Superconducting Nb DHEB Mixer Arrays for Far-Infrared Spectroscopy

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***ABSTRACT* -** We are developing a heterodyne focal plane array with up to eight elements to study lines of the interstellar medium and planetary atmospheres with frequencies of 2 THz and above. Our fabrication process utilizes selective ion milling techniques to produce Nb Diffusion-Cooled Hot Electron Bolometeric (DHEB) mixers from a bi-layer thin film of Au/Nb deposited on a silicon substrate. A micro-bridge of 10 nm thick Nb forms the HEB device. The first generation of devices with lateral dimensions of 100 nm by 80 nm were fabricated at the feed of a broadband spiral antenna with a frequency response designed for up to 16 THz. Harmonic multiplier sources becoming available within the next few years should have sufficient power to provide a local-oscillator source for small-format, quasi-optically coupled arrays of these mixers. First generation devices measured at our laboratory have demonstrated a critical temperature (T_c) of 4.8 K with a 0.5 K transition width. These DHEB mixers are expected to have an optimum operational temperature of 1.8-2.0 K. The current four element array mixer block will ultimately be replaced by a dual polarization slot-ring array configuration with up to eight elements.

I. INTRODUCTION

Spectral line observations have played a major role in expanding our understanding of the interstellar medium and planetary atmospheres. Improvements in receiver design have enabled observations at ever shorter submillimeter and far-infrared wavelengths. Improved instrumentation justifies the construction of specialized ground-based observatories for submillimeter spectroscopy. The complexity and expense of the latest telescopes for both air and space borne platforms designed for astronomical observatories (FIRST, SOFIA, etc.), as well as space-based remote sensing of the Earth's atmosphere (EOS-MLS), demand that spectrometers perform close to the theoretical limits which imply that heterodyne receivers need to have sensitivities close to the quantum noise limit. Heterodyne spectroscopy is capable of providing the required sensitivity and spectral resolution over the entire far-infrared spectral region. The development of low-noise receivers in the THz frequency region is primarily motivated by the need for low noise and low power consumption receivers. Up until recently GaAs Schottky Barrier Diodes (SBD) were used almost exclusively for heterodyne receivers in the THz region. THz SBD mixer technology has recently made a transition from cumbersome whiskered diodes in corner-cube mounts to planar versions in waveguide. Fabrication technology and material parameters limit the size of the monolithic junction and therefore limit the noise temperature performance. Below 1 THz, SIS (Superconductor/Insulator/Superconductor) mixer receivers have excellent noise temperature (only a few times the quantum noise limit). The noise performance is limited to frequencies below or about equal to the superconducting bandgap frequency.

Hot Electron Bolometric (HEB) mixers, which use nonlinear heating effects in superconductors near their transition temperature [1], have become an excellent alternative for applications requiring low noise temperatures at frequencies from 1 THz up to the near IR. There are two types of superconducting HEB devices, the Diffusion-Cooled (DHEB) version [2][3] and the Phonon-Cooled (PHEB) version [4]. The two versions differ mainly by the cooling mechanism of the hot electrons. The devices under development here are DHEBs with a projected Local Oscillator (LO) power requirement of less than 100 nW and bath temperature of less than 2 K. The only practical LO source presently available is an FIR gas laser, although solid state LO sources with sufficient amount of power are under development and will be available in the future. The present state-of-the-art of different THz receivers is compared in FIG. 1.

The Intermediate Frequency (IF) bandwidth for the conversion gain is determined by the thermal time-constant (τ_m) of the DHEB device. The DHEB dissipates the power it absorbs by diffusion of hot electrons through the contacts. This requirements dictates that the dimension of the device be very small in order to maximize the IF gain bandwidth. The receiver noise temperature bandwidth (BW_{NT}) is wider than the conversion gain bandwidth (BW_G). The fact that the receiver noise temperature bandwidth is two to three times wider

