Fabrication of Terahertz $YBa_2Cu_3O_{7-\delta}$ Hot-Electron Bolometer Mixers

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***Abstract* — Superconducting hot-electron bolometer (HEB) mixers are promising heterodyne detectors for THz frequencies. HEB mixers operating at 4 K or below offer the possibility of near-quantum-limited performance without an upper frequency limit imposed by the superconducting energy gap. High temperature superconductor HEB mixers offer very sensitive, low power heterodyne detectors operating at temperatures approaching 90 K for applications requiring closed-cycle refrigeration. We report on recent progress in fabricating and characterizing high-T_c mixers based on ultra-thin (10-20 nm) $YBa_2Cu_2O_{7-\delta}$ films patterned to submicrometer dimensions (0.1-1 μm) and incorporated into 1-3 THz planar mixer circuits.**

I. INTRODUCTION

Sensitive heterodyne receivers are widely used in radio astronomy and atmospheric science at frequencies from 100 GHz to 3 THz. Nb-based superconductor-insulator-superconductor (SIS) tunnel junction mixers operating at 4 K are the most sensitive devices demonstrated to date, but the Nb energy gap limits their useful operation to frequencies below approximately $4\Delta/h \approx 1.4$ THz. SIS mixers based on larger-gap materials have not achieved the desired levels of performance despite extensive research. At higher frequencies, up to ≈ 3 THz, room-temperature Schottky diode mixers are generally used. Recently, however, hot-electron bolometer (HEB) mixers have been demonstrated to be the most sensitive devices in this frequency range. Low-noise performance at THz frequencies has been demonstrated with NbN [1] and Nb [2,3] HEB mixers. It was recently predicted that quantum-limited performance can be approached using Al HEB devices operating at ≈ 1 K [4].

HEB mixers require orders of magnitude less local oscillator (LO) power than semiconductor ones. In principle, this enables the use of solid state LOs rather than the large laser-based LOs required by Schottky diode mixers. Low LO power makes HEB mixers particularly attractive for remote sensing systems such on balloons or satellites. High temperature superconductor (HTS) HEB mixers operating in the range of 60-85 K, are particularly attractive for space based applications since they can be cooled with existing single-stage space qualified refrigerators. Only basic demonstrations of bolometric mixing have been done with HTS devices to date [5,6]. However, theory predicts [7] that $YBa_2Cu_3O_{7-\delta}$ (YBCO) mixers operating at ambient temperatures around 70 K can outperform Schottly diodes.

We have previously reported the fabrication of 1 μm YBCO HEB mixers [8] and the demonstration of smaller structures with suitable superconducting transitions for mixing. Here we report on an improved fabrication process that has enabled us to fabricate prototype YBCO HEB mixers with lengths as small as 0.1 μm.

II. DEVICE REQUIREMENTS

An HEB mixer consists of a narrow, thin superconducting film in close contact with the substrate. Signal power is coupled to the device via a normal metal antenna. HEB mixers are expected to operate at signal frequencies up to several tens of THz. Operating at an ambient temperature below T_c, the device is biased near the midpoint of the superconducting transition using dc and LO power. The signal mixes with the LO producing temperature and, therefore, resistance changes at an intermediate frequency (IF). The speed of thermal response of the device, limited by its size, coupling to the substrate, and the details of the cooling mechanism, determines the IF bandwidth.

Cooling of the carriers excited by the incident radiation occurs as hot electrons give up their energy, via the electron-phonon interaction, to phonons which escape into the substrate [9]. Alternatively, hot carriers can diffuse from the active region into the normal-metal contacts [10]. Due to the short electron mean-free-paths in HTS materials, the latter cooling mechanism dominates in HTS HEB mixers. It has been proposed that phonon diffusion into the leads can aid the performance of very short HTS HEB devices [7]. The operating principles of THz HTS HEB mixers have been described in detail elsewhere [7].

The major design requirements for an HTS HEB are: (1) The substrate must be compatible with epitaxial YBCO growth. (2) The substrate must have high thermal conductivity. (3) The Kapitza boundary resistance between HTS film and substrate must be small. (4) The substrate must have a small loss-tangent at the signal and IF frequencies. (5) The substrates must have a suitable dielectric constant at both frequencies. (6) The device must be small enough to

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operate at acceptably low LO power levels. (7) It is desirable that the device be short enough that phonon diffusion is the dominant cooling mechanism. (8) The device impedance should be suitable for matching with an appropriate antenna.

