Fabrication of High-T_c Hot-Electron Bolometric Mixers for Terahertz Applications

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Abstract - Superconducting hot-electron **bolometers (HEB) represent a** promising **candidate** for **heterodyne** mixing at **frequencies exceeding 1THz.** Nb **HEB** mixers offer performance competitive with tunnel junctions without the frequency limit imposed **by** the superconducting energy gap. **Although** the performance of **$YBa_2Cu_2O_{7-\delta}$ HEB mixers** is not **projected** to **be** superior **to** that of Nb **devices,** which operate at **low temperatures,** they **introduce** the possibility of sensitive, low power **heterodyne detectors operating** at **temperatures approaching 90** K for applications requiring portability and closed-cycle **refrigeration. We** report on the fabrication **and** characterization, both **DC** and **RF,** of **high-T_c** mixers **based** on ultra-thin (<20 nm) **$YBa_2Cu_2O_{7-\delta}$** films patterned to **micrometer dimensions and** incorporated into 2.5 **THz** planar mixer circuits.

1. IN'I'ROIIUCI'1ON

1 leterodyne receivers based on superconductor-insulator-superconductor (S1S) junctions arc used in submillimeter astronomical and atmospheric studies at frequencies up to 1 THz. At higher frequencies, Schottky diode mixers or direct detection techniques arc generally used. Superconducting hot-electron bolometers (HEB), consisting of a thin film intimately coupled to a cooled substrate, have been proposed for usc in mixing applications in the terahertz (THz) range [1,2]. Superconducting HEB mixers require orders of magnitude Jcss local oscillator (1.0) power than semiconductor mixers, allowing for solid state LOs rather than the large lasers required of Schottky diode mixers. Nb mixers operating at 2-4 K have shown excellent performance at 530GHz [3], and recently demonstrated low noise at 1.2THz [4] and 2.S1'1 lz [5]. While some initial experiments on device physics and heterodyne performance [6,7] have been carrier out on high-temperature superconductor (1 1'1'S) bolometers, no optimized devices have been reported to date.

The lower LO power requirements of superconducting HEB mixers makes them particularly attractive for remote sensing systems with constraints on the availability of power or weight, such as on balloon or sJJacc-based platforms. HEB mixers made from HTS operating in the range of 60-85 K arc particularly attractive for space based applications since they can be cooled with existing space qualified closed-cycle refrigerators.

II. REQUIREMENTS

The operating principles of a 2,5 T11~. WI'S HEB mixer have been described in detail elsewhere [8]. HEB mixer operation depends 011 breaking heating the electrons with incoming radiation, resulting in a nonequilibrium energy distribution. Cooling, occurs via electron-phonon interactions whereby the hot electrons give their energy to phonons which escape into the substrate. Alternatively, cooling can occur by diffusion of the hot electrons out of the device and into the normal-metal electrical contacts [2]. Due to the short electron mean-free-palhs in 11'1'S materials, the electron-phonon cooling mechanism dominates in HTS HEB mixers. In space applications, sysicm-level power restrictions constrain mixers to operate at low 1.0 power levels, with major implications for device size.

As a result of these considerations, the major design requirements [8] for} 1'1'S HEB's arc described below. The first four requirements pertain to the substrate. While a large number of substrates can individually meet these conditions, it is important for optimal mixer performance to meet all simultaneously.

(1) The substrate must have a high thermal conductivity and be compatible with epitaxial $YBa_2Cu_2O_{7-\delta}$ (YBCO) growth. This requirement can be met by a number of substrates compatible with high-quality YBCO films. MgO, $LaAlO_3$, Al_2O_3 and $YAlO_3$ have thermal conductivity's at 90 K of 3.4, 0.35, 6.4 and 0.2-0.4 W K-' cm^{-1}, respectively. For comparison, yttrium stabilized zirconia (YSZ) has a thermal conductivity at 90 K of only 0.015 W $K^{-1}cm^{-1}$ [8].

