INFLUENCE OF JUNCTION-QUALITY AND CURRENT DENSITY ON HIFI BAND 2 MIXER PERFORMANCE

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Introduction

The current density of $Nb/Al_2O_3/Nb$ SIS junctions that are used as sub-millimeter wave mixers is a determining parameter in the device design. Integrated tuning circuits for single junction designs typically have a fractional bandwidth of $1/\omega RC$, with ω the angular frequency, R the junction normal state resistance and C the junction capacitance. As $RC \sim 1/j_c$ (j_c is the current density), for higher frequencies and/or larges bandwidths one would like to use a devices with higher current density.

Admittedly large bandwidth can also be achieved by parallel arrays of junctions with a lower current density[1]. However a higher j_c will also improve the coupling for tuning circuits with normal metal lines that have some of loss, as are used at frequencies above the gap frequency of niobium (700 GHz). In addition at higher frequencies and for certain applications like array- or satellite mixers, one wants to avoid unnecessary complexity in the operation of the mixer. for example in tuning the magnetic field for an array of junctions.

For higher current densities it is observed that junctions start to exhibit a lower quality, expressed in the ratio of the sub-gap resistance ($R_{sub\text{-}gap}$) and the normal state resistance (R_N). This is attributed to an increasing number of imperfections in the barrier (pinholes). Dieleman[2] has shown that the additional sub-gap current through the pin-holes leads to a disproportionately high additional shot-noise generation in the SIS junction, because the charge transport through the pinholes is multiple Andreev reflections (MAR).

The increase in current density at the expense of quality leads to a trade off between improved coupling and higher junction noise in the optimization of a mixer design. For future design decisions it is important to obtain mixer data to verify the predictions of performance by the Quantum theory of mixing[3] (QTM) that take into account the MAR in the barrier.

In the course of the development for HIFI[4] Mixer Band 2 (636-802 GHz) KOSMA has access to twin junction devices with an integrated tuning structure consisting of a NbTiN ground plane and aluminum wiring, from two different fabrication facilities, DIMES[5,6] and KOSMA[7]. The devices from DIMES have in general an excellent $R_{sub\text{-}gap}/R_n$ ratio of around 20 with current densities of 6-8 kA/cm^2, where devices from KOSMA have a high current density of 12-14 kA/cm^2 and an $R_{sub\text{-}gap}/R_n$ of around 7. We present measurements and analysis of comparable devices of both fabrication facilities. For the RF measurements we use a HIFI Band 2 fixed tuned waveguide mixer with a 4-8 GHz IF.

Device Design

The twin junction devices are of a standard design. The junctions are connected by a micro-strip line of suitable length and width to tune out both junction capacitances at the center frequency of the design band. This junction pair is connected to the antenna (in this case a waveguide probe) by an approximately quarter wavelength micro-strip-line that matches the junction pair impedance to the antenna impedance. The layout of the device is shown in Figure 1. The tuning structure has a superconducting NbTiN ground plane, and an aluminum wiring layer[8].

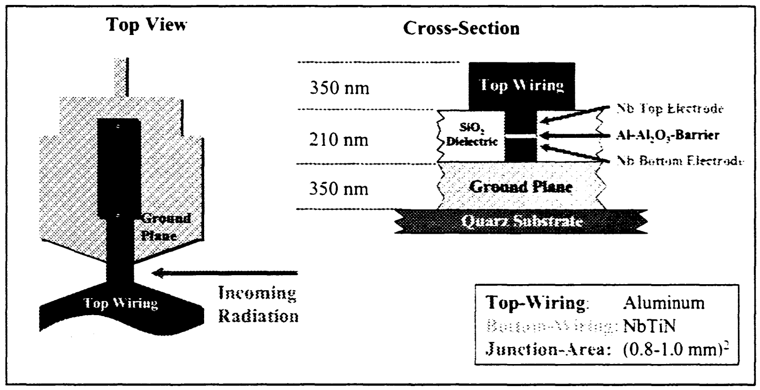

Figure 1: Realization of Twin-Junction-Device

The calculated coupling between the antenna and the devices as a function of frequency, dependent on device current density, is given in Fig. 2. The dimensions of the transformer part of the tuning structure are slightly adapted to achieve optimum coupling at each current density.

