Tuning Y–Ba–Cu–O Focused Helium Ion Beam Josephson Junctions for Use as THz Mixers

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***Abstract*—We present Josephson junctions fabricated from high transition temperature superconductor $YBa_2Cu_3O_7$ coupled to spiral THz antennas. The fabrication process involves creating a Josephson junction at the center of a superconducting bridge embedded into a THz spiral antenna using irradiation from a focused helium ion beam. For low doses of helium irradiation, the junctions have metallic barriers and operate at temperatures as high as 67 K. For higher doses of irradiation, insulator barriers are created. These devices have higher resistance but require cooling to lower temperatures (∼10 K) due to smaller critical currents. Through optimization of the dose and by trimming the width of the junctions, we have created high resistance devices to improve the impedance match to a spiral antenna. Under 90-GHz radiation, we observe up to 17 Shapiro steps in the *I–V* curve out to approximately 3 mV at a temperature of 10 K.**

***Index Terms*—Heterodyne detector, Josephson junction, mixer, THz, YBCO.**

I. Introduction

HIGH resolution spectroscopy in the THz region of the electromagnetic spectrum is a useful tool for both astrophysics and planetary science applications. For example, it can enable a remote sensing measurement of the deuterium/hydrogen (D/H) ratio in both the interstellar medium and planetary targets [1]. Heterodyne detection or mixing of the source signal with a local oscillator (LO) in a nonlinear device is the only method capable to achieve the necessary spectral resolution to resolve the fine structure of these lines. The output of a mixer is the difference between the LO and that of the source which is defined as the intermediate frequency (IF). The figures of merit for mixers include: sensitivity, usually measured in noise temperature (NT), the IF bandwidth, and the LO power needed to optimally pump the mixer.

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Superconductor-Insulator-Superconductor (SIS) mixers, Hot Electron Bolometers (HEB), and Schottky diodes (SD) are currently the state-of-the-art (SOA) for THz mixers. SIS mixers operate at the quantum limit (QL) up to approximately 700 GHz but losses in the ground plane superconductor cause a reduction in sensitivity above 1 THz [2]. In contrast, HEB detectors can operate at higher frequencies, but typically have NT about ten times the QL [3]. Although, it has been shown that by assuming zero optical loss and zero IF amplifier NT an HEB mixer can operate at two times the QL at 5 THz [4]. SOA NbN HEBs have an IF bandwidth around 4 GHz [3] while more recently developed MgB_2 HEBs offer bandwidths in the 7–11 GHz range but have not yet achieved SOA sensitivity [5], [6]. SD mixers have much less sensitivity but can operate at temperatures ranging from 20 K all the way to room temperature [7], making them easier to develop for space instruments. The major drawback to SD mixers is the large LO power requirement, on the order of ≥0.5 mW, which limits receivers to single pixel elements and restricts the upper frequency limit. Combinations of these technologies are currently used to cover the THz spectral range which requires additional space and power. Therefore, it would be desirable to have a single mixer technology to span the full range.

Josephson junction (JJ) based radiation mixers have been pursued since the 1970's (see [8] and references therein for the review of the early development phase). Nb junctions were used in the past to show that NT should be in the range of 6-20 times the physical temperature of the mixer. A double-side (DSB) NT of about 30 K, close to the theoretical prediction, has been achieved in Nb based JJ mixers below 100 GHz. However unfortunately, the NT quickly increases to 300 K as frequency increases to 500 GHz. This is likely from the presence of the intrinsic noise from Josephson oscillations [9] and the large impedance mismatch due to the low voltage state resistance (R_N) junctions.

Alternative materials and new junction fabrication techniques could hold the key to the realization of low noise Josephson mixing at higher frequencies where SIS mixers cannot operate because they are physically limited by the superconducting energy gap Δ. The maximum frequency of operation is proportional to the superconducting energy gap given by the relation $f_{max} \propto K_J \cdot \Delta$, where $K_J = 483.6$ GHz/mV. In addition, the energy gap of a superconductor is proportional to the critical temperature T_C. Therefore, mixers from higher T_C materials are desirable.

