

Final Report

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Superconducting Mixers for Far-Infrared Spectroscopy

P.I. : A.L. Betz, University of Colorado, Boulder

Co-I: R.T. Boreiko, University of Colorado, Boulder

Co-I: E.R. Grossman, C.D. Reintsema, R. H. Ono, E. Gerecht*
National Institute of Standards & Technology, Boulder

I. OVERVIEW

The goal of this project was to fabricate and test planar arrays of superconducting mixers for the 2-6 THz band. The technology is intended for multi-beam receivers aboard Explorer-class missions and the SOFIA Airborne Observatory.

The mixer technology is the superconducting transition-edge microbolometer, which is more commonly known as the Hot-Electron micro-Bolometer (HEB). As originally proposed, two superconducting technologies were to be developed: (1) low- T_c niobium HEBs which could approach quantum-noise-limited sensitivities but require cooling to 2-4 K, and (2) high- T_c YBCO HEBs with sensitivities 10 times worse but with a relaxed cooling requirement of 30-60 K. The low- T_c devices would be best for astronomy applications on SOFIA, whereas the high- T_c devices would be more suitable for planetary missions using systems without stored cryogens.

The work plan called for planar micro-fabrication and initial testing of HEB devices at the NIST Boulder cleanroom facility. Subsequent assembly and RF testing of selected devices would be done at the CASA laboratory at U. Colorado. Approximately 1-year after work began on this project, Dr. Eyal Gerecht joined the NIST group, and assumed day-to-day responsibility for Nb-HEB development at NIST outside of micro-fabrication. The YBCO-HEB work was to be guided by Dr. Ron Ono, who was the NIST expert in YBCO technology. Unfortunately, recurrent health problems limited the time Ron could devote to the project in its first year. These problems became aggravated in early 2001, and sadly led to Ron's death in October, 2001. His loss was not only a blow to his friends and associates at NIST, but was mourned by the US superconductivity community at large. With his passing, work on high- T_c HEBs ceased at NIST. There was no one to replace him or his expertise. Our work subsequently shifted solely to Nb-HEB devices. In

the sections which follow, our progress in the development of diffusion-cooled Nb-HEB mixers is detailed. To simplify the terminology, these devices will subsequently be called DHEB mixers to distinguish them from phonon-cooled devices (PHEBs).

The presentation begins with a brief justification for the research and review of the current state-of-the art for DHEB mixer technology. It then proceeds to details of the fabrication process, and description of the mounting and preliminary RF testing. Finally, we present the sensitivity results and conclusions regarding further development needs. A brief summary at the end outlines the successes and failures of the project, and points the most promising directions for further research. These new directions are already being pursued with support from subsequent NASA grants.

The successful end result of the project can be summarized as follows. We report a respectable noise temperature measured on a diffusion-cooled hot electron bolometric (DHEB) mixer designed for a heterodyne focal plane array in the 2-6 THz band. Our fabrication process utilizes selective ion milling techniques to produce Nb-DHEB mixers from a bi-layer thin film of gold/Nb deposited on a silicon substrate. A micro-bridge of 10 nm thick Nb forms the HEB device. The devices are fabricated at the leads of a broadband spiral antenna with a frequency response of up to 20 THz. A FIR laser was used as the LO source at 2.52 THz (119 μm). A double-sideband (DSB) receiver noise temperature of 2500 K was measured. This noise temperature result is not corrected for losses and mismatches, and was measured at a bath temperature of 2K and an intermediate frequency (IF) center frequency of 1 GHz. The Nb-HEB has a critical temperature $T_c = 6$ K with a 0.5 K transition width.

II. INTRODUCTION

Spectral line observations have played a major role in expanding our understanding of the interstellar medium and planetary atmospheres. Further improvements demand that submillimeter 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. 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, have become an excellent alternative for applications requiring low noise temperatures at frequencies from 1-10 THz. There are two types of superconducting HEB devices, the diffusion-cooled (DHEB) version and the phonon-cooled (PHEB) version. 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 present state-of-the-art of different THz receivers is compared in FIG. 1.