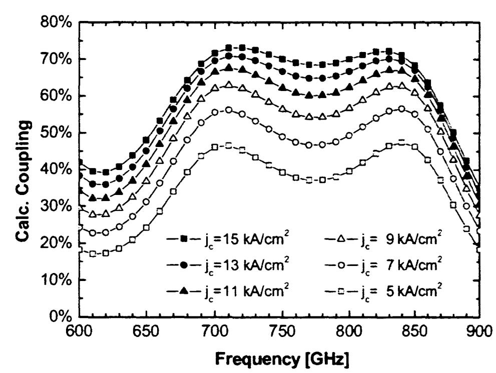

Figure 2: Impact of Current Density on calculated Power Coupling

The DIMES device has an NbTiN ground plane with a resistivity of about 110 μΩcm at approximately 20K and T_c~14.4K. The aluminum wiring layer has a resistivity of approximately 1.2 μΩcm. The NbTiN ground plane of the KOSMA devices has a resistivity of 90 μΩcm and a T_c of 14.5 K. The aluminum wiring layer shows a resistivity of approximately 0.8 μΩcm.

Measurement Setup

The devices are used in a standard fixed tuned waveguide mixer-block. The mixer-block is used in a HIFI Band 2 mixer unit, which contains a corrugated horn, a magnet and a 4-8 GHz IF coupling, including a bias tee.

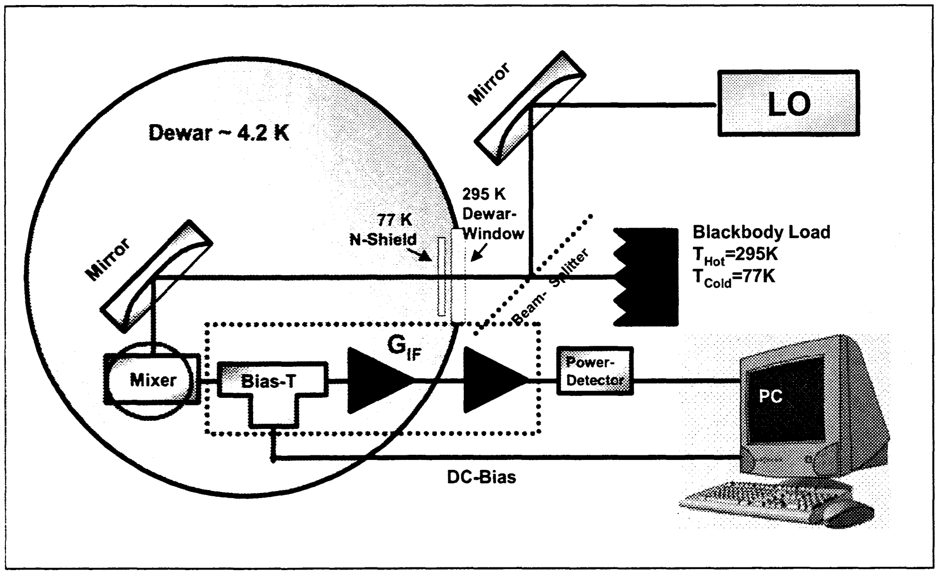

Figure 3: Sketch of the heterodyne Measurement Environment; measurements are made in a liquid helium Dewar, noise- and gain-contributions can be classified into three groups: beam-splitter and windows are the optics contribution, the mixer noise contribution, the contribution of the IF-chain, composed of bias-T, isolator, HEMT-amplifier and warm amplifiers.

The measurement set-up is shown in Figure 3. The mixer unit is mounted to the cold plate of a liquid helium dewar. The operating temperature of the mixer during all measurements is 4.3 K. We use a solid state LO source, a 10 μm Mylar beam-splitter and a standard 300K/77K load calibration unit. The IF output power is measured over the full 4-8 GHz bandwidth. The noise temperature of the IF-amplifier varies in different measurements and is calibrated with the shot-noise method.

Measurements

The devices of comparable area are characterized by DC-measurements. The DC-characteristics of three measured devices are shown in Figure 4. Clearly the differences in current density can be seen in the higher current of the solid curve in the normal conducting branch above the gap frequency (a)). In b) the axes are scaled to see the differences below the gap. The sub-gap-current of the high-current density devices is clearly visible. Even if one would scale the current of the low current density devices to the values of the solid line, their sub-gap-current would be much lower.

