.2 K. The solid line shows a linear least squares fit to the data. (Data extracted from Refs. [4,5,12–15]).

7.3 Measurement setup

The junctions are connected via an integrated low-pass filter, a circulator with 0.5 dB loss, to the amplifier chain with a noise temperature of 3.2 K and a gain of 80 dB at 1.5 GHz with 85 MHz bandwidth. The output power is given by[16]:

$$\begin{aligned} P_{out} &= G_{amp}B\,(\frac{1}{4}S_I R_{dyn}(1-\Gamma^2)G_{iso} \;+\; k_B T G_{iso}\Gamma^2 \\ &+ k_B(1-G_{iso})T + T_{amp}) \end{aligned} \tag{7.1}$$

in which G_{amp} is the amplifier gain, B is the bandwidth, I, V and R_{dyn} are the current, voltage and the differential resistance dV/dI of the junction respectively, T is the measurement temperature, Γ is the reflection coefficient $|R_{dyn} - R_{amp}|/(R_{dyn} + R_{amp})$, G_{iso} is the isolator gain, and T_{amp} stands for the noise temperature of the amplifier chain.

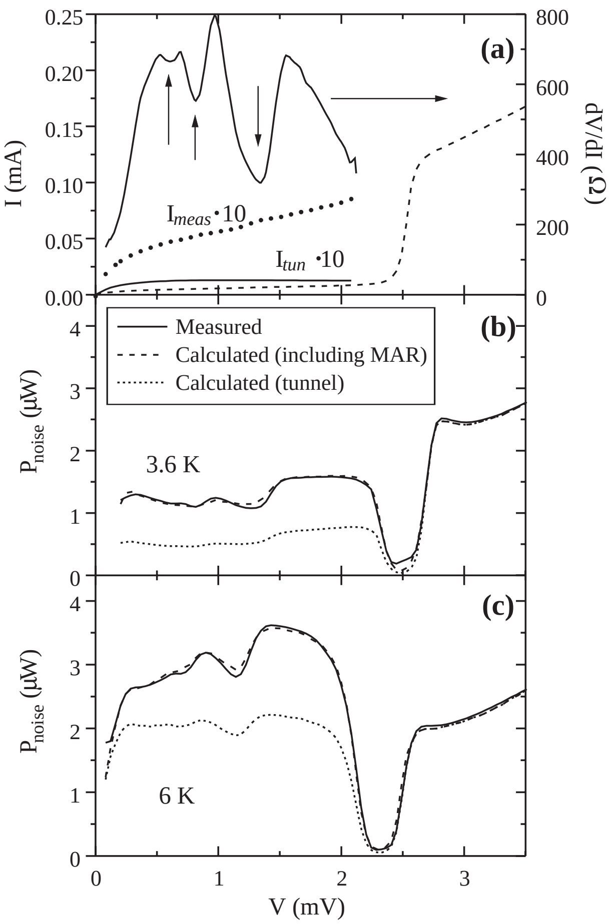

FIGURE 7.2. **(a).** I-V curve and differential resistance dV/dI at 3.6 K. The subharmonic gap structure in dV/dI is indicated by the arrows at $V = 2\Delta/ne$, $n = 2, 3, 4$. The solid line labeled $I_{tun} \cdot 10$ is the theoretical thermal current, to be compared to the actual measured current $I_{meas} \cdot 10$ shown by the solid circles. **(b).** Shot noise contribution at 3.6 K, at which temperature 80 % of the current is carried via pinholes. The solid line gives the power derived from the measurements, the dotted line indicates the noise calculated assuming all current is tunnel current, and the dashed line is calculated as explained in the text. **(c).** Shot noise contribution of the same junction at a temperature of 6 K, at which temperature 50 % of the current is carried via pinholes.

7.4 Noise measurements

In Fig. 7.2(b) and (c) the measured and calculated junction noise contribution after amplification, $P_{noise} = \frac{1}{4} S_I \cdot R_{dyn}(1-\Gamma^2) G_{iso} G_{amp} B$, is plotted as a function of voltage for temperatures of 3.6 and 6 K, respectively. The dotted lines show the shot noise of the junction if the subgap current is attributed to single - electron tunneling.

7.5 Shot noise calculation

The dashed noise curve is calculated as follows. Two conduction channels exist in parallel; the tunnel barrier carrying I_{tun} and the pinholes carrying I_{MAR} via higher-order processes. Hence, the shot noise spectral density S_I is the sum of two contributions:

$$S_I(V) \quad = \quad 2\,e\,I_{tun}(V) \;+\; 2\;q(V)\;I_{MAR}(V) \tag{7.2}$$

The effective charge of an Andreev cluster is approximately given by $q(V) = (1 + \frac{2\Delta}{eV})e$[2]. The pinhole transmission is measured to be 0.2 from the relative magnitude of the current steps at the subharmonics[17,18]. The corresponding shot noise suppression calculated from this transmission value is a mere 1 %[2,19], hence Eq. 7.2.