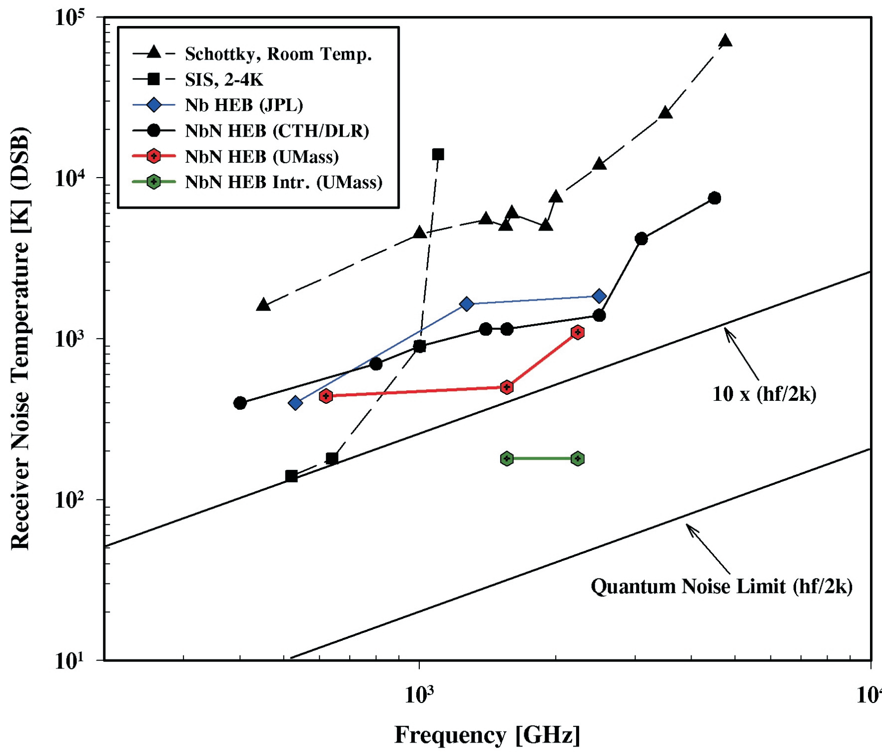


FIG. 1. Noise temperatures vs. frequency for receivers in the terahertz regime.

than the conversion gain bandwidth is a well-known feature of HEB mixers. For these devices, the main noise process in the device (temperature fluctuation noise) yields a noise output which falls at the same rate as the conversion gain, flattening the net receiver noise dependence on the IF frequency.

II. DEVICE DESIGN AND FABRICATION

A quasi-optical coupling design was chosen. The focal plane array is of the "fly-eye" configuration, with individual substrate lenses for each pixel. (Obviously, this configuration is suitable only for relatively small format arrays.) The incoming energy couples to the device through an elliptical lens 4mm in diameter, made from high-purity silicon, and a spiral antenna with a maximum frequency response of 16 THz [5]. The spiral wrap angle is 20 degrees, with a nominal separation of the feedpoints of 1.2 μm. The spiral design is self-complementary, implying an antenna impedance of 75 Ω. The array includes two antennas with 2 1/4 turns and two with 2 3/4 turns, which imply lower frequency limits of 520 GHz and 160 GHz, respectively. (These approximate frequency limits are derived from the criterion that the antenna radius be equal to 1/4 of an effective wavelength. The radius of the inner edge of the antenna is used for the lower frequency limit and the outer edge for the upper frequency limit, with an additional quarter-turn left for engineering margin.) The IF signal is coupled out of the bolometer thru a 50 Ω coplanar waveguide (CPW), the center conductor of which contacts the center conductor of a microminiature K-type connector. The CPW groundplane is common to all four array elements, and directly contacts the body of the mixer block through an indium foil "gasket". The four-element array configured with lenses and spiral antennas is shown in FIG. 2. We are planning to implement a dual polarization design with eight devices in the future.

