A 100 GHz JOSEPHSON MIXER USING RESISTIVELY-SHUNTED Nb TUNNEL JUNCTIONS[1]

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Abstract – We describe preliminary mixer results using resistively shunted Nb/AlOx/Nb tunnel junctions in a 100 GHz waveguide mixer mount. The mixer utilizes robust, lithographically-defined devices which have non-hysteretic I-V curves. We have obtained a receiver temperature of 390 K (DSB), with a conversion loss of -6.5 dB. The receiver's behavior agrees qualitatively with the behavior predicted by the resistively shunted junction (RSJ) model. Substantial improvements in performance are expected with the use of better optimized shunted junctions, and numerical simulations suggest that if devices with higher $I_C R_N$ products can be obtained, Josephson effect mixers could be competitive with SIS mixers at high frequencies.

INTRODUCTION

Josephson effect mixers utilizing point contacts or planar hybrid junctions have previously obtained good conversion efficiency and reasonable noise performance[1-5]. However, the lack of robustness and reproducibility of the point contacts made them undesirable for many applications. Due to advances in the production of high current density tunnel junctions and in electron-beam lithography, it is now possible to produce nonhysteretic devices with reasonable impedances, and to control their parameters (e.g. normal-state resistance, critical current, capacitance) via the fabrication process. In addition, the advent of high-T_c materials makes it likely that nonhysteretic devices such as SNS bridges may become available with large $I_C R_N$ products in the near future. In contrast, it may never be possible to use SIS mixers made with high-T_C materials due to the extremely short coherence lengths. Josephson effect mixers using devices with $I_C R_N$ products in excess of a millivolt could become competitive with SIS mixers at frequencies above 500 GHz.

Josephson effect mixers have been shown, both experimentally and in analog and digital simulations, to exhibit an "excess" noise [6,7]. New numerical studies of the resistively shunted junction (RSJ) model have made advances in the understanding of this noise source, and in the optimization of the mixer performance in its presence. We will not discuss the numerical modelling in detail here (see [8]), but the simulations predict good performance for frequencies up to half the critical frequency ($\omega_C = 2eI_C R_N/\hbar$). These predictions are encouraging for high frequency work if the $I_C R_N$ product can be increased. We are therefore studying the performance of Josephson effect mixers at 100 GHz using shunted Nb junctions, in order to compare them to the numerical simulations, and to study the mixer performance as a function of the device parameters, as a first step toward developing high frequency receivers.

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DEVICE REQUIREMENTS

Ordinary superconducting tunnel junctions have relatively high capacitance, which makes them generally unsuitable for use as Josephson effect mixers. Their current-voltage characteristics are hysteretic, and they cannot be stably biased in the low voltage region where the Josephson mixing is most effective. In the RSJ model, the parameter which measures the importance of the device capacitance is the McCumber beta parameter, $\beta_c = 2eI_c R_N^2 C/\hbar$, where I_c is the critical current, R_N is the normal state resistance, and C is the device capacitance [see e.g. 6]. For values of β_c greater than one, the I-V curve is hysteretic, and a wide variety of complicated behaviors are possible, including chaos and subharmonic generation. High current-density (5,000-10,000 A/cm^2) Nb tunnel junctions have β_c values of about 15-20 [9], and when used as quasi-particle (SIS) mixers, a magnetic field is commonly used to reduce the critical current and minimize the chaotic behavior which occurs under illumination by the local oscillator.

To avoid the complications of hysteresis and the possibility of chaos, our approach was to reduce β_c by adding a resistor in parallel to the junction. This reduces the value of the normal state resistance, and therefore reduces beta. Since β_c is initially about 15-20, it is necessary that the resistance be reduced by approximately a factor of 4-5, since β_c is proportional to the square of R_N. This resistive shunting has two undesirable results, however. First, in order to obtain devices with good impedances for RF and IF matching (R_N = 20 - 50 Ohms), the initial tunnel junction must have fairly high R_N, which implies very small (sub-micron) areas for these high current-density junctions. Second, by reducing R_N while holding the critical current fixed, we have reduced the $I_C R_N$ product, and therefore the critical frequency, which limits the highest frequency of operation. For Nb, the optimal shunted junction would have R_N of 50 Ohms, junction area of 0.1 μm^2, critical current of $10 \mu A$, and an $I_C R_N$ product of 0.5 mV, which would allow good conversion efficiency up to about 300 GHz. Clearly, materials with higher initial $I_C R_N$ products and/or lower specific capacitance will be required for high frequency mixers. However, the typical high-quality requirements of junctions for SIS mixers, such as low leakage and sharp gap structure, are not needed for shunted Josephson applications, so that this may be a suitable application for high-T_C materials.