The tunnel current, I_{tun}, is calculated[8] and subtracted from the measured current, yielding the pinhole current, I_{MAR}. The shot noise is obtained by using I_{tun} and I_{MAR} as inputs for Eq. 7.2. The magnified currents in Fig. 7.2(a) give an impression of the ratio of those currents. The shot noise is increased by 63 % at a voltage just below $2\Delta/e$ when half of the current is tunnel current (See Fig. 7.2(c)) and the noise is doubled when only 20 % is tunnel current, as shown in Fig. 7.2(b). Clearly, high current density junctions exhibit single and multiple electronic charge transport mechanisms which have to be treated separately to obtain the total junction noise contribution.

7.6 Implications for the noise temperature

The noise temperature of a device when operated as heterodyne mixer is calculated by modifying the Tucker equations[1] to include noise arising from multiply

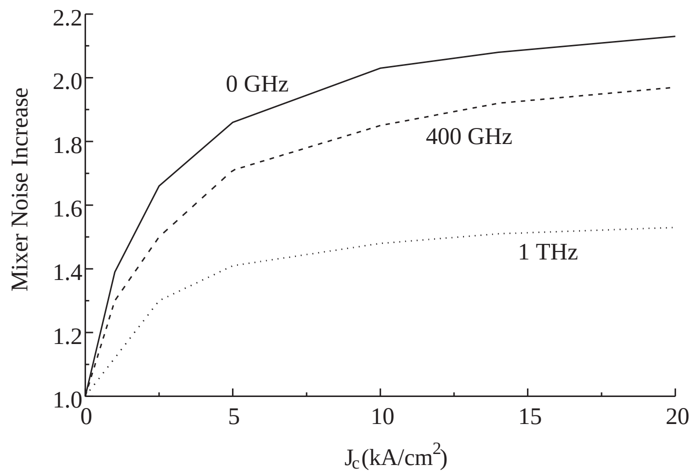

FIGURE 7.3. Correction factors to the Tucker[1] mixer noise due to the presence of MAR as a function of critical current density. At low frequencies the mixer noise is close to the shot noise at the bias voltage (the solid line). At higher frequencies the correction factor decreases because the contribution from voltages $V_{bias} + \hbar\omega/e$ becomes important where single electron transport is dominant.

charged current transport. The current correlation matrix element H_{00} becomes:

$$\begin{aligned} H_{00} &= 2 \sum_{n=-\infty}^{n=\infty} J_n(\alpha)\, q\, I_{MAR} \coth \frac{q\,V}{k_B\,T} \\ &+ 2 \sum_{n=-\infty}^{n=\infty} J_n(\alpha)\, e\, I_{el} \coth \frac{e\,V}{k_B\,T} \end{aligned} \tag{7.3}$$

The remaining matrix elements, H_{10}, H_{11} and H_{1-1}, are rewritten similarly by substituting q for e in the noise calculation of I_{MAR}. The ratio of the mixer noise temperatures calculated with the modified theory and the original theory is plotted in Fig. 7.3. The relation between J_c and the pinhole current contribution of Fig. 7.1 is used to obtain the input currents for Eqs. 7.2 and 7.3. The values shown are calculated for an optimized radiation power level at 4.2 K.

A common method to improve the mixer noise temperature is to lower the operating temperature from 4.2 to 2 K. As a result the thermal current becomes nearly negligible, but the pinhole current remains unaffected. Therefore the shot noise correction factor is increased when the temperature is lowered.

7.7 Effects on the receiver characteristics

With the results of Fig. 7.3 the receiver noise temperature can be calculated to obtain an optimum design value for the current density. In the calculation we assume a double junction aluminum coupling circuit[12] with a resonance frequency of 1 THz, junctions with areas of 0.8 μm^2 and I-V curves as modeled in [20]. The receiver noise is given by

$$T_{REC} = T_{opt} + \frac{T_M + 2T_{qf}}{2G_{opt}} + \frac{T_{amp}}{2G_M G_{iso} G_{opt}} \tag{7.4}$$

in which T_{opt} and G_{opt}, respectively, stand for the total noise and gain of the dewar window, heat filter and aluminum stripline together, the vacuum fluctuations T_{qf} contribute 24 K at 1 THz, the mixer gain G_M and noise T_M are calculated from the model I-V curve. The resulting receiver noise temperature is shown in Fig. 7.4 with, and without, a correction for the Andreev reflection enhanced shot noise. The initial improvement in the noise with increasing J_c is due to a lower loss in the Al stripline. The minimum noise is clearly shifted towards lower J_c because of the increased influence on the noise of MAR at high J_c, where the mixer noise dominates.

