High quality tantalum superconducting tunnel junctions for microwave mixing in the quantum limit

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We report on a novel step-defined process used to produce small area ($1-6\,\mu m^2$), high critical current density (10^2-10^4 A/cm^2) superconducting tunnel junctions with Ta base electrodes and $Pb_{0.9}Bi_{0.1}$ counterelectrodes. These junctions have extremely small subgap leakage currents, a "sharp" current rise of width $\Delta V \sim 30\,\mu V$ at the sum-gap voltage, and show strong quantum effects when used as microwave mixers. Accurate measurements at 34.5 GHz with a 1.5 GHz intermediate frequency (IF) give single sideband mixer gains up to $G = 1.1 \pm 0.1$ and mixer noise temperatures as low as $T_M = 3.8 \pm 1.0$ K. This value of T_M is close to the quantum limit $T_Q = \hbar\omega/k \ln 2 = 2.5$ K. The lowest receiver noise temperature measured at the 1.3 K input to the mixer block, $T_R = 24 \pm 1$ K, is the best value reported for any heterodyne receiver. Infinite available gain is obtained for a low (25 MHz) IF and a coupled gain as large as 1.6 ± 0.4 is observed.

The performance of superconductor-insulator-superconductor (SIS) quasiparticle mixers has surpassed other technologies in recent years for low noise millimeter wave heterodyne receivers.[1-3] A number of radio astronomy observatories use SIS receivers on a regular basis.[2] According to the quantum theory of mixing,[4] strong quantum effects are seen when an SIS tunnel junction is used which has low leakage current below the sum-gap voltage, and a current rise at the sum-gap voltage which is "sharp" on the voltage scale of $\hbar\omega/e \approx 150\,\mu V$ at 36 GHz. A junction with these characteristics is predicted to have a single sideband (SSB) mixer noise temperature T_M approaching the quantum limit[5] $T_Q = \hbar\omega/k \ln 2 = 2.5$ K at 36 GHz. Conversion gain $G > 1$ is also predicted, which cannot be achieved in the classical mixer theory. A recent review of this field is given in Ref. 1.

The nature of the tunnel barrier is critical in obtaining the *I-V* characteristics needed to observe strong quantum effects. In addition, practical tunnel junctions must withstand repeated cooling to liquid helium (LHe) temperatures and have high Josephson critical current densities of $\sim 10^3$ A/cm^2. Most recent mixer experiments have used Pb-alloy junctions[6] whose *I-V* characteristics are not generally sharp enough to observe strong quantum effects. Nevertheless, receivers of excellent sensitivity are produced using these junctions.[2] Niobium is also a desirable junction material because of its high $T_c \approx 9.2$ K and refractory nature. Recent developments in Nb[7,8] and Pb-alloy[9] junctions make use of tunnel barriers other than the native oxide of the base electrode and yield improved *I-V* characteristics.

In this letter, we describe a new fabrication technique which produces extremely high quality Ta junctions. To our knowledge, these are the sharpest and lowest leakage junctions to be evaluated for SIS mixer performance. Ta was selected because it is a refractory metal and is known to form a high quality native oxide (Ta_2O_5) barrier in low current density (10^{-2} A/cm^2) junctions.[10] The T_c of Ta, 4.4 K, is acceptable for mixer operation below 2.0 K. Using these junctions, detailed measurements of mixer performance were made at 34.5 GHz using a novel test apparatus[3] which was developed for this experiment. The observed performance was excellent, giving T_M(SSB) $< 2T_Q$ and $G \sim 1$. A previous study of SIS mixers in the quantum limit[15] produced T_M(SSB) $< 7T_Q$ using high quality Sn junctions. In the present work, junction leakage currents have been reduced by a factor of ~ 2 and the accuracy of the measurements improved by a factor of ~ 6.