Recently, Josephson mixing was demonstrated at THz frequencies up to 1.9 THz [10] in MgB_2 devices by utilizing a planar

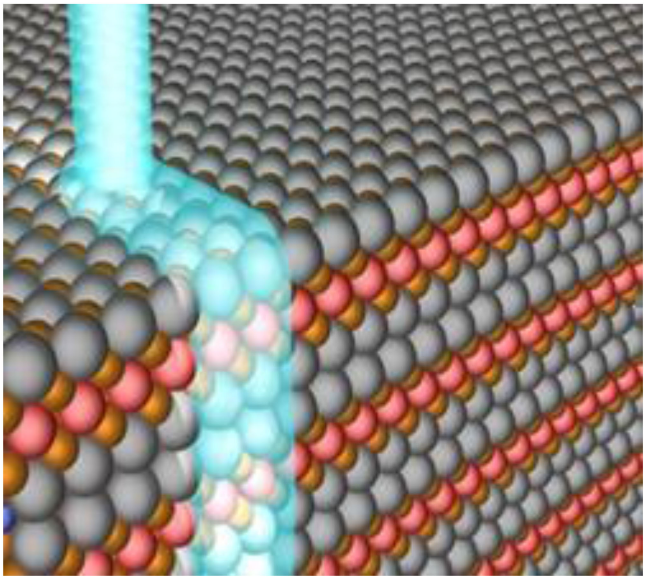

Fig. 1. Illustration of a focused helium ion beam implanted into the YBCO crystal, resulting in the creation of a Josephson junction.

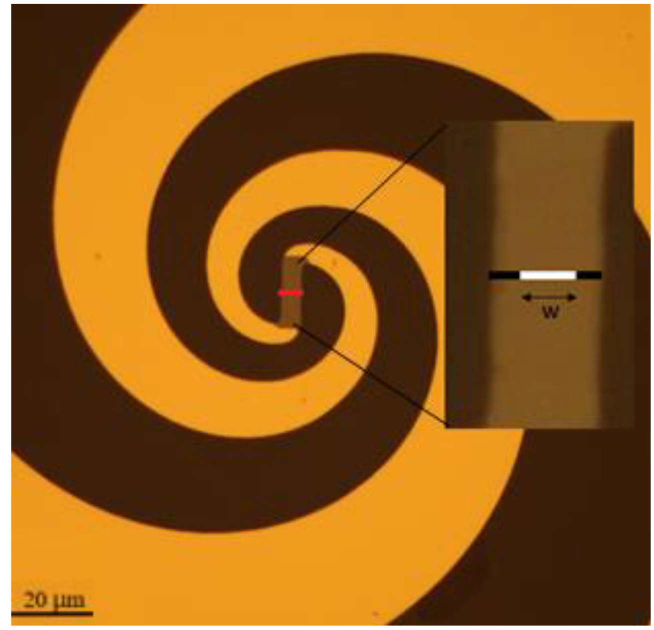

Fig. 2. YBCO mixer after fabrication. Spiral covered with gold and the bridge at the center has the gold removed which exposes the YBCO. The junction, depicted as a horizontal line, is placed across the center of the uncovered electrode bridge of YBCO. An inset depicts the zoomed-in center of the bridge where the width of the junction is shown as a horizontal white line.

junction geometry coupled into a spiral THz antenna. This successful demonstration of mixing in planar junctions motivates mixers fabricated with high transition temperature superconductors (HTS).

HTS offers the prospects of higher frequency due to their much larger energy gap. Recent work in $Bi_2Sr_2CaCu_20$ (Bi2212) devices demonstrated THz emission up to 11 THz [11]. Unfortunately, Bi2212 devices are very difficult to process and are typically mechanically cleaved. The HTS $YBa_2Cu_3O_7$ (YBCO) is much easier to process and typical gap energies are reported to fall between 10 and 40 meV [12]–[17]. This corresponds to a theoretical frequency limit of 4.8 THz to 19.3 THz.

Recently, several YBCO mixers have been demonstrated [18]–[21]. A mixer utilizing step-edge JJs operated at 0.6 THz with a NT of 1000 K (34 times the QL) operating at 20 K [22]. This shows the great potential of YBCO as a THz mixer. However, even through exhaustive impedance engineering of the THz antenna, coupling efficiency of the low impedance junction is reported to be just 15% [20]. Therefore, further improvements can be made to the noise performance through better impedance matching of the components. The development of the two-junction tuning circuit for SIS mixers was the breakthrough that led to the quantum-limited devices in that technology [23]. If a similar advance can be made for Josephson junctions it may bring JJ mixing to fruition.

