HIGH QUALITY Ta/PbBi TUNNEL JUNCTIONS FOR 85-110 GHz SIS MIXER EXPERIMENTS

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ABSTRACT

We report on the fabrication of small area (1-6 μm^2), high critical current density (10^3-10^4 A/cm^2) Ta/Ta oxide/ $Pb_{0.9}Bi_{0.1}$ SIS tunnel junctions and six junction series arrays designed for use as broadband SIS quasiparticle mixers at 85-110 GHz. These junctions have small subgap leakage currents (1 to 5%), and a "sharp" current rise of width ΔV~30-50 µV at the sum gap voltage. An RF filter is fabricated on the substrate along with the junctions. The impedance of this filter combined with the junction capacitance is designed to provide a broadband RF match to the mixer over the entire frequency range. A sliding backshort is the only mechanical tuning element. The single junctions as well as arrays are fabricated with a window geometry on fused quartz substrates. The fused quartz substrates require the deposition of a thin amorphous Ge layer which is conducting at room temperature to avoid charging effects during the ion-beam processing steps. Preliminary measurements at 85-100 GHz show a relatively low gain (-6.9 dB) compared to the performance expected for junctions of this quality. Model calculations suggest that the low gain arises from errors in the implementation of the RF filter design; this can be improved in future work.

INTRODUCTION

In recent years, SIS mixers have demonstrated excellent low noise performance in millimeter-wave heterodyne receivers [1-6]. High quality Ta/Ta oxide/PbBi tunnel junctions have recently been used [2] to observe and accurately measure strong quantum mixing effects, conversion gain G > 1, and a noise level within a factor of two of the quantum limit at 36 GHz. These experiments required Ta junctions with a current rise at the sum gap which was "sharp" on the voltage scale $\hbar\omega/e$ (≈ 150 µV at 36 GHz) and a low subgap leakage current in order to achieve large gain and low noise. In addition, the ability to make accurate noise measurements [3] was crucial near the quantum noise limit. The extension of these techniques to higher frequencies (85-110 GHz) is clearly desirable for radio astronomy and communication applications. At those frequencies, high gain is more readily obtained because of the reduced requirement on the I-V "sharpness". To approach the quantum noise limit, a low subgap leakage is still needed to minimize the mixer shot noise. This is especially important when using high gain mixers where the receiver noise is dominated by the mixer noise. The use of series arrays of junctions should provide improved dynamic range due to their increased saturation power limit. At even higher frequencies (f > 500 GHz), the ultimate limits of SIS mixers with respect to gain and noise are just beginning to be explored [6].

Recent work on broad-band RF coupling [4,5,7] demonstrates that good mixer performance can be achieved in conjunction with a large instantaneous signal bandwidth. This large instantaneous bandwidth requires that the junction with its intrinsic capacitance see approximately the same impedance in the image and signal frequency bands. Previous experiments, with a technically useful IF of 1.5 GHz [2], achieved a gain of G ~ 1 with narrow-band coupling. However, computer simulations and measurements with a low (25 MHz) IF demonstrate that gains G >> 1 (rather than G ~ 1) can be achieved with broad-band RF coupling.

With these considerations in mind, we have produced high quality Ta/PbBi tunnel junctions and six junction series arrays. The RF filter geometry shown in Fig. 1 was designed to provide a broad-band RF match to the mixer at 85-110 GHz [7,8]. These junctions have nearly ideal I-V characteristics and a small area (~1 μm^2 for the single junctions and ~6 μm^2 for each junction of the six junction array) which provides an $\omega R_N C$ product of ~ 5 at the signal frequency [9]. Values of $\omega R_N C$ in this range are believed [1,4] to be optimal in suppressing deleterious harmonic frequency effects while still providing a sufficiently broad-band (low-Q) tuned circuit at the signal frequency. The excellent tunneling characteristics of the junctions described in this paper and Ref. [2] are largely due to the high quality native oxide (Ta_2O_5) tunnel barriers [10] that can be grown on Ta base electrodes by O_2 dc glow discharge oxidation.