The Ta junctions are fabricated with the step-defined process shown in Fig. 1. This procedure eliminates photoresist processing between the depositions of metal layers in a way that is analogous to the process developed by Dolan.[11] This allows the rapid optimization of oxidation conditions and offers the possibility of complete junction fabrication in a single system without breaking vacuum. The process begins by patterning a Cr line 1–2 μm wide by 500 Å thick using standard photolithography. A 0.7-μm-high step in the Si substrate is produced by reactive ion etching (RIE) in 90% CF_3Br and 10% O_2 as shown in Fig. 1(a). The Cr film is then removed by a wet etch. An undercut resist stencil suitable for liftoff is used to define the width of the junction perpendicular to the plane of Fig. 1. This stencil is a three-

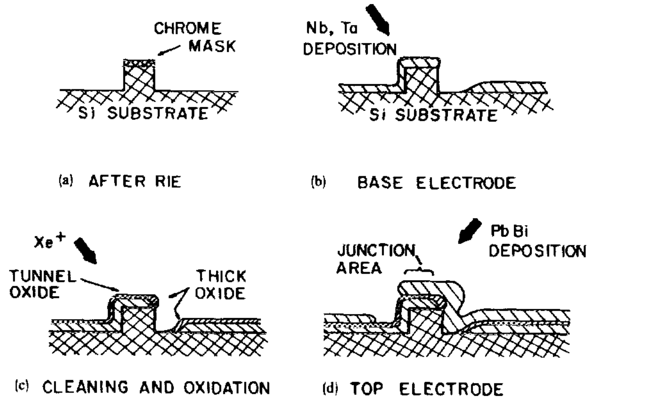

FIG. 1. Step-defined fabrication sequence showing the importance of the thick oxide for edge protection.

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layer photoresist structure[11] consisting of an exposed 1.5-μm bottom layer of AZ1350J, a 500-Å Al isolation layer, and a 1.0-μm top layer of AZ1370. After patterning the top layer, the Al interlayer is wet etched and the bottom layer is developed to produce the desired undercut stencil.[11] The result is a resist stencil with a 1–2 μm open slot over the Si step. On each side of the step, the slot flares out to form the 500-μm-wide leads to the junction.

The 3000-Å-thick Ta base electrode is deposited by ion beam sputtering[12] at a 45° angle, leaving a break in the shadow of the step as shown in Fig. 1(b). The multiple target capability of our sputtering system allows us to deposit a thin 200-Å Nb underlayer to nucleate the Ta film in the bcc (superconducting) phase without the use of substrate heating. Ta films without the Nb underlayer grow in the nonsuperconducting β phase.[12]

Following the Ta deposition, a thick oxide layer is grown over the entire Ta film by exposure to air for 1–2 h. After pumping to a pressure of $< 7 \times 10^{-7}$ Torr in a separate vacuum system, a small Kaufman ion source is used to clean the surface of the Ta film with low-energy (150 eV) Xe^+ ions at a current density of 100 μA/cm^2 for 3 min. The Xe^+ ion beam impinges on the surface from the same angle that the Ta film was originally deposited. As illustrated in Fig. 1(c), this process leaves a thick oxide layer on the shadowed edges of the film at the break and thus eliminates tunneling into this region. Damaged regions at the Nb/Si interface on the edge of the film may have reduced energy gap values which would contribute to an increased width of the current rise at the sum gap and thus to degraded mixer performance. All photoresist layers which are exposed to the ion beam during cleaning are covered with a Ta film. This helps to reduce contamination of the junction surface due to photoresist sputtering during cleaning.

After cleaning, the surface is reoxidized in an oxygen dc glow discharge at a pressure of 125 mTorr for 10–30 s, depending on the current density desired. For 20-s oxidation, $J_c \approx 10^3$ A/cm^2. We estimate that the O_2 ion energies at the junction surface are less than 20 eV. This provides a relatively gentle ion-assisted oxidation process. Without the glow discharge, the oxidation rate at this pressure is found to be negligible. As can be seen in Fig. 2(a), junctions made with this technique have nearly ideal *I-V* characteristics, even at current densities of 1300 A/cm^2. There is no evidence of a proximity layer at the interface.[7] The low levels of suboxide (TaO) found in Ta surface oxides[13] may favor the formation of a very abrupt metal to oxide interface and a nearly ideal tunnel barrier in Ta junctions. Attempts to use thermal oxidation or low energy ion beam oxidation always resulted in lower quality junctions.