A typical device fabrication begins with the deposition of a uniform bilayer metallic film across a 75 mm silicon wafer which has been wet oxidized to a thickness of 300 nm. The bilayer is composed of a 12 nm niobium base layer capped by 20 nm of gold. The films are deposited in-situ using DC magnetron sputtering. The HEBs are ultimately formed in the base Nb layer as the last step of the process. The gold cap layer is intended to protect the Nb during initial fabrication steps as well as to mitigate contact resistance problems between the device and overlying metallic layers. Following the bilayer deposition, a 100 nm thick gold layer is deposited through a photoresist liftoff mask patterned using conventional

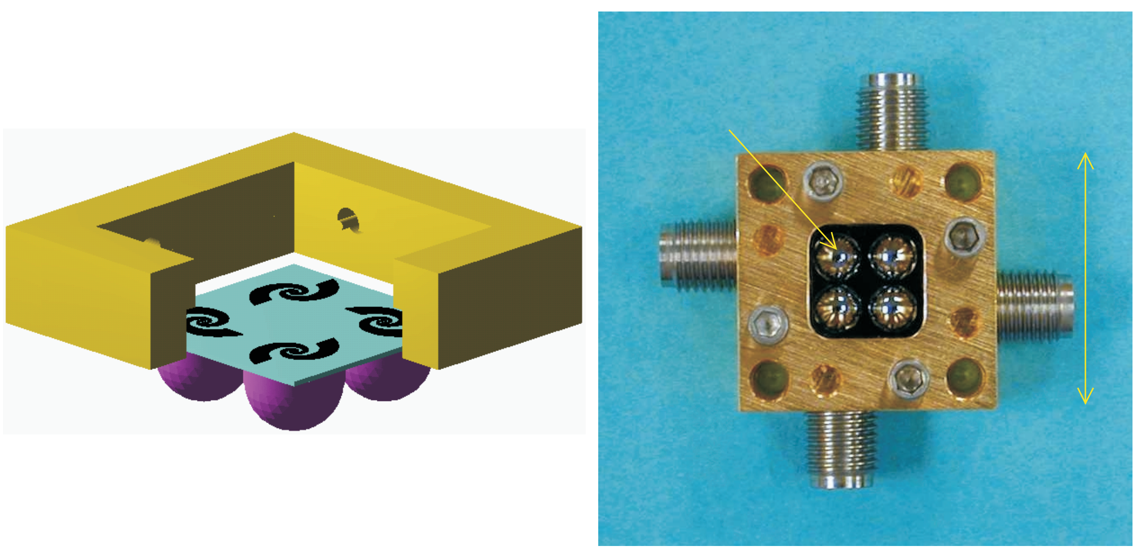


FIG. 2. Array configuration; on the left, a conceptual rendering showing the chip with four elements and substrate lenses nested in the mixer mount, on the right, a photograph of the assembly.

UV lithography. This mask defines the log spiral antennas, ground plane, and the coplanar waveguide (CPW) feed structure to the four array elements. The gold is deposited using thermal evaporation following a 1 minute Ar *rf* plasma cleaning step to treat the contact regions. These steps take us through step (b) in the accompanying FIG.3.

Since optical lithography was used for the antenna deposition, the lead separation at the feed of the antenna remains much too large (~ 2 μm) for useful HEB device dimensions. Therefore, a second contact metallization step, using E-Beam Lithography (EBL), to define the length scale of the devices was performed. Again gold lift-off is used only through