We discussed most of these requirements in an earlier publication [8]. They led to pursuing bolometers with deep-submicrometer lengths based on 10-20 nm-thick YBCO films on $YAlO_3$ (YAO) substrates.

III. FILM GROWTH

Our HEB devices are based on trilayers of $PrBa_2Cu_3O_{7-\delta}$ (PBCO), YBCO and Au deposited on 250 μm-thick, 1x1cm^2 (001) YAO substrates polished on both sides.. Film growth was done *in situ* in order to minimize the resistance of the superconductor-normal metal contacts.

Prior to growth, the substrate is mounted on a Haines alloy plate using Ag paint. The plate is transferred into the HTS deposition system via a load-lock. The oxide films are deposited by pulsed laser deposition (PLD) at 825-835°C in a 200 mTorr O_2 ambient at a fluence of 1.6 J/cm^2,with λ=248nm. Substrate heating is radiative, monitored by a thermocouple that is cross checked prior to film growth using optical pyrometry of two heavily-doped Si chips located adjacent to the substrate. The 10 nm-thick PBCO layer is followed immediately by a 10-20 nm thick YBCO layer. This bilayer is cooled to room temperature at 10-40°C/minute in a 500 Torr O_2 atmosphere. Finally, a 30 nm-thick Au film is deposited *in-situ* by DC magnetron sputtering in a 10 mTorr Ar atmosphere at a power level of 2.5 W/cm^2 to complete the trilayer.

Typical transition temperature (T_c) for these trilayers, as determined by AC susceptibility, is 85-88 K with a transition width of less than 2 K.

IV. DEVICE FABRICATION

Patterning of the sample begins by spinning on a bilayer of 500 nm-thick polyimide (OCG 285) and 500 nm-thick PMMA. The polyimide layer is baked at 130 °C for 5 minutes, which is sufficient to render it resistant to acetone. The polyimide/PMMA bilayer is also baked at 130 °C. The PMMA is patterned by electron beam lithography into narrow lines, shown schematically in Fig. 1a, that will later define the length of the bolometers.

The patterned resist acts as a liftoff mask for an evaporated 30-nm thick Cr layer. The Cr is deposited at 0.1 nm/s to minimize stress in the film. The narrow Cr line remaining after liftoff with acetone is used as a mask for reactive ion etching of the polyimide in O_2, as shown in Fig. 1b. Low pressure (15-20 mTorr), high energy (-450 V DC self-bias) conditions are used in order to maximize etch anisotropy. A Kapton tent over the sample is used to minimize the deposition of backsputtered electrode material onto the substrate. The etch rates of polyimide and Au under these conditions are 76±2 and 2.3±0.1 nm, respectively, allowing the polyimide to be etched away without excessive sputtering of the thin underlying Au layer.

The patterned polyimide layer acts as a liftoff mask for a 100-200 nm-thick layer of Au, deposited by evaporation. The thick Au covers the entire PBCO/YBCO/(thin) Au trilayer except for the narrow polyimide-covered strips that will later define the lengths of the HEB devices. The thick Au layer acts as a mask for etching away the thin Au layer in the active device regions (Fig. 1c).

