New technology of high Tc superconducting hot electron bolometer for terahertz mixing

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Abstract. The recent rise of interest for imaging in the terahertz (THz) domain has started the research to any possible material property that could be useful for detection in this frequency range. Superconducting hot–electron bolometers (HEB) represent a very valuable alternative to the Schottky diode in the detection for frequencies exceeding 1 THz because of their wide bandwidth, high conversion gain, low intrinsic noise level, and for the possibility to use low local oscillator power for heterodyne detection. The high critical temperature materials, with respect to the low critical temperature ones, allow searching ultra-wide instantaneous bandwidth applications requiring portability and closed-cycle refrigeration. The working principle of such devices require to reduce down to the nanometric scale the dimensions of the sensing bridge, which works as mixing element. To achieve this target, high-performance microelectronic technologies are required for ultrathin film deposition together with a combination of optical and e-beam lithography processes. We report on the fabrication and the characterization of high Tc HEB structures based on ultrathin PrBa2Cu3O7-δ/YBa2Cu3O7-δ/PrBa2Cu3O7-δ films (20-45 nm) patterned in constrictions in the 0.8×0.8 to 0.45×0.45 µm2 range.

1. Introduction

In heterodyne detection, receivers based on superconducting-insulator-superconducting (SIS) junction are normally used for astronomical and atmospheric studies at frequencies up to 1 THz. At higher frequencies Schottky diodes are generally used, but since the early 80s hot electron effect has been investigated in superconducting thin films and then after the pioneering work in 1990 [1], hot electron bolometers (HEB) were considered as broadband mixers for submm and terahertz frequencies with electron phonon inelastic scattering [2].

A HEB THz detector typically consists of an ultra-thin (i.e. a few 10 nm thick) superconducting micro-bridge coupled with a planar antenna. The ultimate bandwidth of a high-Tc superconducting (HTS) HEB is determined by the electron-phonon scattering rate, which is about 1.5 to 5 ps at 80-90 K in YBCO, and so makes it an ideal candidate to achieve several tens of gigahertz intermediate frequency (IF) in heterodyne receivers. Moreover, superconducting HEB mixers require orders of magnitude less local oscillator (LO) power than semiconductor mixers, allowing for solid state LOs rather than large lasers as required for Schottky diodes. These properties make the superconducting HEB mixers particularly attractive for remote sensing systems with constraints on both power and weight, such as balloon or space based platforms. HEB mixers made from HTS operating in the 60 to 85 K range are very interesting in this context since they can be cooled with existing space qualified closed cycle refrigerators.

Data concerning the most popular THz heterodyne receivers are shown in figure 1. In particular, one can observe the frequency limitation of SIS devices due to the superconducting gap [3], the Schottky sensitivity limitation and the good sensitivity of low-Tc superconducting (LTS) film HEBs over a large wavelength range. Recently a ~ 1 THz receiver using an NbN film HEB cooled at 4.2 K, operating on a ground based telescope has been reported in [4]. In the very near future, the Herschel
space project will run LTS HEB receivers covering the 60-670 µm wavelength range. The first published data on high-Tc superconducting (HTS) THz HEBs with YBa$_2$Cu$_3$O$_{7-\delta}$ (YBCO) films are shown in figure 1. Although falling short of performance expectations, mainly related with YBCO nanostructuration challenges, it should be stressed that Karasik et al. [5] predicted ~ 2000 K (single sideband) noise temperature at 2.5 THz for an YBCO mixer operating at 66 K with 11 µW LO power (to be compared with the several mW required by Schottky mixers).