High R_N YBCO nano-JJs are a possible solution [12], [24]–[29]. New advances in focused helium ion beam (FHIB) nanopatterned YBCO junctions [12] could yield the needed increase in performance. FHIB YBCO JJs can achieve very high resistance that could greatly benefit impedance matching [28]. The junctions are directly written using a FHIB with a diameter of just 0.3 nm. In this method, the FHIB modifies the material by suppressing superconductivity through disorder of the crystal lattice. This interaction disrupts the superconductivity at the local nanometer scale and allows for the formation of in-plane JJ that are approximately only 2 nm long in the direction of the current [12] (Fig. 1).

At low doses, the irradiated material behaves as a normal metal and forms superconductor-normal metal- superconductor Josephson junctions (SNSJJ). Whereas at higher doses the material goes through a metal-insulator-transition [30] and superconductor-insulator-superconductor Josephson junctions (SISJJ) are created. These SISJJ are markedly different from the SIS tunnel junctions used in conventional mixing. The nature of the insulator in a SISJJ is semiconducting and there are multiple transport mechanisms for conduction, eg. Mott variable range hopping, Josephson tunneling, and quasi particle tunneling. This is in contrast to SIS junctions which typically only exhibit quasiparticle tunneling.

In this work, we investigate utilization of the FHIB approach for tuning the junction impedance through optimization of the irradiation dose and the width of the junction (dimension perpendicular to the flow of current). Optimally the junction R_N should have an impedance in the range of 50–75 Ω because the impedance of a spiral antenna is known to be about 75 Ω [31] and typical IF circuits consist of amplifiers with 50 Ω impedance. Our aim is to show that YBCO junctions can be tuned to match the necessary THz and IF circuits because impedance mismatch has been a key setback for JJ mixers [32].

II. Design and Fabrication

The design of our test structure for this work is a spiral atenna with a JJ coupled into the central bridge that is 6-μm wide (Fig. 2). To fabricate these devices, we began with 35-nm thick

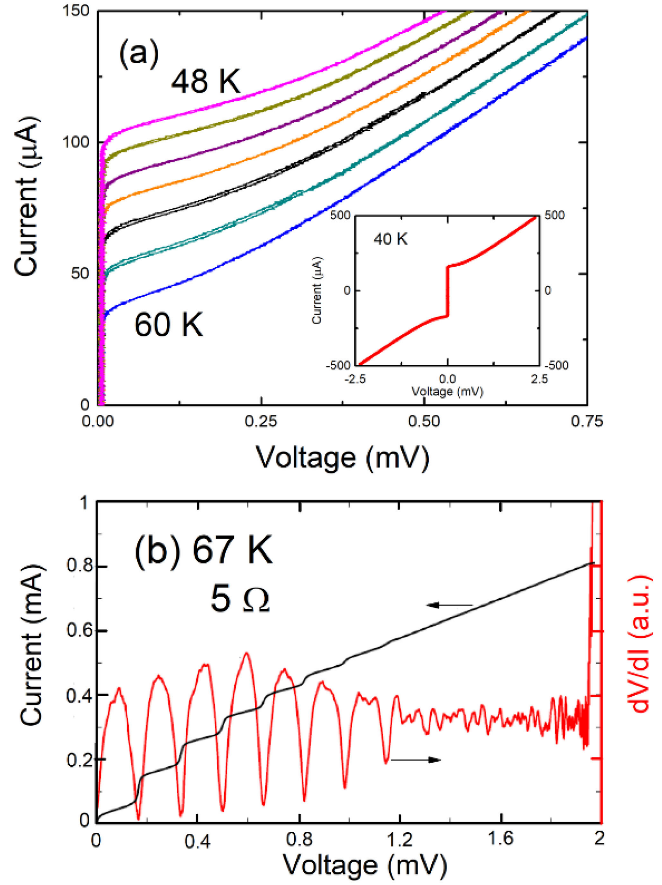

Fig. 3. (a) *I-V* curve of the YBCO 1-μm-wide junction without RF irradiation taken from 48 K to 60 K in 2 K increments. An inset of the 40 K data is shown with excess current. (b) Differentiated plot of the irradiated 90 GHz *I-V* data corresponding to the 1-μm-wide junction, superimposed with the irradiated *I-V* curve taken at 67 K.