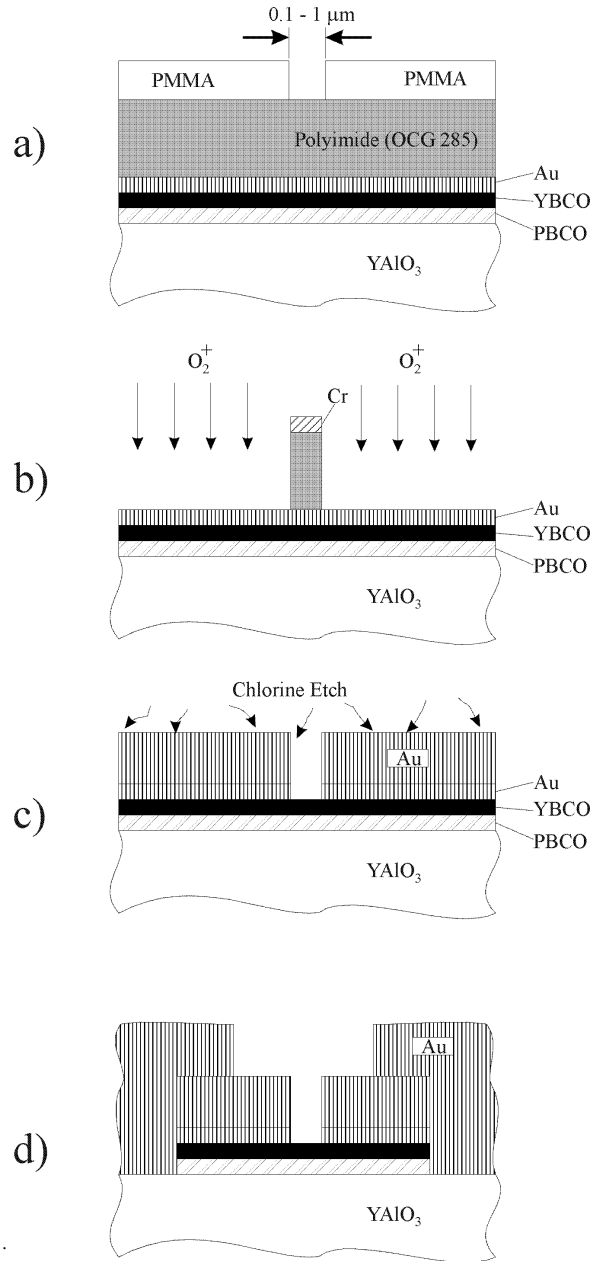

Fig. 1 - Cross section of the mixer at various stages of the fabrication process. The details are described in the text.

The 30 nm-thick Au layer covering the active device area removed by plasma etching with $CCl_2F_2(90\%)/O_2$ (10%), under high pressure (200 mTorr), low energy (-20 V self-bias) conditions to eliminate sputtering. This step is illustrated in Fig. 1c.

Conventional photolithography is used to complete the definition of the mixers. Thin strips defining the width of the mixer (the length was defined in the previous Au etching step) are formed by ion milling completely through the PBCO/YBCO/Au trilayers, using patterned AZ 5206 photoresist as a mask. The damage caused by the electron beam exposure dusing the initial lithographic step is healed by annealing the substrate in flowing oxygen at 450° C for several hours.

The antenna structure is defined using photolithography. The antenna is a 200 nm-thick evaporated film of Au. A nominally 0.5 nm-thick Ti layer is evaporated in-situ prior to the Au deposition to promote adhesion. The completed structure is illustrated in Fig. 1d. After completing device patterning, the entire substrate is coated with an evaporated 50-100 nm-thick SiO film to passivate the devices. Finally, the completed 1 cm wafers are diced into 1.5×2.0 mm^2 chips, each containing a single antenna-coupled HEB mixer, for measurements.

This process has been used to make HEB devices with widths of 1 μm and lengths (in the direction of current flow) of 0.1-1 μm. The process is easily adapted to produce narrower devices, in which case an additional e-beam lithography step is required. In addition to this hybrid e-beam/optical process, we also employed an all-optical process to fabricate devices with minimum linewidths of 1 μm or larger. In this case, the PMMA layer is replaced AZ 5206 photoresist and contact uv lithography is used for patterning. In this case, no special anneals are required in order to recover the original T_c of the YBCO film.

V. DC ELECTRICAL CHARACTERIZATION

For DC characterization, a chip containing either a completed mixer or a set of test devices with no antennas is mounted with Ag paint in a 28-pin Keocera ceramic chip package that plugs onto a cryogenic probe. Ultrasonically bonded Al wires easily make good mechanical and electrical contacts through SiO layer covering the Au pads.

Fig. 2 shows the temperature dependence of the resistance of 10 separate 1×1×0.02 μm^3 HEB test devices on a single test chip without an antenna, illustrating R and T_c and their uniformity for the all-optical process. Fig. 3 shows current-voltage (I-V) characteristics at 80 K for the same 10 devices. I-V characteristics for a typical device at 50-80 K are shown in Fig. 4. Device resistivity just above the superconducting transition is approximately 100 Ω/square. The critical current density of the devices exceeds 10^6 A/cm^2 at 80 K. Both parameters have values similar to those of much thicker (200 nm) YBCO films deposited on $LaAlO_3$ substrates.

In the hybrid e-beam/optical process, when no anneal step during patterning, T_c was reduced below 10 K. Annealing at 450 °C in an atmosphere of flowing O_2, recovered a high transition temperature. Fig. 5 shows the resistive transition of a 0.2×1×0.02 μm^3device after successive three anneal steps, which were applied after completion of the entire device structure. After 1 hour of annealing, the transi-

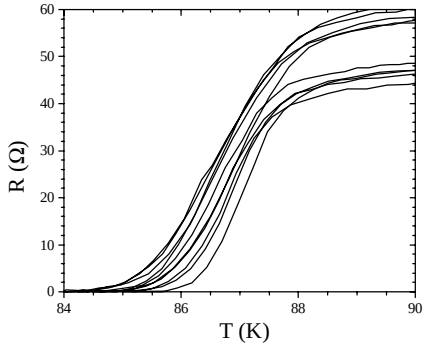

Fig. 2. Resistive transition for 10 individual 1×1×0.02 μm^3 HEB devices on a single chip.