![Figure 1. Double sideband (DSB) noise temperature as a function of operating frequency (or wavelength in the vacuum) for various heterodyne receivers (after [6]). For low-Tc HEBs, “DC” and “PC” mean “diffusion cooled” and “phonon cooled”, respectively. For NbN HeBs, “Bas”, “Haj”, “Yan” and “Gao” apply to [7] to [10], respectively. For YBCO HEBs, “Gou” and “Lee” labels apply to [11] and [12], respectively.](image)

2. Working principle and requirements

In heterodyne detection the response of HEB mixers is obtained by an oscillation of the resistance of a superconducting film bridge at the beat frequency between the LO and the signal waves. In contrast to SIS-junction and Schottky-diode mixers, HEB mixers have no response at both LO and signal frequencies and respond only to the modulation of RF power. While for normal metals the resistance does not depend on electron heating, but on phonon heating only, superconductors in the resistive state exhibit strong resistance vs. electron energy dependence, since under these circumstances resistance is proportional to the concentration (and then to the electron energy) of quasi-particles but not to the energy of the lattice oscillations. So, the working principle of HEB is based on cooling the electrons, heated by the incoming radiation in a non-equilibrium temperature distribution, via electron-phonon interaction whereby the hot electrons give their energy to phonons which escape into the normal-metal electrical contacts and the substrate. Due to short electron mean free path in HTS materials, the electron-phonon cooling mechanism dominates in HTS HEB. Then the necessity to evacuate quickly the heat induced us to seek a substrate with high thermal conductivity as well as compatibility with epitaxial YBCO. Substrates need also to have a small loss-tangent and a convenient dielectric constant at both RF (THz) and IF (GHz). Moreover, the final choice of the substrate is made considering also the boundary thermal resistance between the HTS film and the substrate that should be as small as...
possible. We found a compromise with all these requirements by using (100) oriented and one side polished MgO substrates of 250 µm thickness and 20×20 mm² area.

3. Growth and patterning

3.1. General
To generate the hot electron bolometer effect the active area should be very small and well coupled to the substrate in order to favor the heat removal. We present a technological process to fabricate HEB devices with YBCO ultra-thin films in relation with previous simulations concerning the micro-bridge dimensions (length and width significantly smaller than 1 µm) [13].

3.2. Film growth and micro-bridge patterning
YBCO growth was optimized in the 12 to 40 nm thickness range [14, 15]. Sequential inverted (hollow) cathode sputter deposition of [PBCO (2 to 4 nm) - YBCO (12 to 40 nm) - PBCO (2 to 4 nm)] tri-layers was achieved by controlling the deposition time under each target. The just deposited tri-layer was in situ cooled down to room temperature, following a temperature decrease / pressure increase controlled procedure, including a 40 minute plateau at 450°C in a 900 mbar pure oxygen atmosphere. Following the tri-layer deposition, 300 nm thick gold contact pads were ex situ DC sputtered through a mechanical copper mask in a 0.03 mbar Ar atmosphere at room temperature. Right after this, the sandwiched gold - tri-layer structure was heated again up to 460°C with a 10-15 minute plateau under 1 bar oxygen pressure, and then cooled down slowly. This procedure was chosen both to insure a low enough contact resistance between the tri-layer and gold, as well as a satisfactory stability of the tri-layer superconducting properties during further processing steps. To qualify this initial process, electrical tests were performed on optically patterned micron-size bridges.

After the trilayer growth process and the gold contacts deposition the sample underwent a lithographic process to define nano-bridge exhibiting both width and length in the 0.5 to 1 µm range. This process comprised the main following steps:
- Initial patterning of the PBCO-YBCO-PBCO tri-layers using e-beam lithography to form narrow lines, in order to define the length of the nano-bridge;
- Xenon ion beam milling of these features;
- Regular optical lithography to complete the definition of the micro-bridge structure. Critical alignment between the optical mask and the initial e-beam pattern was required during this step;
- Defining the nano-bridge width by xenon ion milling using patterned photoresist as a mask.

3.3. YBCO antenna process
A wideband planar antenna of the log-periodic type has been chosen with a self-complementary geometry, which offers the attractive feature of frequency independent and purely resistive input impedance (80 Ω for MgO substrate, assuming a relative permittivity of 10). Following the micro-bridge patterning, a lift-off technique has been used to pattern the antenna metal (DC sputtered gold of 280±20 nm thickness).