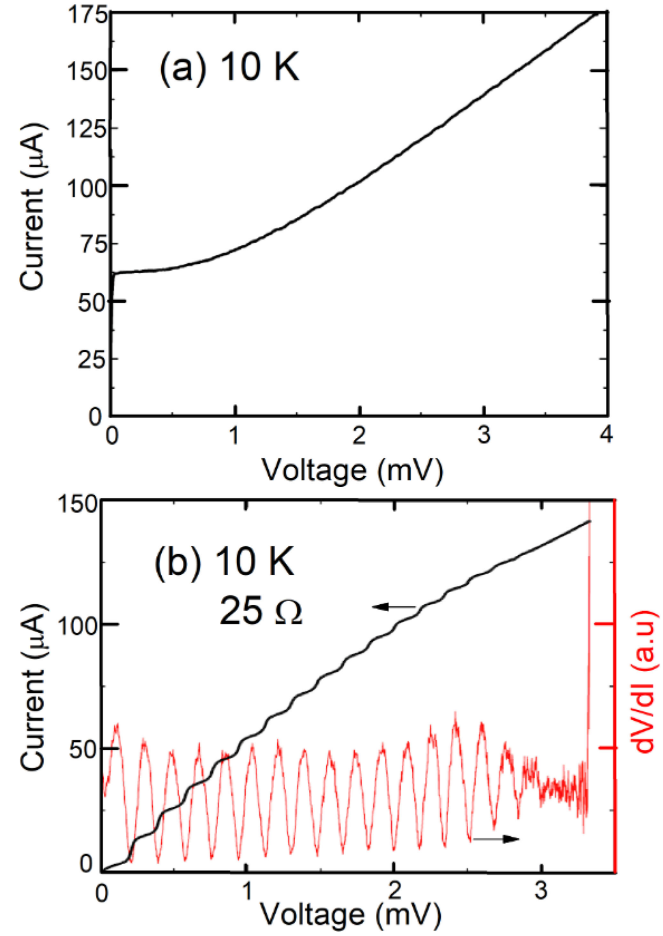

Fig. 4. (a) *I-V* curve of the YBCO 800-nm-wide junction without RF irradiation taken at 10 K. (b) Differentiated plot of the irradiated 90 GHz *I-V* data corresponding to the 800-nm-wide junction with a dose of 1.0×10^{17} He^+/cm^2, superimposed with the irradiated *I-V* curve taken at 10 K.

YBCO thin films grown by reactive coevaporation on r-plane sapphire by Ceraco GmbH. Afterwards, a thermally evaporated 200-nm thick layer of gold was deposited in-situ for electrical contacts. The films were then diced into 5 mm $\times$ 5 mm chips. Large features consisting of a THz spiral antenna and contact structures were patterned into both the gold and YBCO layers using photolithography and argon ion milling. A subsequent lithography step followed by a KI-I gold etch was used to uncover the YBCO bridge at the center, for irradiation of the junction. The samples were then loaded into a Zeiss Orion Plus helium ion microscope. The Josephson barrier was created by scanning the 32 kV FHIB across the center bridge.

Common photolithography methods restrict the width of the junction to its smallest feature size to be of the order of 2 μm. However, the width of the junction can be aggressively scaled down by utilizing the FHIB [28]. The edges of the bridge are irradiated with high doses such that the superconducting material becomes insulating, leaving only a narrow superconducting path where the junction is created. This final trimming step was used to tune R_N for better impedance matching to the THz spiral antenna.

In total, five spirals were created on two different chips. The first chip, M1, had a single device written with a dose of 1.2×10^{17} ions/cm^2 and width trimmed with the FHIB to 1 μm. The second chip, M2, had 4 devices with junctions trimmed to widths of 400 and 800 nm. In addition, on M2, the FHIB irradiation dose was varied from 1.0×10^{17} ions/cm^2 to 1.4×10^{17} ions/cm^2. We calculate the dosage from the exposure time and ion beam current measured by the in-column faraday cup. We acknowledge that this is an imprecise measurement because we see a variation in the dosage calculated in this manner after reforming the ion source. As a result, it is difficult to make accurate comparisons between junction properties and doses between different process runs.