(2) The Kapitza boundary resistance (R_b) between the HTS film and the substrate should be as small as possible. This second requirement can be met by several of the aforementioned substrates. The values of R_b, inferred from measurements of the phonon escape time, between YBCO and MgO, $LaAlO_3$ and Al_2O_3 at 90 K arc 5, 10, and 11 x 10^{-4} K cm^2 W-' respectively [9-13].

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(3) Substr'ales need to have a small loss-tangent al both 2.5 THz and al the 1 F frequency. The fourth requirement can also be met by a number of the aforementioned substrates. MgO, $LaAlO_3$, Al_2O_3 and $YAlO_3$ have loss tangents of 7, 5, 8, and 10, x 10^{-6}, respectively at 90 K and ~10 GHz. For comparison, yttrium stabilized zirconia (YSZ) has a loss tangent of 400x 10^{-4} al 90 K at -10 GHz [8].

(4) Subs.[rates need to have a convenient dielectric constant at both 2.5THz and at the IF frequency. This fifth requirement can also be met by a number of HTS compatible substrate materials. The dielectric constants of MgO, Y_2O_3, Si-on-Al_2O_3 and $YAlO_3$, measured in a Fourier transform spect rometer at JPL, arc 10.0, 12.9, 9.9 and 21.2, respectively, at 77 K and 2.5 THz.

(5) The HTS mixer film volume must be small enough to allow device operation at microwatt LO power levels. This third requirement dictates that the mixer be constructed from ultra-thin (10-20 nm) films patterned to micron or submicron dimensions [8].

In this work, ~20 nm YBCO thick films on $YAlO_3$ substrates were used to fabricate HEB mixers.

III. GROWTH AND PATTERNING

Growth of the superconductor and gold (Au) contact layers arc performed completely *in situ* without exposure of interfaces to the ambient environment. The devices arc grown on ?.50 μm thick, 1 x1cm^2 (001) $YAlO_3$ substrates polished on both sides. The nominal growth process is: The substrates arc mounted on Haines alloy plates using Ag paint. These arc transferred into tbc HTS deposition system via a load-lock. The substrates arc buffered using a 20 nm $PrBa_2Cu_3O_{7-\delta}$ (PBCO) layer deposited by pulsed laser deposition (PLD) at 790°C, 400 mTorr of O_2, at a fluence of 1.6 J/cm^2 at λ=248nm. Substrate heating is radiative, monitored by a thermocouple that is cross checked by an optical pyrometer prior to film growth. Tbc PBCO layer is followed by a 20 nm YBCO layer deposited at 8 10°C, 200 mTorr of 0_2, and 1.6 J/cm^2. The deposited bilayer is cooled *in situ* al 40°C/minute in a 500-650 Torr O_2 atmosphere from the growth temperature down to room temperature. Then 100 nm of Au is deposited *in situ* by DC magnetron sputtering in a 1mTorr Ar atmosphere (Fig. 1A). Typical transition temperature (T_c) for these trilayers, as determined by AC susceptibility, is 83-86 K with a transition width of less than 2 K.

After the trilayer growth process, the substrate is mechanically removed from tbc Haines alloy plate. Photoresist (AZ5214) is spun onto the blank trilayers at 3000 rpm to a thickness of 1.5 μm and soft-baked at 95 'C for 2 minutes. The sintered Ag paste residue remaining from substrate mounting on tbc Haines plate is scraped off of tbc substrate, followed by swabbing with 10OOA HNO_3 and rinsing in water. The photoresist is then removed with acetone and the devices arc rinsed in 100% ethanol and blow-dried with dry N_2.

The initial patterning of the PBCO/YBCO/Au trilayer into the antenna, RF filter, IF/DC contacts and bolometer microbridge is performed using optical contact lithography. Photoresist (AZ5206) is spun onto the unpatterned trilayers at 5000 rpm 10 a thickness of 0.5 μm and soft-baked at 95°C for 2 minutes. The resist is exposed through a chrome contact mask for approximately 15 seconds at a 350 nm UV flux of 10 mW/cm^2, and then developed for approximately 20 seconds in AZ developer diluted 1:1 with waler. The resist is sof~-baked again at 95°C for 1 minute and ashed for 30 seconds in a 40 mTorr oxygen plasma in a Semi Group 1000TP reactive ion ctcb (RIE) tool at 120 watts, with a DC substrate self-bias of -320 volts. The minimum feature size with good definition for ibis process is 1 μm.