7.8 Conclusions

In conclusion, Nb tunnel junctions with moderate critical current densities exhibit subgap currents which are much larger than the thermal current due to the presence of pinholes in the tunnel barrier. Since the pinhole current is carried in Andreev clusters with charge $q \gg e$ the associated shot noise is significantly enhanced. Due to this effect, the mixer noise can be more than twice as large as expected from the Tucker theory. This causes a 25 % increase in the receiver noise temperature at THz frequencies.

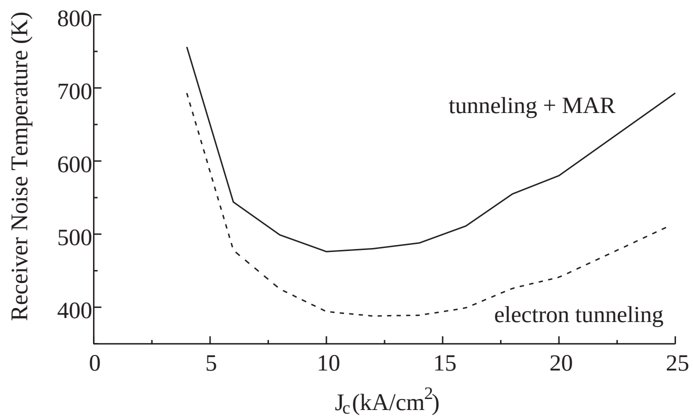

FIGURE 7.4. Receiver noise temperature calculated for a Nb junction at 1 THz with an Al tuning structure. The dashed line is calculated ignoring MAR.

References

[1] J.R. Tucker and M.J. Feldman, Rev. Mod. Phys. **57**, 1055 (1985).

[2] P. Dieleman, H.G. Bukkems, T.M. Klapwijk, M. Schicke, and K.H. Gundlach, Phys. Rev. Lett. **79**, 3486 (1997).

[3] W.R. McGrath, P.L. Richards, D.W. Face, D.E. Prober, and F.L. Lloyd, J. Appl. Phys. **63**, 2479 (1988).

[4] C.E. Honingh, J.J. Wezelman, M.M.T.M. Dierichs, G. de Lange, H.H.A. Schaeffer, T.M. Klapwijk, and M.W.M. de Graauw, J. Appl. Phys. **74**, 4762 (1993).

[5] G. de Lange, C.E. Honingh, J.J. Kuipers, H.H.A. Schaeffer, R.A. Panhuyzen, T.M. Klapwijk, H. van de Stadt, and M.W.M. de Graauw, Appl. Phys. Lett. **64**, 3039 (1994).

[6] S. Withington, K.G. Isaak, S.A. Kovtonyuk, and R.A. Panhuyzen, *European SIS user meeting*, 1994, Cologne, Germany.

[7] F. Schäfer, P. van der Wal, E. Kreysa, and K.H. Gundlach, *Eighth Int. Symp. on Space THz Techn.*, 1997, Cambridge, MA, USA.

[8] E.L. Wolf, *Principles of Electron Tunneling Spectroscopy*, (Oxford University Press, New York, 1985).

[9] A.W. Kleinsasser, R.E. Miller, W.H. Mallison, and G.B. Arnold, Phys. Rev. Lett. **72**, 1738 (1994).

[10] T.M. Klapwijk, G.E. Blonder, and M. Tinkham, Physica **109- 110B,C**, 1657 (1982).

[11] M.M.T.M. Dierichs, R.A. Panhuyzen, C.E. Honingh, M.J. de Boer, and T.M. Klapwijk, Appl. Phys. Lett. **15** 774 (1993).

[12] M. Bin, M.C. Gaidis, J. Zmuidzinas, T.G. Phillips, and H.G. LeDuc, Appl. Phys. Lett. **68**, 1714 (1996).

[13] A.W. Kleinsasser, F.M. Rammo, and M. Bushan, Appl. Phys. Lett. **62**, 1017 (1993).

[14] D. Maier, H. Rothermel, K.H. Gundlach, and R. Zimmerman, Physica **268 C**, 26 (1996).

[15] P. Dieleman, T.M. Klapwijk, J.R. Gao, and H van de Stadt, IEEE Trans. Appl. Supercond. **7**, 2566 (1997).

[16] N.B. Dubash, G. Pance, and M.J. Wengler, IEEE Trans. Microwave Theory Tech. **42**, 715 (1994).

[17] N. van der Post, E.T. Peters, I.K. Yanson, and J.M. van Ruitenbeek, Phys. Rev. Lett. **73**, 2611 (1994) and N. van der Post, Ph.D. Thesis, University of Leiden, 1997.

[18] The transmission value of 0.2 agrees with the value obtained in Ref. [9] when the difference in definition of the transmission is taken into account.

[19] M.J.M. de Jong and C.W.J. Beenakker, Phys. Rev. B **49**, 16070 (1994).

[20] W.C. Danchi and E.C. Sutton, J. Appl. Phys. **60**, 3967 (1986).