JUNCTION FABRICATION

We have developed a method for fabricating shunted junctions based on the Nb trilayer process for sub-micron area junctions described by LeDuc et al [10]. After trilayer deposition, the junction areas are defined by direct electron beam writing. A reactive-ion etch (RIE) of freon 12 (CCl_2F_2), freon 14 (CF_4) and O_2 allows etching of the top Nb layer with nearly vertical sidewalls, and junction sizes as small as $0.3 \mu m$ x $0.3 \mu m$ can be obtained reliably. After etching, the device is

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planarized with evaporated SiO. Then a resistor layer of AuGe eutectic (88% Au/12% Ge) is evaporated on top of the SiO, in close proximity to the tunnel junction. Finally, the usual Nb counterelectrode is sputtered and patterned. A photomicrograph of a completed junction is shown in Figure 1. The counterelectrode runs onto the planarized window, and contacts the junction and one end of the resistor. Another section of the counterelectrode contacts the other end of the resistor and continues off the planarization area, thereby connecting the resistor in parallel with the tunnel junction. Junctions were then tested at cryogenic temperatures. As a final step, the tested junctions can be subjected to low-energy Ar-ion milling to thin the resistor layer, allowing fine tuning of device resistances without damaging the junction, which is protected by the counterelectrode.

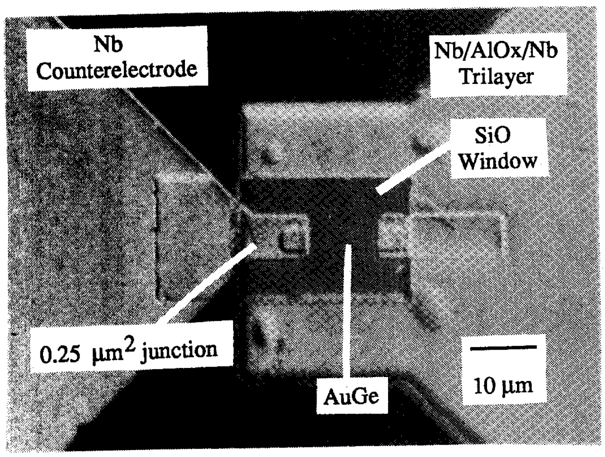

Figure 1: Photomicrograph of resistively-shunted junction (magnification ~ 1,000)

This choice of geometry is important because the shunting resistor must have very small parasitic reactances in order to prevent undesired resonances and allow application of the RSJ model, which assumes a frequency-independent resistor. Because the resistor lies on top of the SiO, the bottom of the trilayer acts as a ground plane. The resistor can then be thought of as a section of very lossy transmission line. Analysis of this stripline structure predicts that it has negligible reactance even up to about a THz. The AuGe material was chosen because of its relatively high resistivity, which is necessary to allow large resistances in the short physical length allowable. It also proved to be resistant to the etch used to define the counterelectrode, and did not develop contact resistance at the interfaces with the Nb. The resistivity was reproducible and nearly independent of temperature. Typical resistivities were about 10 μ-Ohm-cm, so layers about 100-200 Å thick gave sheet resistances of 5-10 Ohms/square.

Devices fabricated with this process displayed critical currents which scaled with junction area, and the normal state resistances could be controlled by the thickness of the resistor layer. Non-hysteretic devices (see Figure 2) typically displayed nearly ideal RSJ I-V curves, had normal resistances of 25-50 Ohms, critical currents of 5-20 μA, and $I_C R_N$ products of 200-500 μV. A small, broadened current rise occurs at the gap voltage ($\sim 3 mV$) of the Nb junction, but the change in current is small since most of the current flows through the shunt. The relative shunting can be varied, and devices with partial hysteresis, and correspondingly larger $I_C R_N$ products could be obtained. The devices are extremely stable and reproducible, being resistant to aging in atmosphere, and unchanged with repeated thermal cycling, unlike point contacts.

MIXER MEASUREMENTS

We have recently begun testing devices fabricated with the above process in a waveguide mixer mount at 100 GHz. The general design of the apparatus is very similar to the design used in several receivers [11-13] at the Caltech Submillimeter Observatory, which use SIS junctions as the mixing element. The junction is mounted on a thin quartz substrate, across a section of full-height rectangular waveguide. Two non-contacting backshorts allow the adjustment of the RF embedding impedance. The waveguide feeds a circular, conical horn. Two filters consisting of fluorogold and black polyethylene at 77 K and 4.2 K block room temperature IR radiation from reaching the junction. The IF signal is amplified by a 1.25-1.75 GHz HEMT amplifier, operated at 4.2 K, with gain of 30 dB and a noise temperature of about 10 K.