Next, the devices arc placed into the load-lock of the deposition system in which an ion mill is located. The etching process uses normally incident 500 CV Ar^+ ions at 1 mA/cm^2 for 5 minutes (Fig 1B). The pressure is 2. 0x10^{-4} Torr. The substrates arc not cooled, however the temperat urc remains below 100 'C during the etching process (Fig. 1 c).

After milling, the devices arc transferred from tbc load-lock directly into the deposition system where 60 nm of YSZ is deposited at room temperat urc by PLD (Fig. 1D).

The photoresist is then removed by ultrasonically cleaning tbc devices in acetone for 1-2 minutes, The: devices arc rinsed in 100% ethanol and blow dried with dry N_2. This YSZ deposition and lift-off process leaves the side-walls of tbc device coated with a protective layer of YSZ. (Fig,. 1E).

At this point in the process, another layer of photoresist (AZ5206) is spun on the device 10 a thickness of 0.5μm, soft-baked, exposed, and developed using the procedure described above. The mask for this step opens a small window in the resist, exposing the 1 μm-wide bolometer bridge, which is still covered with 100 nm of Au. The device is then placed in the RIE system for the following procedure (Fig IF): (1) Oxygen ashing for S minutes in a 200 mTorr oxygen plasma at 60 watts with approximately -80 self bias. (2) Etching for so minutes in a 200 mTorr 1:10 0_2: CCl_2F_2 plasma at 60 watts with approximately -20 volts self bias. The approximate Au removal rate is 2.5 nm/minute. Wc have found that over etching dots not damage c-axis-oriented YBCO. (3) Oxygen ashed for 2 minutes in a 200 mTorr oxygen plasma at 30 watts with approximately -40 volts self bias. The resulting structure is illustrated in Fig. lG. It should be noted that without the YSZ side-wall coating covering tbc *a-b* plane edges of the YBCO layer, lines as wide as SO μm arc no longer superconducting after tbc Au RIE process, presumably duc to chlorine being driven into the film along the *a-b* planes. With the YSZ side-wall coating, we have successfully used this 3-step Au removal process 0020 nm thick YBCO lines as narrow as 400 nm and maintained T_c above 80 K.