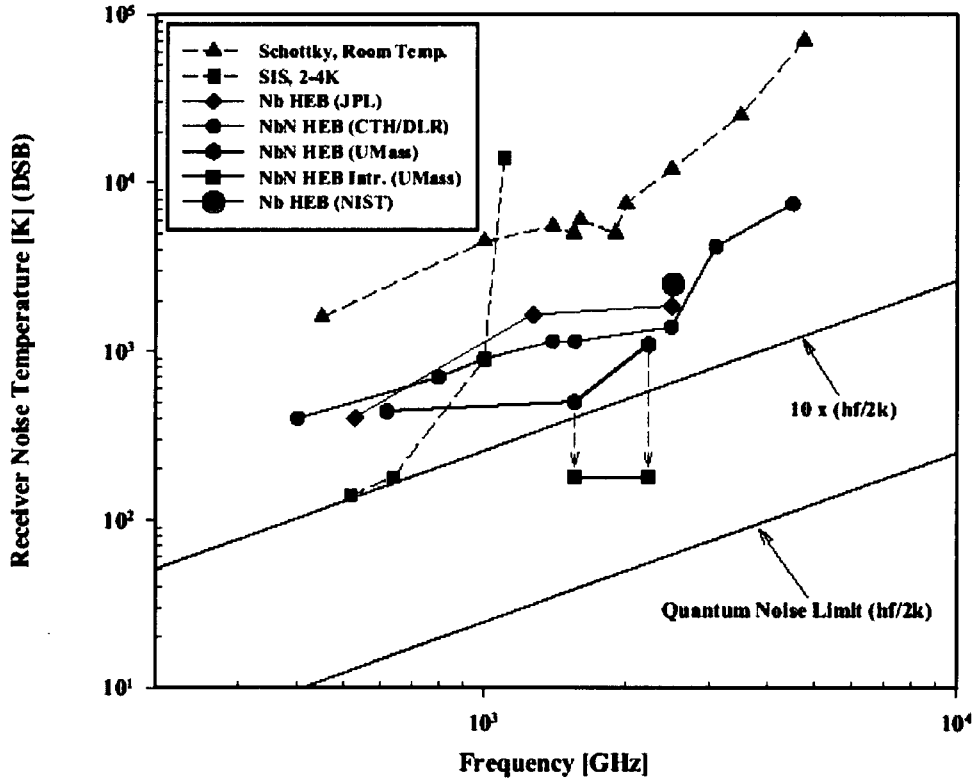


FIG. 1. Noise temperatures vs. frequency for receivers in the terahertz regime.

III. DEVICE DESIGN AND FABRICATION

For coupling of signal radiation to the mixer, a quasi-optical coupling design was chosen. The 4-element 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. 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 through 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.

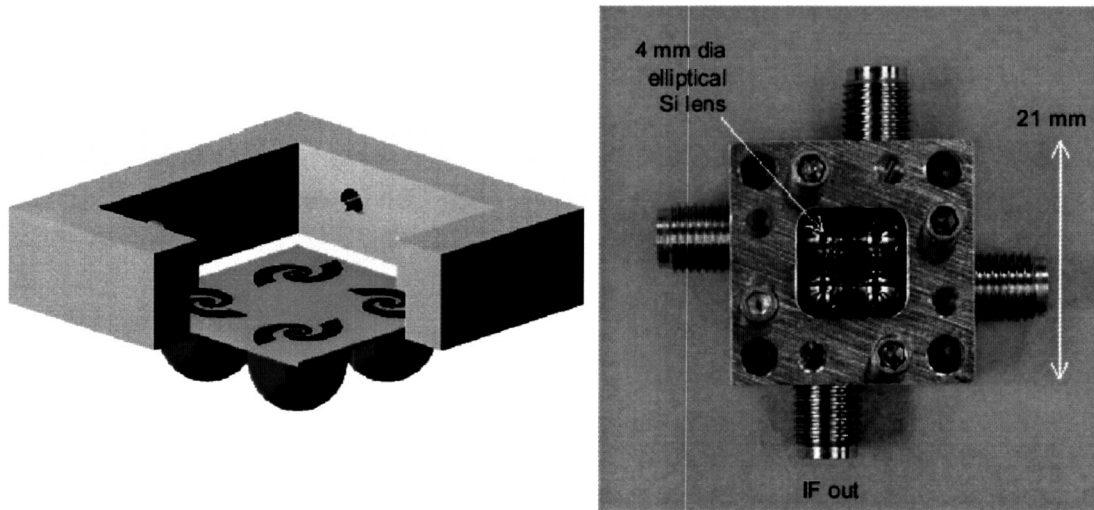


FIG. 2. Array configuration; on the left, a conceptual rendering showing the chip with four elements and substrate lenses, on the right, a photograph of the assembly.