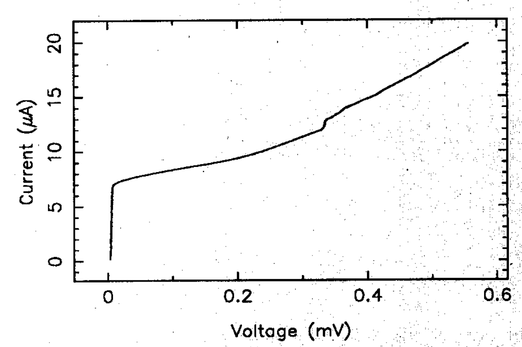

Figure 2: I-V curve of a shunted Nb junction (JJ23-2).

The current-voltage characteristic near zero voltage of a shunted junction is shown in Figure 2. A small feature can be seen at about 335 μV, which is present only when the junction is mounted in the waveguide, and may be due to a waveguide resonance. This voltage corresponds to a Josephson frequency of about 160 GHz, which is close to where the WR-8 waveguide becomes overmoded. The junction's parameters and some important quantities for the RSJ model are given in Table 1.

TABLE 1. Junction Parameters: JJ23-2

Critical Current (I_C)	7.0 μA
Normal State Resistance (R_N)	28.5 Ω
$I_C R_N$ Product	200 μV
Junction Area	$0.25 \mu m^2$
Capacitance	15 fF
Critical Frequency ($2eI_C R_N/h$)	97.0 GHz
McCumber Beta Parameter (β_c)	0.3
Gamma ($2ek_B T/\hbar I_C$)	0.03

When illuminated with 100 GHz radiation from a Gunn diode, the curve develops strong Shapiro steps at the quantized voltages $V_n = n\hbar\omega/2e$. The dependence of the step heights on local oscillator power was measured using a calibrated attenuator on the output of the Gunn, and by measuring the current at a small voltage above and below these quantized voltages. These attenuator setting were converted into relative local oscillator power levels, and the heights of the 0th and 1st order steps as a function of normalized LO voltage are plotted in Figure 3. The solid curves are the well-known Bessel function dependence predicted by a simple voltage-biased model [6]. The vertical axis has been scaled so that the magnitude of 0th order Bessel function equals the critical current at zero applied power, and the horizontal axis has been scaled so that the first minima of the measured and predicted curves coincide. Because the step heights were estimated by measuring the current at a small voltage from the step itself, there is a small offset added, which becomes more important at small step heights, and causes the rounding observed at the step minima.

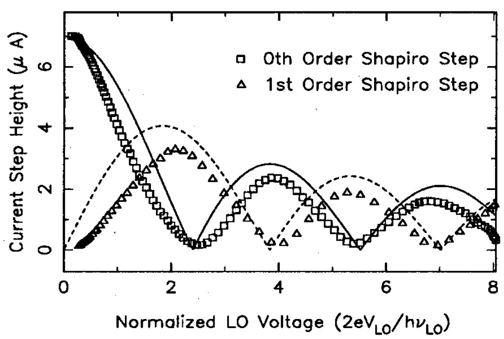

Figure 3: Shapiro step amplitudes as a function of local oscillator voltage for 0th and 1st steps. Curves show the expected dependence $|J_0|$ (full line) and $|J_1|$ (dashed line).

We measured the heterodyne response of the mixer using the standard hot/cold load technique. Figure 4a shows the I-V curve of the junction with LO applied, and the IF output power of the receiver as a function of bias voltage across the first photon step for both hot and cold loads at the input. The low-frequency noise predicted by numerical simulations of the RSJ model under the influence of the local oscillator is shown for comparison in Figure 4b. The similar shape of the curves suggests that the RSJ formalism can account for the observed response.

The IF output response was well-behaved for a variety of tuner configurations (embedding impedances), frequencies, and local oscillator power levels. Tuning was quite reproducible, and the best response was obtained by maximizing the IF output power in the middle of the photon step with respect to backshort position and local oscillator power.

From the hot/cold power measurements, the best receiver noise temperature obtained was 390 K (DSB) at 94 GHz. The receiver's conversion loss could also be estimated using an modified version of the shot-noise calibration technique commonly applied to SIS receivers [14]. For bias voltages above about 3 mV, the IF power increases linearly with bias voltage. In this state, most of the DC current flows through the resistor, but a certain fraction flows through the tunnel junction, and therefore produces shot noise. The normal state resistance of the unshunted junction can be estimated, since the critical current is known, and then an effective shot noise temperature was derived. This allowed a rough determination of the IF system noise temperature and gain, and gave an estimate of the conversion loss. At 94 GHz, the highest conversion efficiency observed was 0.225, or a conversion loss of -6.5 dB. The IF contribution to the receiver noise is then estimated to be ~50 K, which implies a mixer temperature, including front-end losses, of approximately 350 K (DSB).