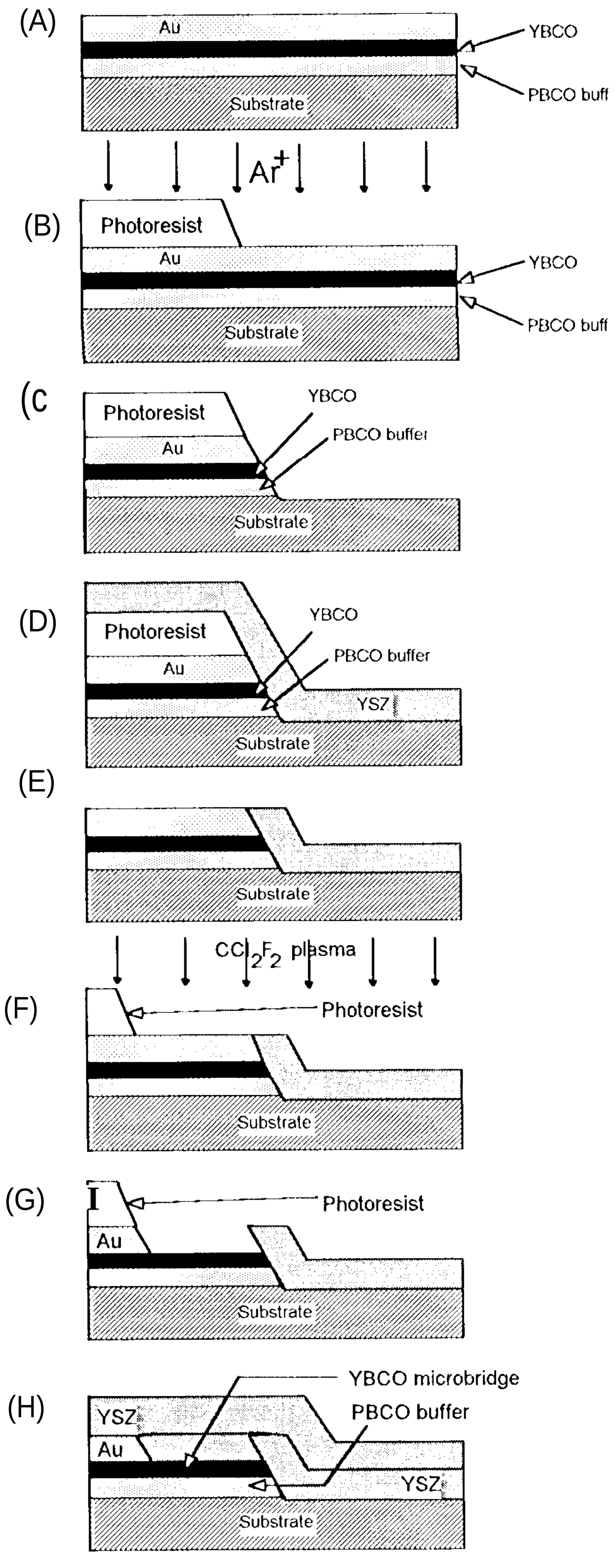


Fig. 1. Cross section of the mixei al various stages of the fabrication piocess. The steps are described in the text.

Next the devices are placed in the PI .D system load-lock, pumped down and immediately transferred into the

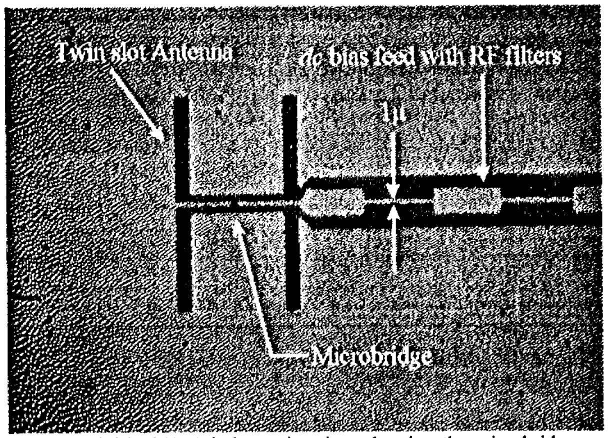


Fig. 2 - Finished HTS bolometric mixer showing the microbridge, twin slot antenna, and RF filter structure for feeding the DC bias in and extracting the intermediate frequency (IF) out.

deposition chamber', where 100 nm of YSZ is deposited by PLD, filling in the area where the Au was just removed. The total t imc from removal from the RIE to pumping down in the load lock is always less than 10 minutes, and typically less than 5 minutes. The photoresist is then removed by ultrasonically cleaning the devices in acetone for 1-2 minutes. The devices arc rinsed in 100% ethanol and blow dried with dry N_2.

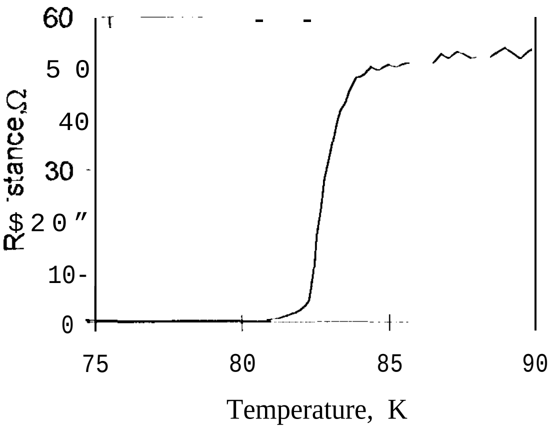
The devices arc next placed back into the deposition system where 100 nm of YSZ is deposited by PLD onto the cnt irc subst rate at room temperat ure (Fig. 11 1).

