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

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The electrical and shot-noise characteristics of high-current-density niobium superconductor–insulator–superconductor (SIS) 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. © 1998 American Institute of Physics. [S0003-6951(98)01113-9]

The standard procedure to calculate the gain and noise of superconductor–insulator–superconductor (SIS) heterodyne detectors is by means of the Tucker theory.<sup>1</sup> 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.<sup>2</sup> 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.<sup>3–6</sup> Second, junctions with progressively thinner oxide barriers are used to improve the  $\omega RC$  product at THz frequencies.<sup>7</sup> An intrinsic dependence exists between the oxide thickness and the current carried by barrier imperfections (pinholes). This is shown in Fig. 1 in which values for the subgap current in junctions fabricated by several groups are normalized to the theoretically expected thermal current.<sup>8</sup> Figure 1 demonstrates that at a commonly used current density ( $J_c$ ) of 10 kA/cm<sup>2</sup> the subgap current is at least four times larger than the expected thermal current, indicating that 80% or more of the current is carried via higher-order processes. The charge transport mechanism in these pinholes is multiple Andreev reflection (MAR),<sup>9,10</sup> 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 the pinholes increases. Moreover, the shot noise associated with the pinhole current is much larger than for single-electron tunneling.<sup>2</sup> To investigate the impact of this effect on the heterodyne mixing performance of Nb SIS junctions we have measured the shot noise as a function of bias voltage and have compared it with the theory of Ref. 2.

The tunnel junction used was fabricated by sputtering 100 nm of Nb and 8 nm of Al. The Al was oxidized *in situ*, after which a top electrode of 100 nm Nb was deposited. The junction size was defined by optical lithography. Fabrication details are described in Ref. 11. The junction has an area of 0.8  $\mu\text{m}^2$  and a resistance of 20.5  $\Omega$ , corresponding to a criti-

cal current density of 13 kA/cm<sup>2</sup>. The current–voltage characteristic measured at 3.6 K is plotted in Fig. 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. 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<sup>16</sup>

$$P_{\text{out}} = G_{\text{amp}} B \left[ \frac{1}{4} S_I R_{\text{dyn}} (1 - \Gamma^2) G_{\text{iso}} + k_B T \Gamma^2 G_{\text{iso}} + k_B (1 - G_{\text{iso}}) T + T_{\text{amp}} \right], \quad (1)$$

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

In Figs. 2(b) and 2(c) the measured and calculated junction noise contribution after amplification,  $P_{\text{noise}} = \frac{1}{4} S_I R_{\text{dyn}} (1 - \Gamma^2) G_{\text{iso}} G_{\text{amp}} B$ , 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. The dashed noise curve is calculated as follows. Two conduction channels exist in parallel: the tunnel barrier carrying  $I_{\text{tun}}$  and the pinholes carrying  $I_{\text{MAR}}$  via higher-order processes. Hence, the shot noise spectral density  $S_I$  is the sum of two contributions:

$$S_I(V) = 2e I_{\text{tun}}(V) + 2q(V) I_{\text{MAR}}(V). \quad (2)$$

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

The tunnel current  $I_{\text{tun}}$  is calculated<sup>8</sup> and subtracted from the measured current, yielding the pinhole current  $I_{\text{MAR}}$ . The shot noise is obtained by using  $I_{\text{tun}}$  and  $I_{\text{MAR}}$  as inputs for

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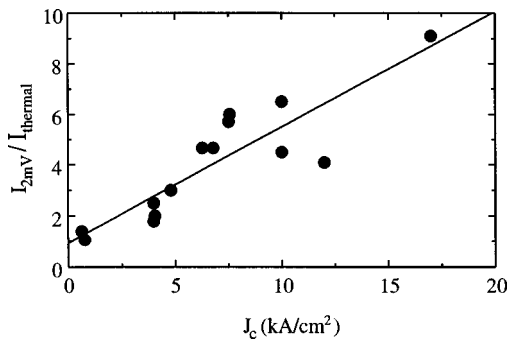


FIG. 1. Subgap current at 2 mV ( $I_{2\text{ mV}}$ ) as a function of the current density  $J_c$  for Nb/AlO<sub>x</sub>/Nb junctions. The current is normalized to the thermal current theoretically expected at 4.2 K. The solid line shows a linear least-squares fit to the data. (Data extracted from Refs. 4, 5, and 12–15).

Eq. (2). The magnified currents in Fig. 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. 2(c)] and the noise is doubled when only 20% is tunnel current, as shown in Fig. 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.