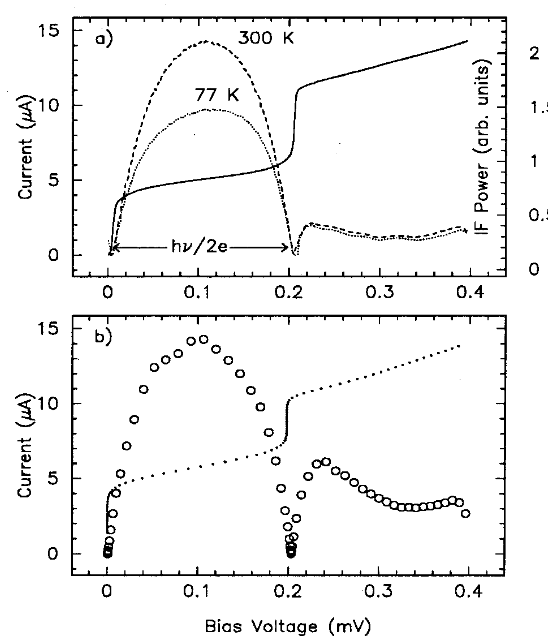

Figure 4: a) Measured IF response for junction JJ23-2. Full line shows pumped I-V curve, dashed line shows IF power vs. voltage for a room temperature load at the input, dotted line shows response for a 77 K load. b) Predicted response from numerical solution to RSJ equations. Dotted line is pumped I-V curve, open circles show low-frequency noise in absence of signal. (i.e. a 0 K load at input)

We have tested the receiver in an identical configuration in which the shunted junctions are replaced by good quality Nb SIS junctions. The performance showed a similar frequency dependence, and gave a best result of 120 K (DSB) receiver temperature, and conversion loss of -7 dB's at 98 GHz, which is about a factor of four worse than expected, given experience with similar receivers at 100 GHz [15] and 230 GHz [12]. Both types of junctions utilized an integral RF choke structure which is fabricated on the junction substrate to prevent RF losses into the channel which holds the junction. This choke is designed to have its best performance at ~100 GHz, but was designed assuming 0.1 mm (4 mil) thick quartz substrates, while the initial devices of both types were fabricated on 0.2 mm (8 mil) thick quartz. We are therefore hopeful that devices on thinner substrates may give substantially better performance in the near future. Also, the optical throughput of the test dewar windows has not been measured.

MEASURED VS. PREDICTED PERFORMANCE

The predicted performance of the Josephson effect mixer can be obtained using numerical integration of the RSJ equations to obtain the conversion and noise-correlation matrices, in the manner described by Taur [7]. After these matrices are determined, the mixer noise temperature and conversion efficiency can be calculated as a function of the RF and IF embedding impedances. The actual impedance presented to the junction is not well known, but it can in principle be determined by fitting the shape of the pumped I-V curve. For RSJ simulations using parameters identical to this junction (see Table 1), the optimum RF embedding impedance is roughly 15 Ohms and real, which is probably not obtainable, especially with the presence of the losses due to the improper choke structure. For RF impedances of 30-60 Ohms and real, the predicted mixer noise temperature is 100-200 K (DSB) (not including any front-end losses), which is substantially lower than the observed mixer noise temperatures of about 350 K (DSB). Conversion efficiencies are predicted to range from 0.15-0.25 (-8 to -6 dB). Improvement of the RF choke structure and detailed fitting of I-V curves to determine the embedding impedances will be required to allow a detailed comparison with the numerical predictions.

Substantial improvement of performance should also be possible for devices whose junction parameters are more nearly optimized. The junctions tested so far are overshunted (β_c = 0.3), and the $I_C R_N$ product can be increased by roughly a factor of two. For operation frequencies greater than or equal to the critical frequency ($\omega_C = 2eI_C R_N/\hbar$), the performance predicted by the RSJ model declines as frequency squared. For frequencies about one-half the critical frequency (i.e. an $I_C R_N$ product of 0.4 mV for 100 GHz), which are obtainable with our shunted Nb procedure, simulations predict mixer temperatures of about 25 K (DSB), with -3 dB conversion loss.

SUMMARY

We have demonstrated a process which produces robust, lithographically-defined non-hysteretic devices suitable for Josephson effect mixers. A receiver using these devices behaves qualitatively as expected from the RSJ model. Initial tests yielded receiver temperatures of 390 K (DSB), with -6.5 dB conversion loss, but substantial improvements are expected with the improvement of RF and optical losses, better RF matching, and optimization of junction parameters. Since the requirements for a suitable Josephson-effect device are less stringent than for SIS devices, this may prove to be a useful application for high-T_C materials.

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