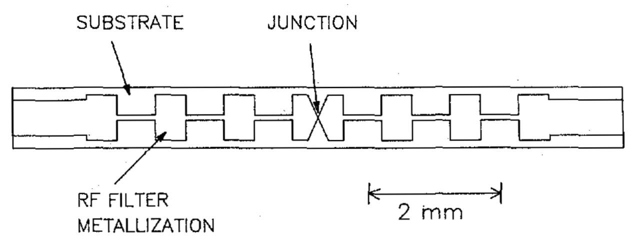

Fig. 1. Filter structure design for the junction electrodes to prevent leakage of RF from the mixer and to provide a broad-band RF match to the mixer.

Materials and Fabrication Considerations

Previous studies of Ta/PbBi SIS mixers were conducted at 36 GHz [2] and used Si substrates. For the present studies at ~100 GHz, we followed the usual procedure [11] of using fused quartz substrates to minimize the dielectric loading of the waveguide. Fused quartz has the lowest dielectric constant (~3.8) of available substrate materials (Si, Sapphire, MgO,...).

Initially, we attempted to fabricate junctions on fused quartz substrates using the same substrate-step technique as was used for the Si substrates [2]. In this technique, a step is formed in the substrate by reactive-ion etching. Two angle depositions are used to form the junction electrodes. Cleaning and oxidation are done prior to deposition of the second film. With quartz substrates, a major difficulty was encountered: the substrates became extremely fragile

Manuscript received September 30, 1986.

0018-9464/87/0300-0688$01.00©1987 IEEE

after reactive-ion etching. This may be due to surface damage caused by the etching, or possibly to the removal of a favorable surface layer on the fused quartz substrates. Very recently, we have been able to circumvent this problem by annealing the etched substrates at 850°C in a N_2 atmosphere for one hour. However, the initial difficulties with substrate handling led us to use an alternative to the substrate-step technique.

The mixers studied in this work used a window geometry [12] to form the junction. In the window method, the base electrode is covered with an insulator, SiO. An opening is made in the insulator to define the junction area. The counterelectrode is then deposited. The use of a relatively thin (3000Å) SiO layer helps to minimize shadowing effects during the directional ion-beam cleaning of the junction window area. With the window method, one may also achieve more efficient cooling of the junction area, due to the large two-dimensional electrode films. With the substrate step, a small length of the film is as narrow as the junction. The film then becomes two-dimensional further from the junction.

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.

Junction Fabrication Sequence

The first step consists of evaporating a 3000-4000 Å film of amorphous Ge onto the fused quartz substrate. (If the quartz substrate is not coated with Ge, we find incomplete cleaning or poor oxidation of the junction area with the ion beam. This is probably due to a charging of the substrate by the ion beam.) During ion beam cleaning and oxidation, the Ge is grounded to the sample holder. This provides a drain for the charge from the ion-beam, which in our case is not neutralized.

Three consecutive lift-off processes are used to pattern the three levels of the junction : the base electrode, the window area, and the counterelectrode (see Fig. 2). A chlorobenzene-soaked photoresist liftoff mask [13] is first used to pattern the Ta base electrode. The Ta film thickness is 3000 Å, deposited over a 100 Å Nb underlayer which is necessary to nucleate the bcc phase of Ta [14]. The deposition of the Ta and Nb films is done by ion-beam sputtering, using a Kaufman-type ion source [15,16]. A second, chlorobenzene-soaked lift-off mask is then used to pattern a 3000Å-thick SiO layer over the Ta. This defines a window in the SiO which will be the junction area. This area is 1 µm^2 for the single junction and 2.5 x 2.5 µm^2 for each junction in the series array of six junctions. The third lift-off mask is a photoresist tri-layer [17].