A typical device fabrication begins with the deposition of a uniform bilayer metallic film across a silicon wafer, which has been thermally oxidized to a thickness of 300 nm. The bilayer is composed of a 12 nm niobium base layer capped by 20 nm of gold (see FIG. 3). 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 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.

Since optical lithography is used for the antenna deposition, the lead separation at the feed of the antenna remains much too large ($\sim 2 \mu\text{m}$) 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, but through an EBL patterned PMMA mask in this case. About 50 nm of Au are deposited with an electrode separation of between 80-100nm at the antenna feed. The deposition process is the same as for the antenna layer.

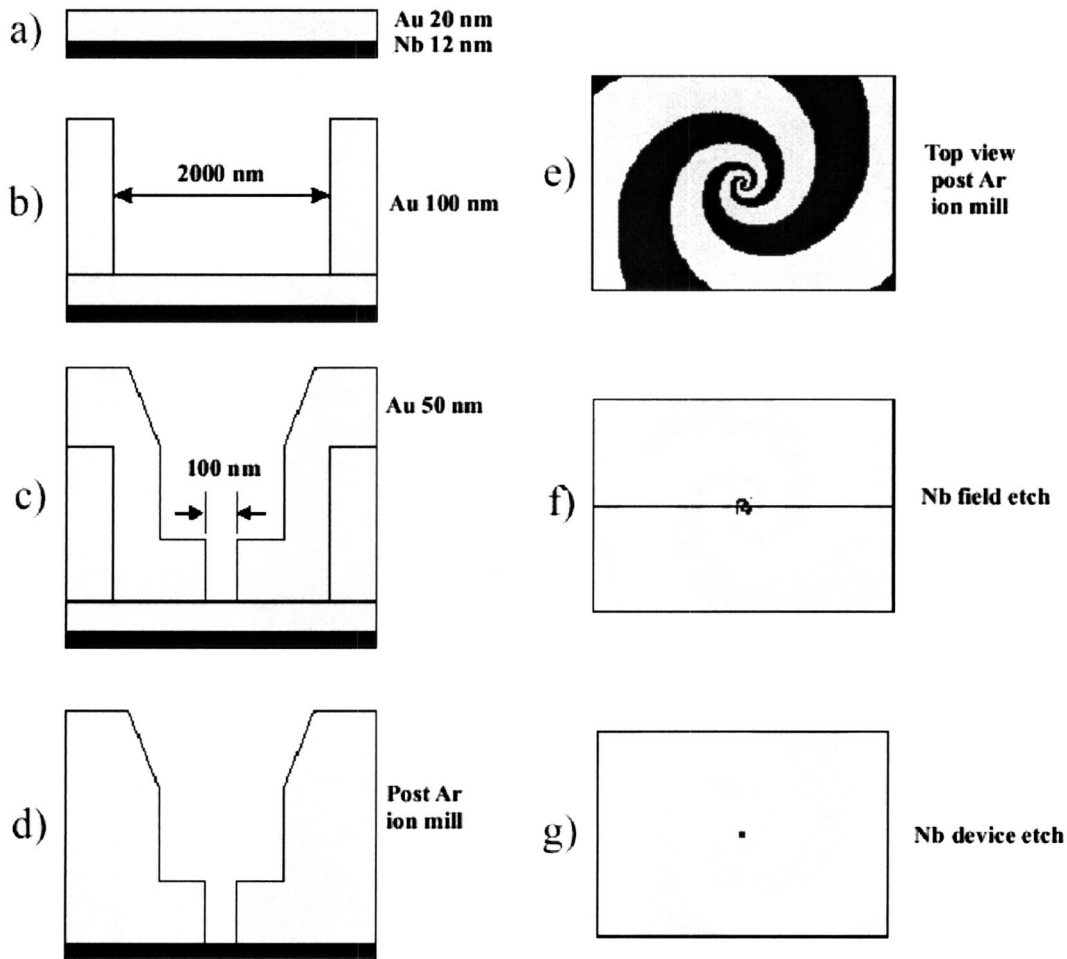


FIG.3. Device fabrication schematic.