Although a refractory counterelectrode is ultimately desirable, we have used a $Pb_{0.9}Bi_{0.1}$ counterelectrode to minimize interactions with the barrier. This yields sharp *I-V* characteristics while still retaining thermal cyclability. Following oxidation, the substrate is rotated and a 3000-Å $Pb_{0.9}Bi_{0.1}$ counterelectrode is evaporated from an alloy source at 50 Å/s as shown in Fig. 1(d). Finally, the photoresist stencil is lifted off in acetone.

High current density (10^3 A/cm^2) Nb-based junctions

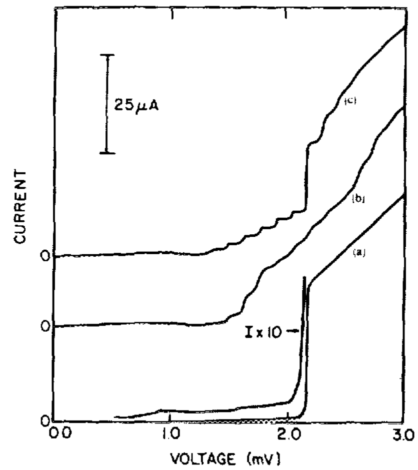

FIG. 2. (a) dc *I-V* characteristic of a high quality Ta/PbBi tunnel junction at 1.3 K. $J_c = 1300$ A/cm^2, $R_n = 47\ \Omega$, and $A = 2\ \mu$m^2. (b) Typical pumped *I-V* characteristic for mixer gain of ~ 1. (c) Same junction with rf tuning adjusted to produce negative quasiparticle resistance on five photon steps simultaneously. Zeros are offset for clarity.

with thin, 80 Å, Ta overlayers have also been produced with a similar process. We find that Ta overlayers on Nb give good quality *I-V* curves similar to those reported for low current density junctions with Ta overlayers.[14] The overlayer junctions, however, are not as high quality as the thick Ta junctions described above.

Junctions which are cycled several times between room temperature and 4.2 K without exposure to air show no changes in their *I-V* characteristics to within 2%. Junctions which are exposed to air display a gradual increase in their resistance depending on the length of exposure. This problem should be alleviated with an appropriate passivation layer such as SiO.

We have used a method employing cryogenic variable-temperature loads developed by McGrath *et al.*[3] to measure mixer noise temperature and gain with an accuracy of better than ± 1 K and $\pm 10\%$, respectively. The local oscillator (LO) frequency was 34.5 GHz, the intermediate frequency (IF) was 1.5 GHz, and the LHe bath temperature was 1.3 K. The results of experiments using several Ta junctions and one Nb junction are given in Table I, where G_A is the avail-

TABLE I. Summary of mixer results. G_A is the available gain and G_C is the coupled gain. Measured noise temperatures are accurate to ± 0.6 K or better unless otherwise noted and approach the quantum limit of 2.5 K. The gain measurements are accurate to $\pm 10\%$. Measurements with IF = 1.5 GHz have sideband ratios > 18 dB.

Junction R_n (Ω)	T_M (SSB) (K)	G_A (SSB)	G_C (SSB)	Photon step
101(Ta)	3.8 ± 1	0.34	0.33	1
47(Ta)	5.2	1.1	0.79	4
	4.7[a]	0.83	0.74	4
	5.7	0.58	0.41	2
	6.0	0.40	0.39	1
73[b](Ta)		4.7 ± 1	1.6 ± 0.4	1
72(Nb)	5.5 ± 0.8	0.56	0.55	4
	9.0 ± 1.6[c]	0.27	0.26	4