After the tri-layer lift-off mask is patterned, the junction area is ion-beam cleaned, first with a mixed beam (50% Xe, 50% O_2) at a beam voltage of 200 V, and then with a pure Xe beam at 160 V [18]. The total chamber pressure during cleaning is ~ 1-2 x 10^{-4} Torr. This cleaning sputters away the Ta oxide and contamination due to air exposure. We found it necessary to include oxygen in the ion-beam cleaning step; this may help to efficiently remove photoresist residue. After ion beam cleaning, the exposed Ta is oxidized by a pure O_2 dc glow discharge for 5-20 seconds at a pressure of ~ 120 mTorr. The $Pb_{0.9}Bi_{0.1}$ counterelectrode is then evaporated from an alloy source at ~50 Å/sec. The final step is the lift-off of the counterelectrode. The completed junctions are then tested at 1.3 K and stored in liquid nitrogen.

Before the microwave measurements can be carried out, individual junctions are cut from the wafer with a dicing saw using a 37 µm thick resonoid blade [19]. The quartz substrate size is 0.925 mm ± 1% wide and 12.7 mm ± 3% long. The substrate is only 0.15 mm thick so that care is required during cutting to avoid breakage. After cutting, the normal state resistance of the junctions typically increases by 5-30%. For most of the junctions the cutting procedure does not significantly change the I-V characteristics.

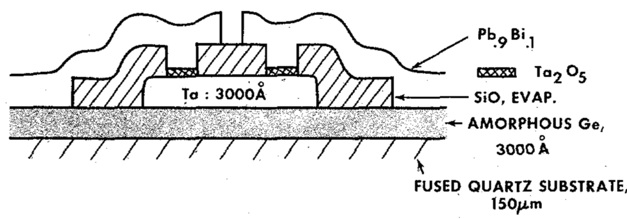

Fig. 2. Cross-section showing two junctions in series. In the case of a six-junction array, this pattern is repeated three times. In the case of a single junction, one of the junctions has a much larger area, so that the current flowing through it is a supercurrent not causing any dissipation.

Junction Characteristics

The Ta/Ta oxide/$Pb_{0.9}Bi_{0.1}$ tunnel junction I-V curves were measured at 1.3K using a four terminal configuration. The current density of 2x10^3 A/cm^2 was chosen to meet the requirements of 85-110 GHz mixers with an $\omega R_N C$ product of 3 to 10 with R_N ~ 50-100 Ω. The current densities studied ranged from 10^3 to 10^4 A/cm^2. Most I-V curves displayed a sharp current rise at the sum-gap voltage and low leakage currents below the sum-gap voltage as shown in Fig. 3a and 3b for a single junction and a six junction array. When the current density approached about 1x10^4 A/cm^2 as shown in Fig. 3c, heating effects due to large amounts of quasiparticle injection were observed in the I-V curve. The larger current density junctions also had increased sub-gap leakage currents. The appearance of increased leakage current at high current densities approaching J_c>10^4 A/cm^2 is consistent with the general trends observed by Raider [20] for many different junction technologies.

The junctions were oxidized in a dc glow discharge of pure O_2 with the oxidation time adjusted to obtain the desired junction resistance as in Ref. [2]. The dependence of the normal state resistance of the junction on oxidation time is shown in Fig. 4 and was reproducible from run to run within a factor of two. An oxidation of 8-10 seconds produced junctions with R_N ~ 30 - 120 Ω as required for the SIS mixer experiments.

Microwave Measurements

In order to obtain optimum RF coupling to the mixer over a broad tunable bandwidth, an RF matching structure on the substrate was designed based on scaled model measurements [7,8]. In this design, the RF filter reactance on the substrate is used as a fixed RF matching element while a noncontacting backshort provides a single adjustable tuning element. This design should allow junctions with capacitances of 30-300 fF and RF resistances of 10-100 Ω to be matched.