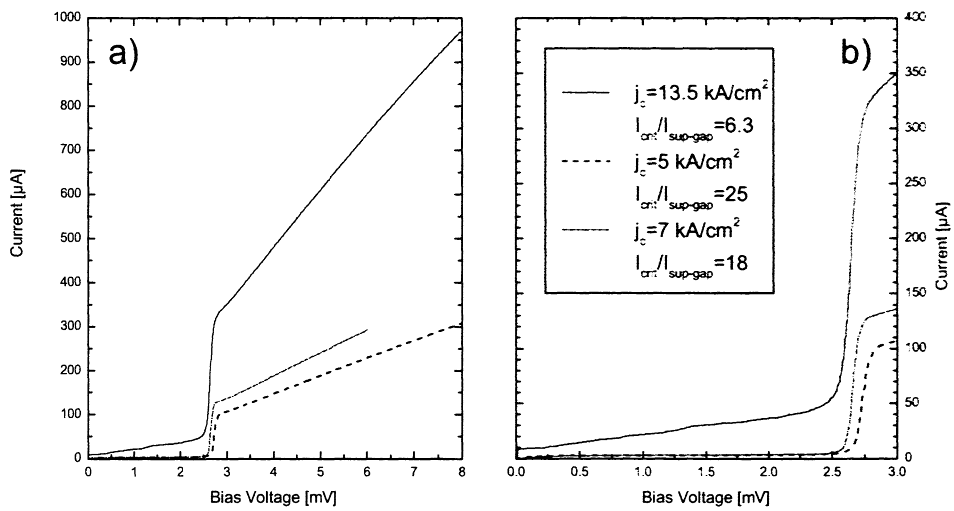

Figure 4: I-V-Characteristics of measured junctions fabricated by DIMES (j_c=5-7 kA/cm^2, Q=25-18) and KOSMA (j_c=13.5 kA/cm2, Q=6.3)

The band pass of these devices is measured with a Fourier-Transform-Spectrometer (FTS). The data are plotted in Figure 5. The FTS-conversion is in arbitrary units scaled to comparable values.

The performance of the three devices is also characterized by their measured mixer noise and mixer gain. In the measurement setup which is shown in Figure 3, a total receiver noise temperature is obtained. The optics contribution has been measured separately in an FTS-measurement. The contribution of the IF-chain is determined by a shot-noise-fit, which is described below.

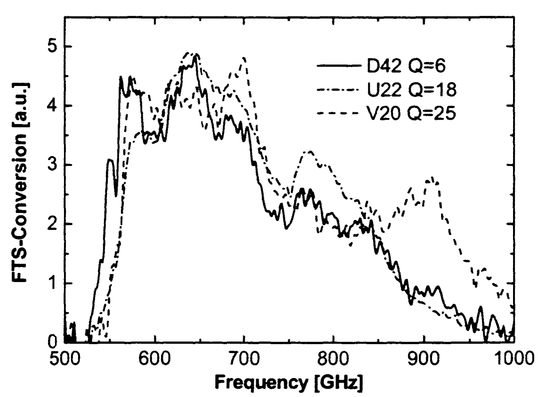

Figure 5: Measured band path for three devices; all devices show the best coupling below and around 700 GHz

After subtracting the optics- and IF-chain-contributions the corrected mixer gain and mixer noise are obtained which characterize the influence of the mixer-device itself. The corrected mixer noise and mixer gain are shown in Figure 6.

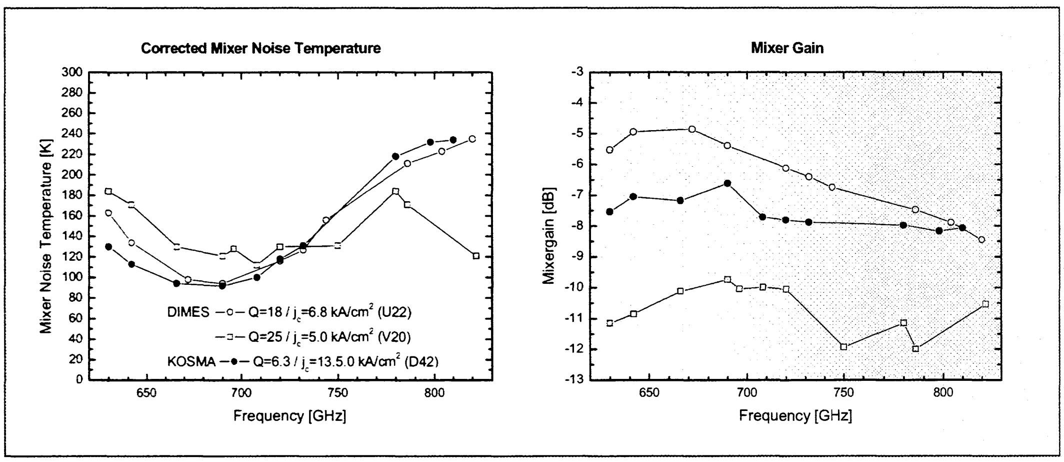

Figure 6: Mixer Noise Breakdown for three junctions

The devices U22 (DIMES) and D42 (KOSMA) show very similar values for the mixer noise although they have very different DC-characteristics (quality Q and current density j_c). The higher sub-gap-current of device D42 (KOSMA) apparently does not necessarily lead to a higher noise. The device with a lower current density U22 has a higher mixer gain in comparison to the high current density device D42. The third device V20 shows a wider bandwidth but does not have such good values for mixer noise and mixer gain.