IV. OPTICAL LAYOUT

The apparatus for measuring noise temperatures 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 about 2 K, which is needed for Nb DHEB operation. The THz radiation enters the dewar through a quartz window and a 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 $\lambda=30\text{-}300\ \mu\text{m}$. 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. 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 CO₂ pump laser frequency, and hence the FIR laser output power.

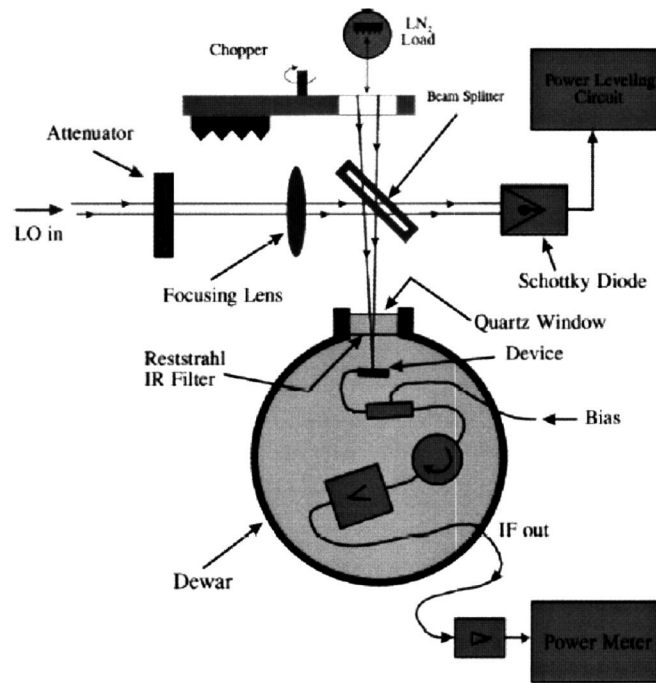


FIG. 4. Measurement setup for noise temperature.

V. RESULTS AND DISCUSSION

Several DHEB devices were fabricated using the method described above. FIG.5(a) shows a SEM image of the device including the spiral antenna, whereas FIG. 5(b) shows an AFM image of the microbolometer at the antenna feeds.

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 20nm 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. Then 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 $6\ \mu\text{m} \times 6\ \mu\text{m}$ 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 (see 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 10–20 nm, defines the final width of the HEB. There is a $10\ \mu\text{m} \times 10\ \mu\text{m}$ window around this strip which fully encompasses the $6\ \mu\text{m} \times 6\ \mu\text{m}$ 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 designed final dimensions of a typical HEB are 100 nm length \times 100 nm width \times 12 nm thickness (see 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 $\pm 5\ \mu\text{m}$ 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 purified bees wax.