[a] These conditions gave the lowest receiver noise temperature of 24 ± 1 K.
[b] Measured for a 25 MHz IF, and a sideband ratio < 1 dB.
[c] Measured at a bath temperature of 4.2 K.

able gain into a matched IF load and G_C is the coupled gain including the mismatch to our 50-Ω IF system. The mixers were adjusted for maximum G_C, which was obtained when the IF reflections were small. Larger gains may be possible with a fully optimized IF transformer. We have also determined the receiver noise temperature T_R referred to the low-temperature rf input of our system by measuring the total IF output noise power versus the input noise power from the rf load and extrapolating to zero IF output noise power. Unlike T_M, the receiver noise includes all of the system losses, impedance mismatches, and IF system noise temperature $T_{IF} \approx 14$–18 K. The lowest value of T_R (SSB) is 24 ± 1 K. For comparison, the niobium junction at 1.3 K reported in Table I, with a more rounded I-V curve, gives a receiver noise temperature of 42 ± 1 K in our system.

The experimental results discussed thus far, using a 1.5 GHz IF, do not show the large gain that can be achieved with such high quality tunnel junctions.[15] By adjusting the backshort and screw tuner, values of the rf embedding impedance could be found that produced regions of negative resistance on as many as five photon steps as is shown in Fig. 2(c). Simple arguments and previous experiments[15,16] suggest that negative resistance implies infinite available mixer gain for a low enough IF that the embedding impedance is the same at the signal, LO, and image frequencies. Since the rf bandwidth of our mixer block is narrow compared with the 1.5 GHz IF, however, the signal frequency is badly mismatched when the coupling is adjusted for negative resistance steps. Low values of gain, $G_A \ll 0.1$, are observed under these conditions.

To explore these effects, gain measurements were also made with a 25 MHz IF. We find that the largest coupled gain, $G_C = 1.6 \pm 0.4$, occurs on the first photon step below the gap with a pumped I-V curve similar to that in Fig. 2(c), but without negative resistance. Measurements of the mismatch at this point suggest an available gain of 4.7 ± 1. When the mixer parameters are adjusted to approach a region of infinite available gain, the mixer output impedance rises causing a severe mismatch with the 50-Ω IF system. Accurate noise measurements are not presently possible at 25 MHz with our apparatus.

We have calculated mixer performance for the 1.5 GHz IF experiments using the embedding impedance measurements from a low-frequency scale model[17] and a three-port approximation of the Tucker theory.[4] The capacitance of our junctions is estimated using $C/A = 140$ fF/μm^2 and an area of $\sim 2\,\mu$m^2 which implies an $\omega R_n C$ product of 3–5. For the Nb junction in Table I, with a rounded I-V curve at 4.2 K, we find that the theoretical gain agrees reasonably well with the experiment. For the sharp Ta junctions, however, we find that the theory predicts infinite or very large G_A. This is true even when the embedding impedances used in the calculation are varied significantly to account for uncertainties in our knowledge of mixer block parameters. We do not observe these large predicted gains with a 1.5 GHz IF. We also find that the measured mixer noise exceeds Tucker's shot noise prediction[4] by 2–4 K for both the Ta and Nb junctions. The inclusion of quantum zero point fluctuations[18] in the signal and image terminations adds ~ 1 K to the shot noise prediction. Some correction to our gain and noise calculation due to harmonic response is expected.[1] Further details of the mixer measurements and theoretical modeling will be presented in a future publication.

In conclusion, we have produced thermally cyclable, high quality Ta/PbBi SIS junctions for quasiparticle mixers. These junctions are of higher quality than others that have been tested for SIS mixers or receivers to date and give large gain as well as low noise temperatures approaching the quantum limit. The improved accuracy of our measurements allows more detailed tests of the theoretical predictions. The measured T_M (SSB) $= 3.8 \pm 1.0$ K and T_R (SSB) $= 24 \pm 1$ K are the lowest reported to date for a heterodyne receiver. Future work on high quality junctions with broadband matching should provide larger gain as well as low noise with a 1–2 GHz IF.

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