Photoresist (AZ52 14) is next spun onto the 1 x 1 cm^2 substrates (now containing 19 chips) at 3000 rpm to a thickness of 1.5 μm and sof(-baked at 95 'C for 2 minutes. The substrates arc mounted on a dicing saw and cut into individual 1x1,5 mm^2 HEB chips. The photoresist is then removed with acetone and the devices arc rinsed in 100% ethanol and blow dried with dry N_2. A photograph of a finished device is shown in Fig. 2.

IV. ELECTRICAL TESTS

For DC device tests, individual dic arc mounted in 28-pin Kcocera ceramic chip packages which plug into the bottom of a cryogenic dipping probe. Four wires arc ultrasonically bonded to the YSZ-covered Au contacts. With proper settings, the wire bonds make contact through the nominally 100 nm thick YSZ over-layer. The wire bond connections arc chosen in order to allow 4-terminal device measurements, eliminating resistance contributions from the probe and instrumentation wiring.

Resistance versus temperature measurements arc taken using a computer controlled system. A Keithley 220 DC current source connected to two leads applies ±1μA and the voltage response of the device under test (DUT) is measured for both current polarities using an HP 3457A multimeter. The difference is used to eliminate contributions from ther-



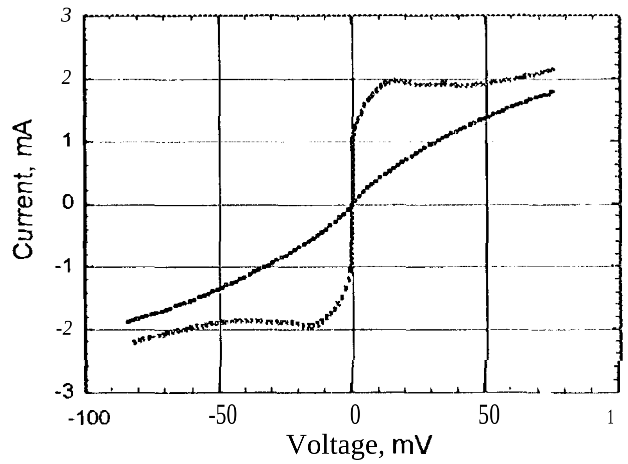


Fig. 3 - Resistance versus temperature, and I-V @ 77 K with and without the application of 2.5 THz local oscillator power, for a 1x1x0.02 μm^3 microbridge HEB device fabricated using the process described above.

really induced voltages in the probe and instrumentation wiring.

After processing, the microbridge T_c determined from the R vs. T data is generally 2-3K lower than the T_c of the initial trilayer film measured by AC susceptibility. The transition widths are also slightly broader. Fig. 3 shows R vs. T for a 1x1x0.02 μm^3 microbridge in the **mixer circuit show in** Fig 2.

The samples are RF tested by mounting in an aluminum block and placed in an optical cryostat. [14] The 2.5 THz LO consists of a methanol far-infrared laser, pumped by a λ=9.6μm CO_2 laser. *I-V* curves at 77 K, with and without applied LO power (estimated to be about a μW), are also shown. With the application of local oscillator power, the critical current of the microbridge at 77 K can be almost entirely suppressed from is initial value of approximately 5X106 A/cm^2.

CONCLUSION

We have designed and fabricated superconducting hot-electron bolometers based on a previously developed model [4]. The devices utilize ultra-thin YBCO ($\leq$20 **run)** films patterned into 1 μm by 1 μm microbridges and passivated with YSZ. These bridges maintain T_c on the order of 80 K and J_c's >1x10^{6}A/cm^2 at 77 K. We have demonstrated that the devices were successfully coupled to a 2.5 THz LO source when operated at 77 K.

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