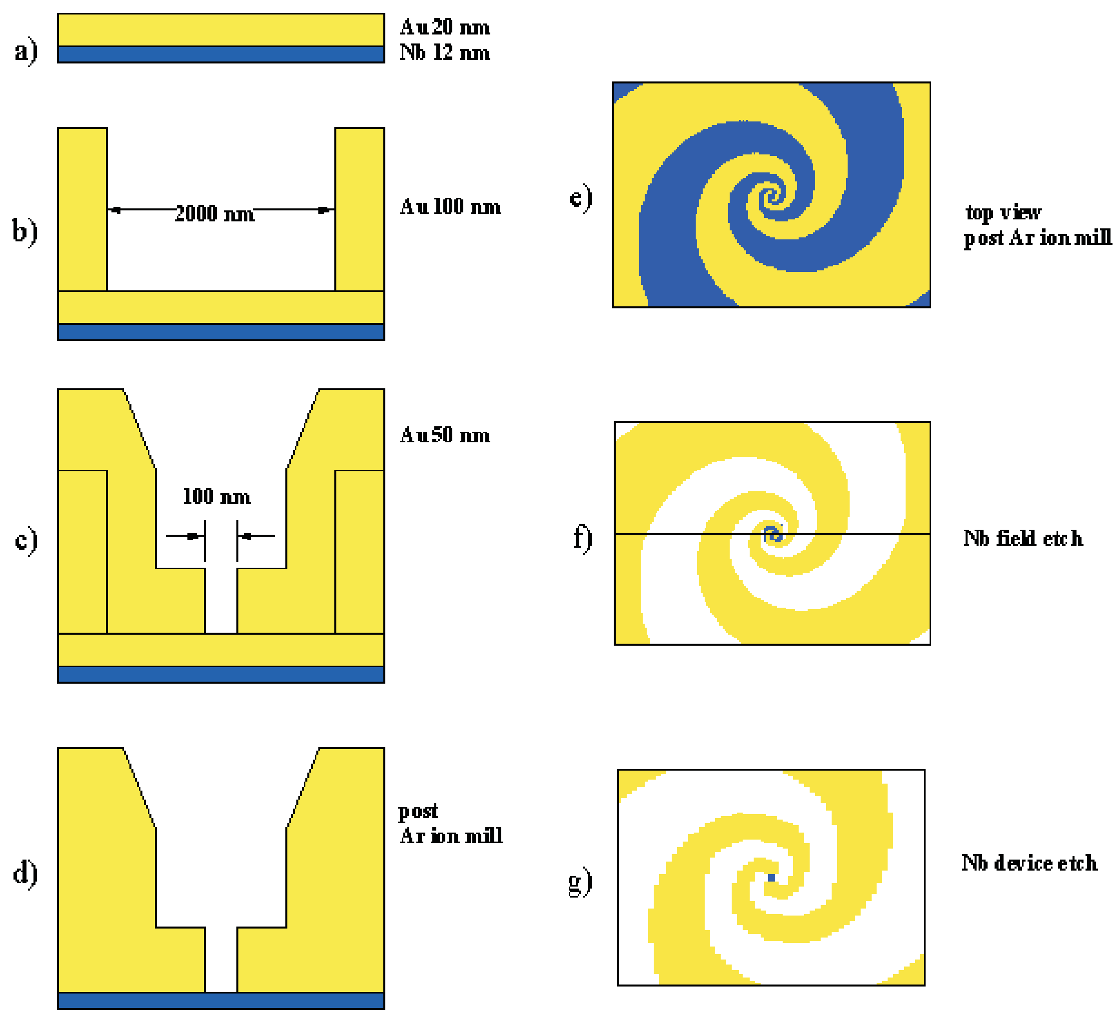


FIG.3. Device fabrication schematic.

an EBL patterned PMMA mask in this case. 50 nm of Au are deposited with an electrode separation of between 80-100 nm at the antenna feed. The deposition process is the same as for the antenna layer.

The last few steps of the process have produced a structure, depicted in FIG.3(c), which includes a complete antenna structure over a blanket Nb/Au bilayer. The 20 nm Au bilayer cap is then removed in an Ar ion mill step using the thick gold as a sacrificial mask. There is no additional patterning associated with this step. 30 nm of the antenna and contact Au are sacrificed to clear the bilayer surface gold from the underlying Nb in the open field areas. The ion mill process has reasonable selectivity to Au as compared to Nb (>5:1).

At this point the device has a Nb layer underlying the entire structure as evident in FIG. 3(e). This Nb must be cleared everywhere except for the final device region. This is accomplished in a two step Reactive Ion Etch (RIE) process. The first step uses optical lithography to pattern a mask which protects a 6 μm × 6 μm square region centered over each device. The chip is then subjected to a SF_6 RIE process to clear the Nb in the exposed field regions (FIG.3(f)). The chip is then patterned one last time using EBL to leave a narrow strip of PMMA bridging the gap between the Au contacts and protecting the final device area. The width of this strip, nominally 80–200 nm, defines the final width of the HEB. There is a 10 μm × 10 μm window around this strip which fully encompasses the 6 μm × 6 μm Nb patch which was protected during the first RIE step. The chip then undergoes an identical SF_6 RIE step to remove the last of the Nb. The resulting final dimensions of a typical HEB are 100 nm length × 100 nm width × 12 nm thickness (FIG.3(g)).