In order to obtain information about the influence of the IF-noise, IF-gain and possible increase of output noise induced by the Multiple Andreev Reflection (MAR), the unpumped IF output power is analyzed. The calculated shot-noise power of the junction at the IF output is compared with the measured output power. For the shot noise power of the twin-junction devices, the formula

$$P_{shot}(V) = \frac{1}{\sqrt{2}} S_I(V) \cdot B \cdot \coth\left(\frac{eV}{2k_B T}\right) \cdot \frac{Y_L}{(dI/dV + Y_L)^2}$$

is used. Here B is the bandwidth, Y_L is the load admittance. The spectral noise density is defined after Dieleman et al.[2] $S_I(V) = 2e \cdot I_{tun}(V) + 2q_{MAR} \cdot I_{MAR}(V)$, where

- $$I_{tun}(V) = \frac{2}{R_N e} e^{-\frac{\Delta}{k_B T}} \sqrt{\frac{2\Delta}{eV + 2\Delta}} (eV + \Delta) \cdot \sinh\left(\frac{eV}{2k_B T}\right) \cdot K_0\left(\frac{eV}{2k_B T}\right)$$

is used for the tunneling current[9] for $eV < 2\Delta$ (with K_0 the zeroth-order modified Bessel function)

- $I_{MAR}(V) = I_{measured}(V) - I_{tun}(V)$ is the current carried by the MAR effect
- $q_{MAR}(V) = e \cdot (1 + r_{MAR} \cdot 2\Delta/eV)$ is the voltage-dependent effective charge of the MAR-carried current with r_{MAR} as fit-parameter. We introduce this "ratio of MAR-effect" in order to estimate, to which degree this effect has to be taken into account for the analysis of the measured devices.

Then the total output power is calculated according to the formula

$$P_{out}(V) = \left\{ P_{Shot}(V) + k_B B \left[T_{IF} + T_{ISO} \left(\frac{Y_L - dI/dV}{Y_L + dI/dV} \right)^2 \right] \right\} \cdot G_{IF}$$

where T_{IF} is the noise temperature of the HEMT-amplifier and bias-T, T_{ISO} is the temperature of the isolator and G_{IF} is the total gain of the IF-chain.

The resulting data for two devices – one of the DIMES devices (V20) and one KOSMA device (D42) – and their fit parameters are given in Figure 7:

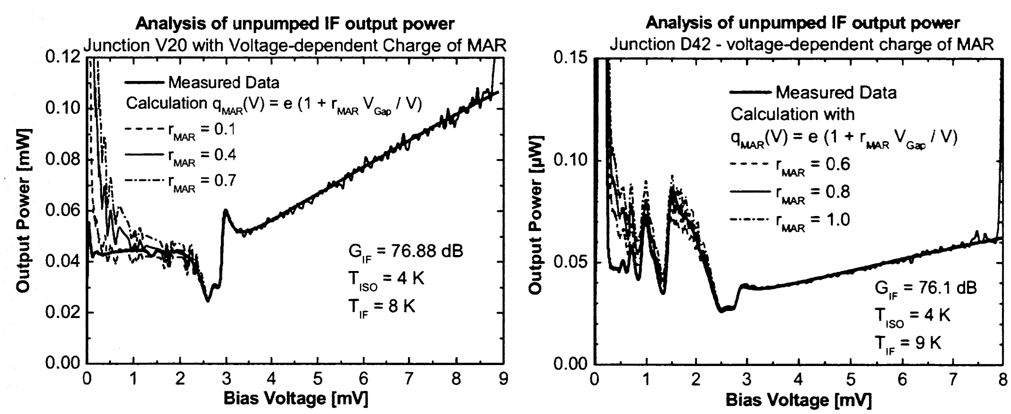

Figure 7: Calculation of shot noise of the junction and IF-noise for two devices in comparison with the measured IF-output power assuming a voltage-dependent charge for the MAR-carried current

It can be seen that the effect of MAR is stronger for the device D42 on the right hand side, which has the higher current density and the lower quality factor Q, as one would expect. The fit seems to be appropriate for voltages from around 1 mV to the gap-voltage. But for lower voltages the calculated power values are too high.