III. Results and Discussion

Current voltage characteristics *(I-V)* for several temperatures are shown in Fig. 3a for the device from chip M1. It has a maximum $I_C R_N$ of 800 μV with, R_N of 5 Ω. These devices are of the SNSJJ type and have diffusive normal metal barriers like those seen in masked ion damage proximity effect Josephson junctions [33]–[35]. In proximity devices, critical current, I_C increases, and R_N decreases with decreasing temperature. At very low temperature Fig. 3 (inset) an excess current appears at

TABLE I
JOSEPHSON JUNCTION PARAMETERS

Dose (He+/cm^2)	Width (nm)	R (Ω)	$I_C R_N$ (μV)
1.2×10^{17}	1000	5	800 (40 K)
1.0×10^{17}	800	25	1500 (10 K)
1.2×10^{17}	800	30	560 (20 K)
1.4×10^{17}	800	55	165 (15 K)
1.2×10^{17}	400	140	105 (8 K)

Junction parameters used for each of the devices and their resulting R and $I_C R_N$ taken at different temperatures.

zero-voltage. This excess current is non-Josephson arising from Andreev reflections [36] and does not modulate in magnetic field or obey the AC Josephson relation.

The AC Josephson properties of the M1 device was tested using a 90 GHz Gunn oscillator. Radiation was emitted directly into the helium Dewar without any other optics present. The pumped *I-V* characteristics and differential resistance for a SNSJJ are shown in Fig. 3b. Shapiro steps [37] were observed at voltages described by the AC Josephson relation [38], V = n hν/2e, where n is an integer corresponding to the step order, ν is the drive frequency, h is planks constant, and e is the charge of an electron. Steps corresponding to n = 7 were observed extending out to 1.2 mV corresponding to 90 GHz.

For chip M2, the irradiation dosage was increased relative to that of M1 to create devices with insulating Josephson tunnel barriers. These devices had R_N that increased with decreasing temperature and no measurable non-Josephson excess current. *I-V* is shown at 10 K for an 800 nm wide junction in Fig. 4a. R_N is approximately 25 Ω with an $I_C R_N$ of 1.5 mV.

A consequence of decreasing the cross-sectional area of these junctions to increase R_N, is a smaller I_C and smaller Josephson binding energy, $E_J = I_C\ \hbar/e$. When the thermal energy $k_B T$ is of the order of E_J, fluctuations dominate that disrupt the zero-voltage super current [39]. As a result, the smaller SISJJ devices must be cooled to lower temperatures to reduce thermal fluctuations.

Fig. 4b shows the AC Josephson properties of the same SISJJ from Fig. 4a measured in the same experimental setup as described for Fig. 3b. Shapiro steps corresponding to n = 17 are observed in the pumped *I-V* out to 3 mV. This implies a maximum mixing frequency of 1.53 THz.

Table I summarizes the properties of all the devices created for this study. M1 is shown in the first row and devices from M2 are shown in rows 2-5. As expected, we observe a trend of higher R_N with higher dose and smaller trimmed dimension. The highest R_N of 140 Ω obtained was in the smallest junction with 400 nm width. Unfortunately, I_C was much too small for RF measurements. The table also illustrates the lower operating temperatures of the smaller devices.

The expected NT can be estimated using previously reported results. The YBCO step edge junctions had a NT of 1000 K at 0.6 THz operating at 20 K with only 15% coupling efficiency to the antenna [22]. Similarly, MgB_2 JJ mixers have been reported with NT around 630 K at 0.6 THz with coupling efficiency estimated to be less than 35% when both the antenna efficiency and IF circuit are accounted for [10]. Optimizing the coupling efficiency through proper impedance matching should yield a NT around 200 K at 600 GHz. The work with MgB_2 JJ mixers showed the NT to scale linearly with frequency and have little dependence on temperature until above Tc/2. Theoretical limits to JJ mixers have typically been between 6-20 times the physical temperature of the mixer [9]. In addition, the optimal LO power can be determined by using the YBCO step edge junctions as a reference. The pumping power used was −34 dB (400 nW) with 15% coupling efficiency [22], therefore we can expect approximately 70 nW of LO power for optimal pumping.

IV. CONCLUSION

The results obtained are very promising for future work with THz mixing utilizing the FHIB fabrication technique to create the JJs. We presented the ability to effectively control R_N needed for optimal coupling to the spiral antenna and IF circuit. This was done by tuning the He ions dosage used to write the barrier and utilizing a FHIB to damage the superconductivity at the edges of the center bridge, effectively trimming the width of the junction to be created. The increase in R_N must be balanced with the accompanied decrease in I_C or the operating temperature will be suppressed by thermal fluctuations. Further study is needed to determine optimal $I_C R_N$ values. This work is an encouraging step forward and with further investigation, FHIB YBCO JJs could potentially provide a single mixer technology that can cover a large spectral range with reasonable sensitivity, small LO power, and eventually operation at elevated temperatures where simple and less expensive cryocooling is available.

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