Following device fabrication an elliptical Si lens is affixed to the backside of the substrate. The lens is positioned within a well etched into the backside of the substrate. The well position is registered to within ±5 μm of the device using an infrared backside contact aligner. This well is etched early in the process before device fabrication. The lens is affixed using a low melting point wax.

III. OPTICAL LAYOUT

An apparatus for characterizing the devices and measuring noise temperature has been constructed and is illustrated in FIG. 4. The mixer block is attached to an OFHC Cu pedestal on the cooled plate of a dewar. The base temperature is below 2 K, which is needed for Nb DHEB operation. The THz radiation enters the dewar through a quartz window and a

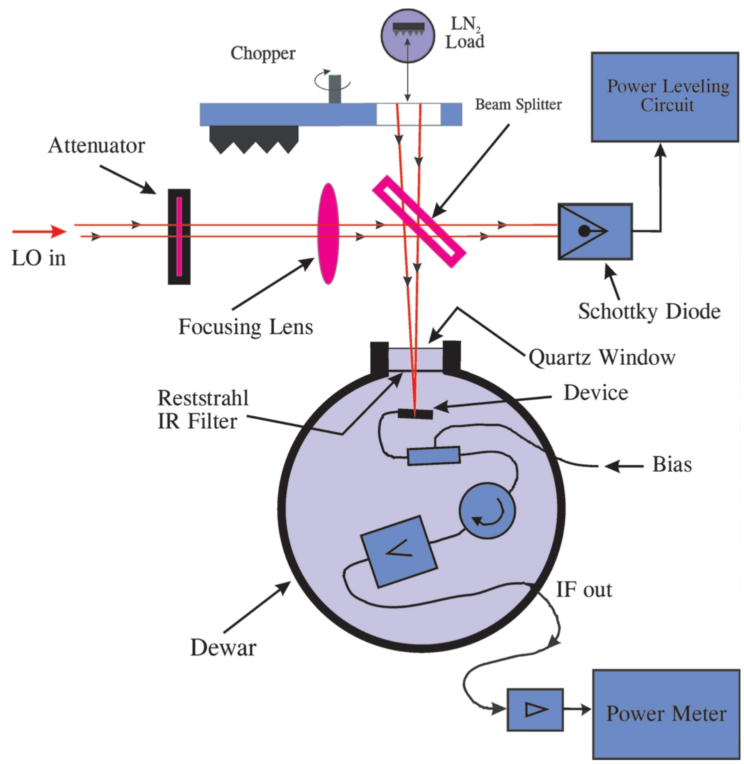


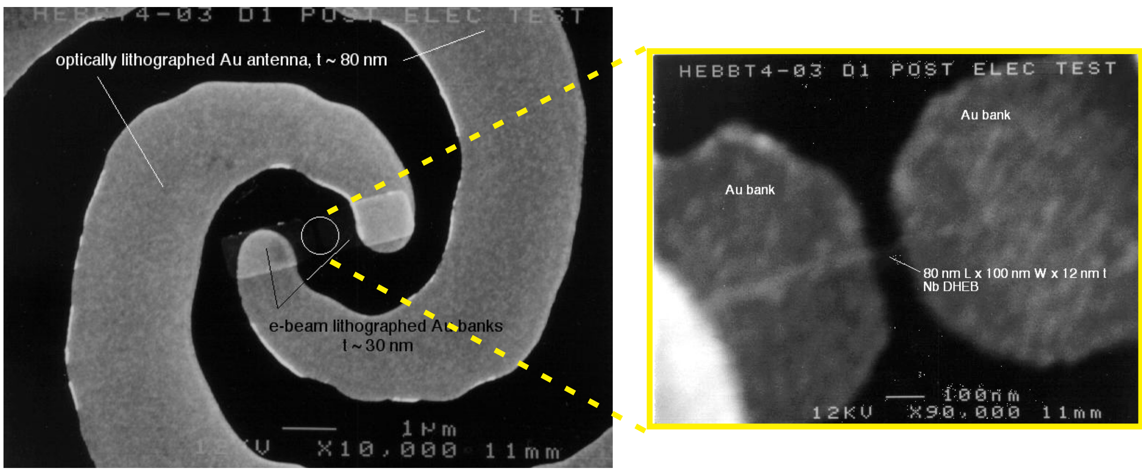
FIG. 4. Measurement setup for noise temperature.

reststrahl filter designed to block radiation above about 6 THz. The mixer is connected through a bias tee and a semi-rigid coaxial cable to a commercial cooled HEMT IF amplifier (L band) with a noise temperature about 5 K.