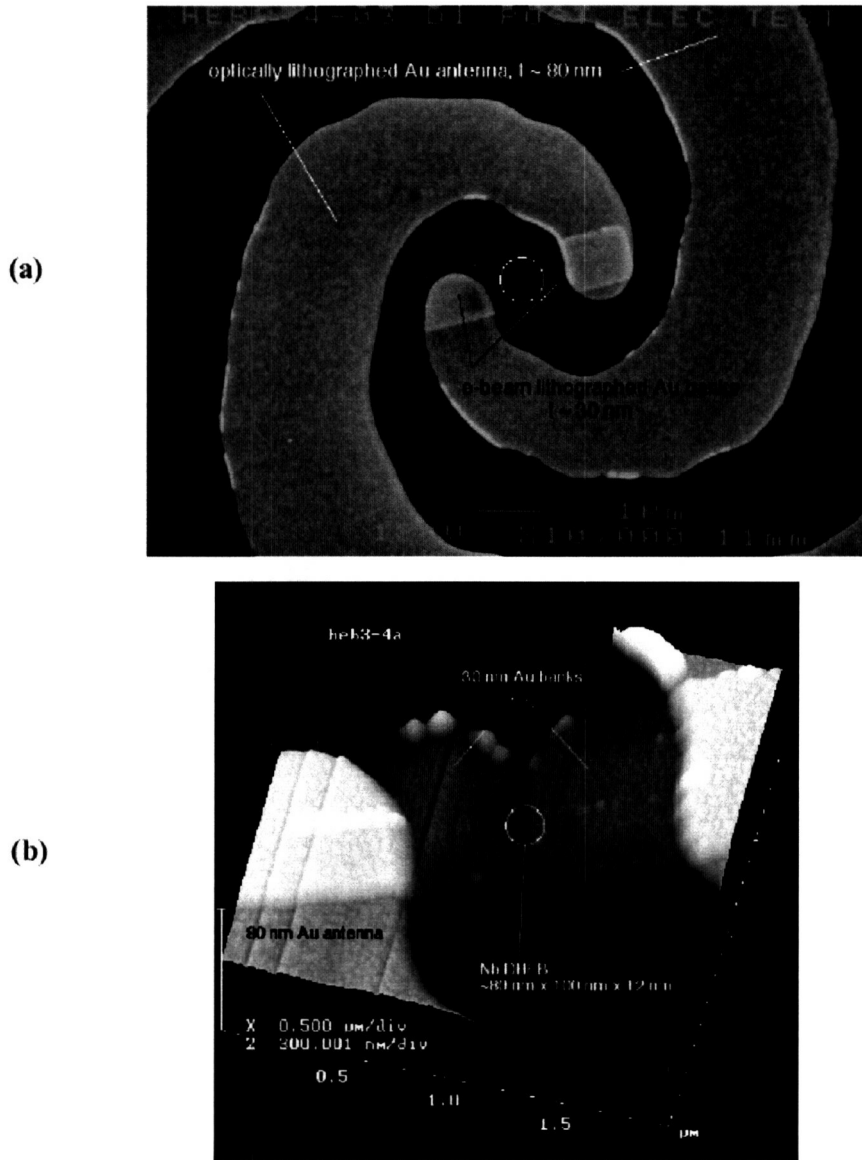


FIG.5. (a) SEM pictures of the DHEB, (b) AFM pictures of the DHEB.

The I-V characteristics of the device are shown in FIG. 6. The critical current is about 2.7 MA at a bath temperature of 2K. The LO power centered at 2.52 THz (119 μm) was coupled to the device through a 6 μm thick mylar beam splitter as illustrated in FIG. 4. The IF power was amplified by a cooled HEMT amplifier with 30 dB gain, a noise temperature of 5K, and centered at 1 GHz and a room temperature IF amplifier with a gain of 60 dB. Y-factor measurements between black body sources at room temperature and at LN_2 (77K) were taken. Y-factors as high as 0.4 were observed. A reproducible double sideband receiver noise temperature of 2500 K was measured at the optimum bias point of 686 μV and 812 μA . This noise temperature result is not corrected for losses and mismatches and therefore can be improved by better power coupling and IF matching

circuitry. The power absorbed by the device was calculated using the constant resistance line (points (I) and (II) on FIG. 6), along which the hot electrons temperature is constant, to be $4.9 \mu\text{W}$. The total laser power of about 2.5mW before the focusing lens and the beam splitter was not sufficient to pump the device optimally. The total power coupling efficiency is estimated to be about 13dB ($\sim 100 \mu\text{W}$ in front of the dewar). The device was therefore LO starved, which implies that a better DSB receiver noise temperature was possible.