The noise temperature of a device when operated as a

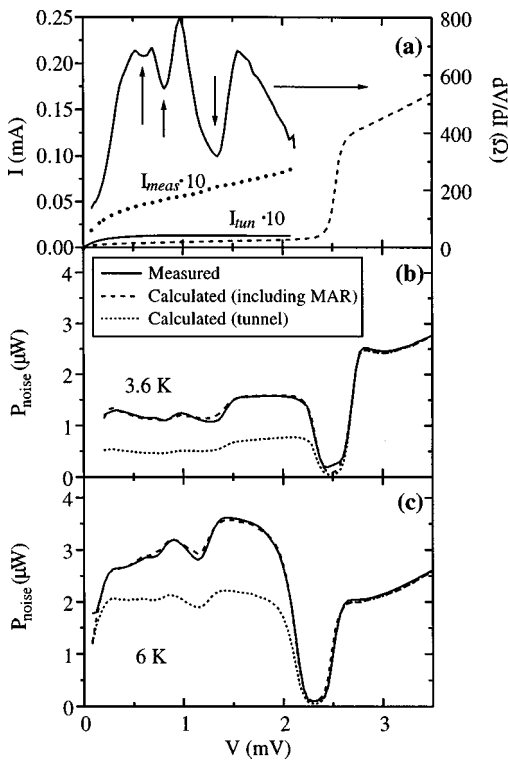


FIG. 2. (a)  $I$ - $V$  curve and differential resistance  $dV/dI$  at 3.6 K. The subharmonic gap structure in  $dV/dI$  is indicated by the arrows at  $V = 2\Delta/ne$ ,  $n=2,3,4$ . The solid line labeled  $I_{\text{tun}} \times 10$  is the theoretical thermal current, to be compared to the actual measured current  $I_{\text{meas}} \times 10$  shown by the dotted line. (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.

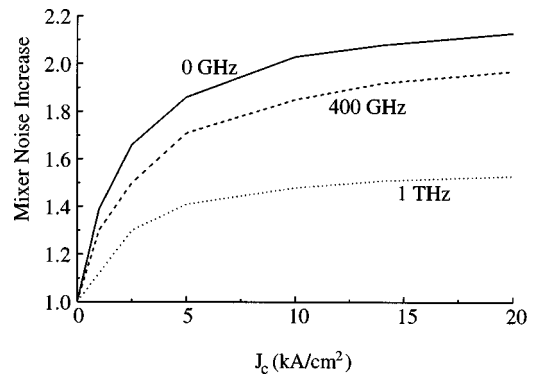


FIG. 3. Correction factors to the Tucker (Ref. 1) mixer noise due to the presence of MAR as a function of critical current density. At low frequencies the mixer noise is close to the shot noise at the bias voltage (the solid line). At higher frequencies the correction factor decreases because the contribution from voltages  $V_{\text{bias}} + \hbar\omega/e$  becomes important where single-electron transport is dominant.

heterodyne mixer is calculated by modifying the Tucker equations<sup>1</sup> to include noise arising from multiply charged current transport. The current correlation matrix element  $H_{00}$  becomes

$$H_{00} = 2 \sum_{n=-\infty}^{n=\infty} J_n(\alpha) q I_{\text{MAR}} \coth \frac{qV}{k_B T} + 2 \sum_{n=-\infty}^{n=\infty} J_n(\alpha) e I_{\text{el}} \coth \frac{eV}{k_B T}. \quad (3)$$

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  $I_{\text{MAR}}$ . The ratio of the mixer noise temperatures calculated with the modified theory and the original theory is plotted in Fig. 3. The relation between  $J_c$  and the pinhole current contribution of Fig. 1 is used to obtain the input currents for Eqs. (2) and (3). The values shown are calculated for an optimized local oscillator 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.

With the results of Fig. 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<sup>12</sup> with a resonance frequency

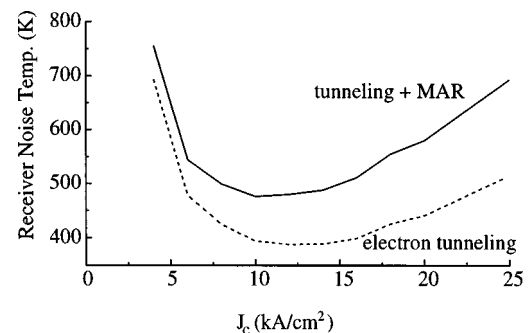


FIG. 4. Receiver noise temperature calculated for a Nb junction at 1 THz with an Al tuning structure. The dashed line is calculated ignoring MAR.

of 1 THz, junctions with areas of  $0.8 \mu\text{m}^2$ , and  $I$ - $V$  curves as modeled in Ref. 20. The receiver noise is given by

$$T_{\text{REC}} = T_{\text{opt}} + \frac{T_M + 2T_{qf}}{2G_{\text{opt}}} + \frac{T_{\text{amp}}}{2G_M G_{\text{iso}} G_{\text{opt}}}, \quad (4)$$

in which  $T_{\text{opt}}$  and  $G_{\text{opt}}$ , 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; and 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. 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.

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.

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