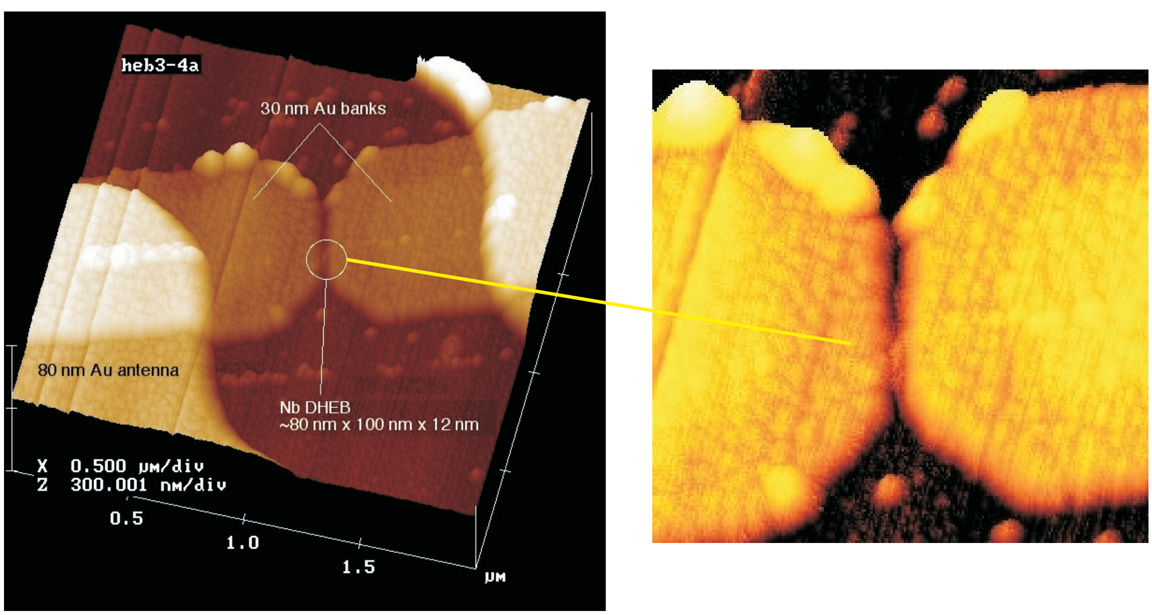
The local oscillator signal is produced by an optically-pumped far-infrared laser. The laser is 1 m long and operates on most FIR laser lines between 30-300 μm. The polarization of the linearly polarized EH_{11} output mode can be rotated or converted to circular (if desired) by a polarization diplexer. The FIR laser and its CO_2 pump source run sealed off, but can be refilled with gas of any isotopic composition. Initially, tests of HEB mixers are being done with the $^{15}NH_3$ line at 153 μm. The output power of the free-running FIR laser is stable to better than 1% over a period of several minutes, but is normally actively stabilized to better than 0.01 % long term by a closed-loop leveling circuit. FIG. 4 shows the GaAs Schottky diode sensor used for power control. An error signal generated from the difference between the diode output and a reference voltage is used to control the CO_2 pump laser frequency, and hence the FIR laser output power.

IV. RESULTS

We have successfully fabricated several devices using the method described in this paper. The extreme restriction on the dimensions of the device required for maximizing the IF gain bandwidth (and minimizing LO power requirements) were achieved in all cases,



(a)



(b)

FIG.5. (a) SEM pictures of the DHEB, (b) AFM pictures of the DHEB.

i.e. device lengths less than 100 nm. The thickness of the Nb in all cases was 12 nm. The critical temperatures exhibited by the devices was 4.8 K with a transition width in the range of 0.5 K. FIG.5(a) shows SEM images of the devices including the spiral antenna, whereas FIG. 5(b) shows AFM images of the microbolometer at the antenna feeds.

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