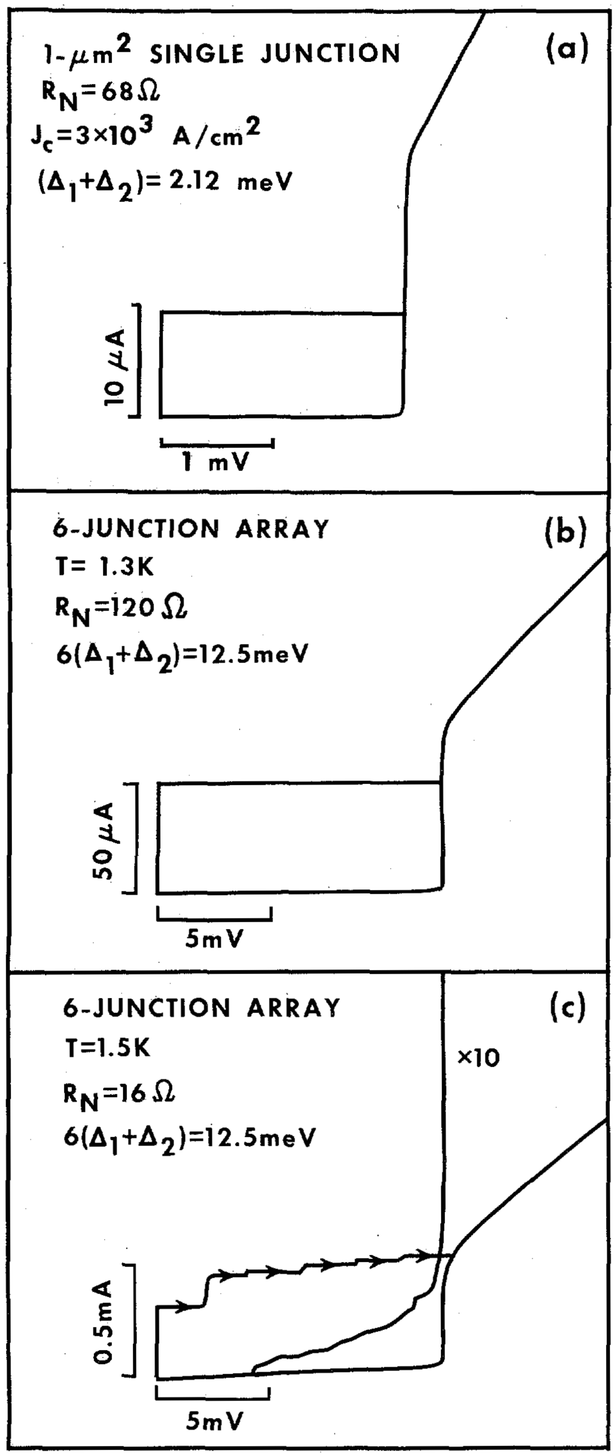

Fig. 3. (a) I-V characteristic of a single junction at 1.4 K. (b) I-V characteristic of a six-junction array (c) Non-ideal I-V characteristic of a six-junction array for current density ~1×10^{4} A/cm^2.

The junction substrate with the RF filter structure is placed across the waveguide in a small channel so that the portions of the substrate outside of the waveguide form a suspended stripline circuit and provide an output for the IF signal. A choice of two transformers between the mixer block and the IF amplifier was available to allow efficient coupling to mixer output impedances of either 50 or 700 Ω. The rest of the