To obtain a better fit, the data were also analyzed assuming a constant effective charge for the MAR carried current ($q_{MAR}(V)$=const). If this constant effective charge has a value of 2e, at the gap-voltage V_{Gap}, it has the same value as the voltage dependent effective charge for r_{MAR}=1, and for lower voltages it is below the voltage dependent function q(V). The results are given in Figure 8.

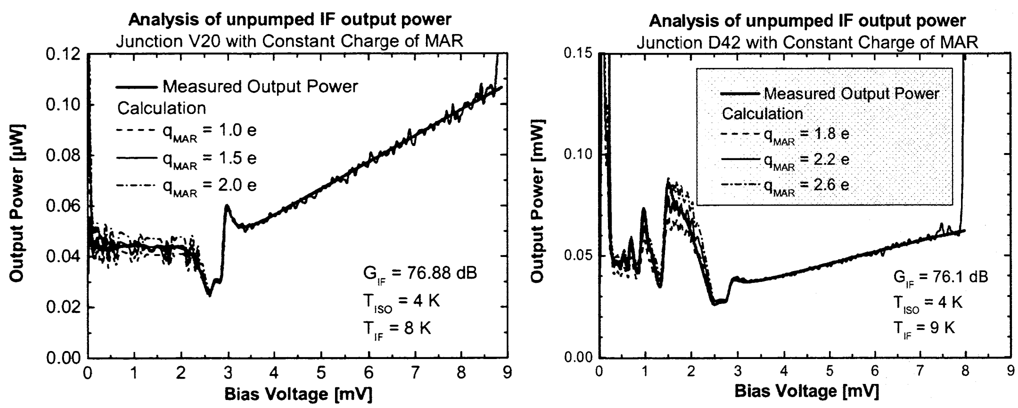

Figure 8: Calculation of shot noise of the junction and IF-noise for two devices in comparison with the measured IF-output power assuming a constant charge for the MAR-carried current

The approach with a constant charge over the bias voltage seems to describe the phenomena better than the previous one. For the DIMES-device the result is an effective charge of 1.5·e. The value for the KOSMA device is 2.2·e. These values are used in the further performance analysis.

Simulated mixer results

The measured DC IV-curves and results of the fit to the IF output power, including the MAR parameter, are used as input to the QTM. The actual embedding impedance of the devices is estimated using actual junction and layer parameters as obtained from DC-measurements. The Band center is shifted towards lower frequencies in agreement with the measured FTS results. We simulate the performance around 700 GHz where the best performance was measured for both devices. The results are given in Table 1.

Table 1: Simulated and measured mixer input noise temperature and mixer gain The simulated mixer performance is calculated with MAR-effect ($q_{MAR}/e \neq 1$) and without MAR ($q_{MAR}/e = 1$).

Device	q_{MAR}/e	T_{Mix} [K] simulated	G_{Mix} [dB] simulated	T_{Mix} [K] measured	G_{Mix} [dB] measured
U22 (DIMES)	1.5	70	-6.5	96	-5.4
	1	66	-6.5		
D42 (KOSMA)	2.2	96	-6.7	91	-6.9
	1	69	-6.7		

Discussion

It would be very desirable to have a reliable way of including the effects of the tunnel barrier imperfections in the performance simulation of high frequency (and high current density) $Nb/Al_2O_3/Nb$ SIS mixers. If we compare the calculated output power using the formula $q_{MAR}(V) = e \cdot (1 + r_{MAR} \cdot 2\Delta/eV)$ with the measurements of the unpumped IF-output power, it is apparent that the effect of the MAR on the shot noise output is overestimated, even for the KOSMA device with a quality of 7. In addition we were only able to obtain a good fit between theory and measurement by removing the voltage dependence of the effective charge. The fit result indicates that only a part of the current in excess of the tunneling current is caused by MAR, and that there are still other charge transport mechanisms involved.

The fitted constant effective charge was used in the QTM as suggested in [2]. The inclusion of the MAR increases the calculated noise, but for the good quality junction the predicted noise is still a little low compared to the measured noise. For the bad quality junction the calculated noise is similar to the measured one.

Based on the measurements and analysis presented here we can conclude that one should take into account the MAR in the imperfect barriers in the analysis of the mixer results. Using the approach with the voltage independent, fitted, effective charge to estimate the influence of the MAR, the optimum design current density probably shifts to higher values than 10 kA/cm^2. To confirm if simulated results with the QTM including the MAR also yield a good prediction of measured mixer performance, we need to analyze more data.

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[5] **D**elft **I**nstitute of **M**icroelectronics and **S**ubmicron Technology, Netherlands

[6] The coorperation with DIMES was made possible under ESTEC Contract N° 11653/95

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