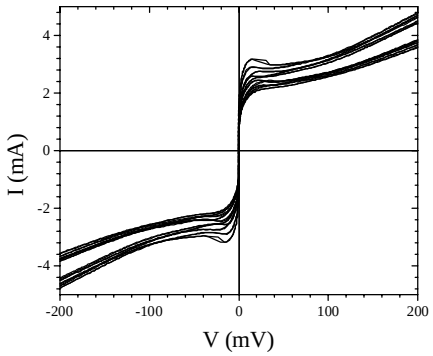

Fig. 3. Current-voltage characteristics at 80 K for the same 1×1×0.02 μm^3 devices as in Fig. 2.

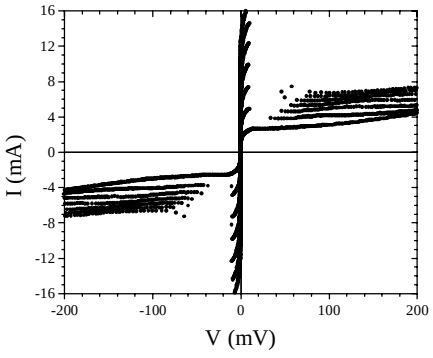

Fig. 4. Current-voltage characteristics at at 50 - 80 K (5 K increments) for a representative 1×1×0.02 μm^3 device from Fig. 2.

tion spanned 58-68 K, after 3 additional hours, 65-80 K and after 10 additional hours, 74-86 K. In earlier work, much shorter anneals were sufficient to recover nearly the original to the greater sensitivity of the resist used in that work; the switch to PMMA was made to improve pattern definition at deep-submicrometer linewidths. More recently, we have improved this process by inserting the anneal step after the devices are defined but before the antennas are added. Results on devices obtained with this process modification will be reported elsewhere.

VI. RF ELECTRICAL CHARACTERIZATION

Characterization of the devices at THz frequencies, including mixing experiments has only recently begun. For RF measurements, the samples mounted in an Al block and placed in an optical cryostat. The 2.5 THz LO consists of a methanol far-infrared laser, pumped by a λ=9.6μm CO_2 laser. As an example of an early measurement, the I-V curves at 77 K for a typical 1×1×0.02 μm^3 device, with and without applied LO power (estimated to be about 200 μW), are shown in Fig. 6. Further high frequency results, including mixing, will be reported elsewhere.

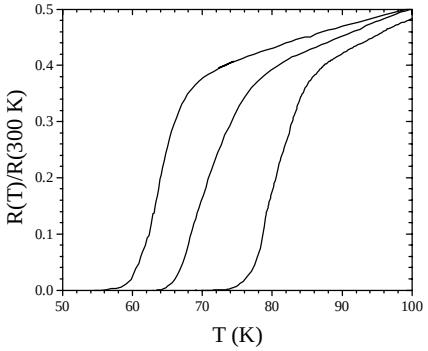

Fig. 5. Resistive transition of a 0.2×1×0.02 μm^3 device after a total of 1, 4, and 14 hours of annealing at 450 °C (T_c increases after each anneal).

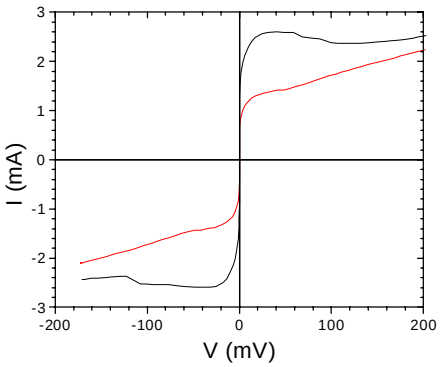

Fig. 6. Current-voltage characteristics at 80 K for the 1×1×0.02 μm^3 devices of Fig. 2 without and without 2.5 THz radiation.

transi tion in e-beam-exposed samples. We attribute the difference

CONCLUSION

We have fabricated superconducting hot-electron bolometer mixers based on ultra-thin YBCO (10-20 nm) films patterned into 0.1-1×1μm^2 microbridges using optical and e-beam lithography and passivated with SiO. 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 coupling of the devices to a 2.5 THz LO source when operated at 77 K.

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