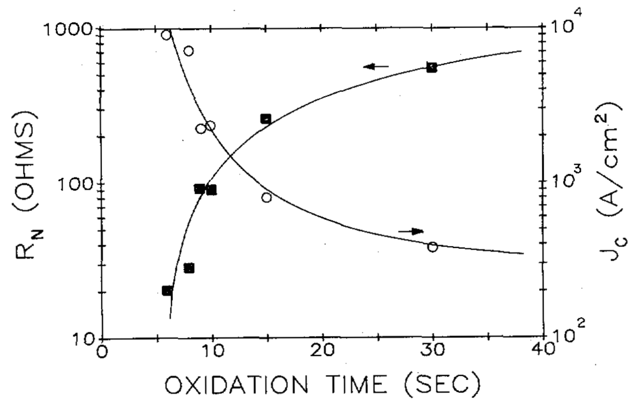

Fig. 4. Normal state resistance R_N and current density (at 13 mV) as a function of glow discharge oxidation times for the six-junction arrays.

receiver used for these measurements is a 100 GHz version of the successful 36 GHz test apparatus that has been described previously [3]. It makes use of cryogenic hot-cold loads at both the IF and RF to make accurate measurements of mixer gain and noise. A coaxial switch is used to compare the output of the IF matching circuit with the output of a 50 Ω IF hot-cold load. The IF mismatch is evaluated using a bidirectional coupler. A cryogenic isolator between the IF transformer and the cooled 1.5 GHz GaAs IF amplifier is used to make the amplifier insensitive to impedance variations in the mixer output.

Before accurate gain and noise measurements were made, each mixer was optimized for the maximum coupled gain at the upper sideband using a coherent signal injected in the LO-waveguide and cross-guide coupler. The double sideband (DSB) receiver noise temperature, mixer gain and noise temperature were then measured using the hot-cold loads [3]. The main results are summarized in Table I. The DSB noise temperatures in Table I should be multiplied by a factor of ~ 2 to compare with single sideband (SSB) measurements such as those in Ref. [2]. Gain was always largest for the lowest frequencies (~ 85 GHz).

TABLE I - Summary of mixer results for single junctions and series arrays of six junctions. R_N is the normal state resistance, R_D is the dynamic resistance at the dc bias voltage, G_A is the available gain, T_M is the mixer noise temperature and N is the number of junctions (N=6 for the array).

Junction R_N(Ω)	Dynamic R_D(Ω)	G_A(DSB) (dB)	T_M(DSB) (K)	Sideband Ratio (dB)	N
50	170	-13.8	117	2.5	1
350	1000	-16.7	196	...	1
77	150	-13.6	69	-0.23	1
31	50	-7.6	72	-1.82	6
19	170	-6.9	21-28	2.85	6

The mixing performance listed in Table I is not outstanding even though the dc I-V characteristics are excellent. Recent measurements in the same apparatus with Pb-alloy junctions from NBS, Boulder showed excellent RF coupling, with large gain and low noise [7]. This demonstrates that the measurement apparatus is not the cause of the poor performance we observe. The most probable cause is a significant discrepancy between the actual dimensions of the RF choke structure and the intended design shown in Fig. 1. Two less likely explanations are: 1. losses or impedance mismatches caused by the evaporated Ge film discussed earlier or 2. an excess capacitance which exceeds the usual value of 150 fF/μm^2 calculated for these junctions [9]. Computer calculations used to fit the pumped I-V curves indicate the presence of an excess parallel inductance. This excess inductance is consistent with a separate set of calculations using an equivalent circuit model of the RF choke structure and the actual (non-ideal) choke dimensions. We anticipate that excellent mixer performance can be achieved with these junctions and plan further work.

ACKNOWLEDGEMENTS

We would like to thank J.Brackemeyre of Thermocarbon Co. for many useful discussions and for dicing the quartz substrates, M. Hatzakis and F. Lloyd for useful discussions, the CSS Materials Laboratory of IBM Research for loan of the ion source, A. Worsham for help with junction fabrication, and Xie-Wen Wang for the annealing studies. This research was supported by NSF grants ECS-8305000 and ECS-8604350, AFOSR 85-0230, and ONR N00014-80-C-0855 and N00014-85-C-0233. Partial support for one of us (G.-J. Cui) was provided by the US-China Basic Research program, sponsored by the American Physical Society, and by Yale University.

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