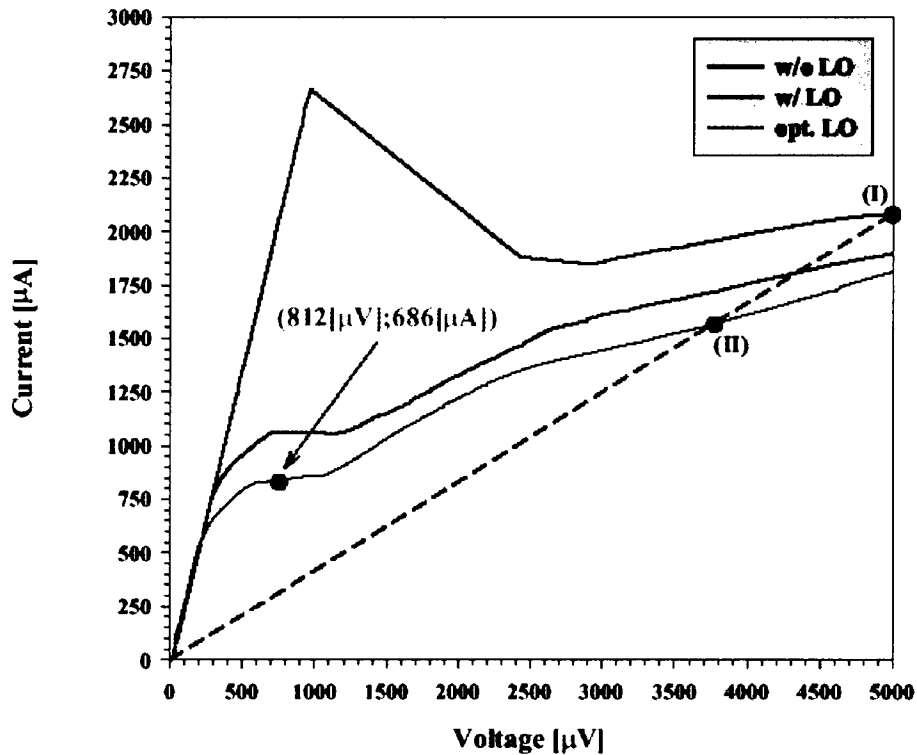


FIG. 6. I-V characteristics of the DHEB device.

The high requirement for LO power is consistent with the relatively high critical current. A microbolometer with a cross section area of 80 nm by 12 nm cannot support such high critical current. We attribute the high critical current to the larger $6 \mu\text{m} \times 6 \mu\text{m}$ square area of Nb around the bridge which was not etched entirely.

These results were presented at the 13th International Symposium of Space-Terahertz Technology at Harvard University in March, 2002, and published in the Proceedings: E. Gerecht *et al*, "Noise Temperature for Nb-DHEB Mixer Receiver for Far-Infrared Spectroscopy".

VI. SUMMARY & FUTURE PLANS

The 2500 K (DSB) noise temperature measured for the Nb-HEB is consistent with the current state-of-the-art for HEB mixers at this frequency (see green dot in FIG. 1). However, as mentioned above we are aware of fabrication errors which undoubtedly degraded the sensitivity of the mixer. These problems are known and can be corrected in the future. Unfortunately, the resources available under this grant at the time were not adequate to fix the e-beam lithography problems we had at NIST. Of course, we also did not foresee that we would encounter problems with e-beam lithography at NIST, where the technique heretofore was commonly used. Our e-beam problems also contributed to poor yields on fabricated DHEBs, such that we were unable to produce 4 functioning mixers on the same wafer. Future efforts in DHEB fabrication may require the expertise of other facilities or personnel to achieve our design goals. On the other hand, we can also adopt the PHEB mixer technology exemplified by NbN devices, which are larger than DHEBs and can be made with simpler optical lithography. In this latter regard we have recently started a follow-on project under NASA support to produce high quality NbN films at NIST and to fabricate THz HEB mixers using this material. This project, under the direction of Eyal Gerecht at NIST and with U. Mass. and U. Colorado as collaborators, is currently underway and making good progress. We are also attempting to resurrect the effort to produce THz mixers using high temperature superconductors. NASA has funded a collaboration between NIST Boulder and U. Colorado to make Josephson mixers with YBCO for the 0.5-2.0 THz band. This latter work builds upon designs proposed but not delivered under this grant.

VII. EDUCATION AND PUBLIC OUTREACH (E/PO)

This grant effort also originally included an Education and Public Outreach (E/PO) component. Co-I Dr. Katie Garmany, in her position as Director of the Fiske Planetarium on the University of Colorado campus, was to lead a collaboration between Fiske and several local Colorado school districts. The E/PO program proposed to review and select curricular materials appropriate for Middle and High School Students, and to prepare workshops for teachers who lacked a strong physical science background but wanted to incorporate astronomy and space science in their classes. The workshops were to be held at Fiske Planetarium and its adjacent observatory. The goal was to choose classroom materials that address the national science standards for grades 6-12 through the medium of astronomy and space science.

Unfortunately, the start-up phase for this E/PO project was delayed during the first year of the grant. Toward the middle of the year Dr. Garmany resigned her appointment at U. Colorado (CU) to take a position elsewhere. No one else at CU had her contacts to the local school districts, and so the original project was abandoned. As a new Director for Fiske was not chosen for some time, the other P.I.'s on the grant were unable by themselves to commit the resources of Fiske to another E/PO effort. As a result of this failure, we returned to NASA the full amount of \$20,000 awarded for the 2-year E/PO component.