The antenna as shown in figure 2 possesses 4×15 branches, allowing to cover the 0.3 to 10 THz frequency range. The YBCO material lying underneath the antenna appears whitish in this picture, which represents a 450×450 nm² nano-bridge at the centre of a 5×40 µm² microbridge.
4. Device characterization

The first electrical characterization of the devices has been a resistive AC, four-point measurement as a function of temperature to verify the critical temperature of the trilayer and the thermal effect of the bias current. For micro-bridges of 4 µm width and thickness in the 20 to 40 nm range, we measured critical temperature values (taken at mid-transition) in the 80 to 86 K range, and a transition width of 5 to 7 K. As shown in figure 3, heating effect is negligible below 500 nA bias current.

Current-voltage characterizations at various temperatures were performed on a micro-bridge of 4 µm width and about 40 nm thickness. We took the value of critical current $I_c$ by using a 1 µV (500 µV/cm) criterion [16]. The $I_c$ vs $(1-T/T_c)$ plots (see figure 4) data were fit with a power law, leading to different values for the exponent $n$ according to the fitting range: $n = 1.31$ for $T/T_c$ in the 0.9 to 0.98 range, $n = 1.25$ for $T/T_c$ in the 0.7 to 0.98 range, $n = 1.18$ for $T/T_c$ in the 0.5 to 0.98 range, and $n = 1.05$ for $T/T_c$ in the 0.1 to 0.98 range.

![Figure 2. 450×450 nm² nano-bridge after the antenna lift-off. The e-beam defined streak is visible in the centre.](image)

![Figure 3. For a microbridge of 4 µm width and 40 nm thickness, $R(T)$ with various bias currents.](image)
Figure 4. Critical current as a function of $(1-T/T_c) \equiv 1-T_r$. The power law fits show exponents $n$ ranging from 1.3 to 1 (see text).

According to the BCS theory, the exponent $n$ has a unique value depending on the type of coupling between the superconducting grains in polycrystalline HTS thin films [17]; $n = 1$ in a superconductor-insulator-superconductor junction and $n = 2$ in a superconductor-normal metal-superconductor junction. The value $n = 1.5$ can be associated with a coupling between the grains of the superconductor-insulator-normal metal-superconductor mixed type. The variation toward $n = 1$ at low temperatures can be associated as a change in the grain coupling from SINS to SIS since at lower temperature a portion of the material between the grains become superconductive [18].

Another possible explanation of the $n$ index variation in the case of single crystal structure can be related to the vortex pinning in the flux creep regime [19] associated to the strong edge pinning [20].

5. Terahertz response

A next step in the device characterization will concern the bolometric response both in direct mode detection at 850 nm wavelength up to 1 GHz modulation frequency and heterodyne detection mode at 2.5 THz, using two gas laser sources.

Radiofrequency response of the device will be tested with a CO$_2$ laser pumped, CW methyl alcohol molecular laser (2.52 THz line), delivering 3 mW average power. Standing metal wire grids will insure a linear polarization direction, so allowing to choose between direct or cross polarization with respect to the antenna. Radiation will be focused onto the antenna with a TPX™ lens. The initial target is to measure the voltage output and to deduce the optical responsivity of the device from estimated sources of loss (optical coupling and insertion losses, antenna/micro-bridge impedance mismatch, etc.). Preliminary direct detection results are reported in [21].
6. Conclusions
We have described a technological process aimed at obtaining stacked YBaCuO and PrBaCuO ultra-thin films (in the 15 to 40 nm thickness range) on a configuration of constrictions (in the 0.8×0.8 to 0.45×0.45 µm range), elaborated on MgO (100) substrates by hollow cathode magnetron sputtering. We found good superconducting electrical properties for the nano-bridge. Further characterization steps concern the device bolometric response in the heterodyne detection mode at 2.5 THz.

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