Development of NbN Terahertz HEB Mixer Devices and Films*

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ABSTRACT - Until recently, the thin-film NbN samples used by most research groups studying phonon-cooled hot electron (PHEB) devices across the world have been produced in Moscow (MSPU). We have developed a process for fabricating NbN thin films at the National Institute of Standards and Technology (NIST) in Boulder, CO. A two-fold approach has been taken. One approach is to maximize the critical temperature, but at the expense of IF bandwidth and noise temperature. With this approach, we can hope to develop NbN HEB receivers that will operate at 6-10 K using alternative, less costly, coolers. The other approach focuses on minimizing the receiver noise temperature and maximizing the IF bandwidth, while operating at 4 K. We have developed a film-deposition process that utilizes our DC reactive magnetron sputtering chamber. The films were deposited on MgO substrates that were heated to about 800 °C during deposition. A typical critical temperature (T_c) is about 10-11 K, and the transition width is very small (0.5 K). The films were then evaluated by measuring their superconducting characteristics as well as their thickness and surface roughness by use of AFM analysis.

PHEB devices were fabricated on the films in order to study their performance as THz HEB mixers. The device fabrication process performed at both NIST and UMass/Amherst involved lift-off lithography of the antenna (gold), and reactive-ion etching (RIE) or wet etching of the NbN. Receiver noise temperatures and receiver noise bandwidths were then measured at UMass/Amherst with a laser local oscillator (LO) that allows testing at a number of different frequencies. The latest results are described and discussed in this paper. A new antenna design and a new generation of monolithic microwave integrated circuit (MMIC) amplifiers to be incorporated with HEBs are also described.

I. INTRODUCTION

Heterodyne detection is the most sensitive spectroscopic technique over a broad frequency range that produces high spectral resolution in the terahertz region. In astronomical applications, observations of spectral lines have played a major role in expanding our understanding of the interstellar medium and planetary atmospheres. In order to achieve the required sensitivity for astronomical, remote sensing, and plasma diagnostics applications, we need to develop receivers operating at sensitivities near quantum noise limits and focal plane arrays with multiple mixer elements. Until recently GaAs Schottky barrier diodes (SBD) were used almost exclusively for heterodyne receivers in the terahertz region. Below 1 THz, SIS (Superconductor/Insulator/Superconductor) mixer receivers have excellent noise temperature (only a few times the quantum noise limit). This 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 to 5 THz. 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 according to the cooling mechanism of the hot electrons. NbN PHEB detectors have demonstrated an order of magnitude increase in sensitivity and a three orders of magnitude decrease in LO power requirement in the last few years. FIG.1 shows a survey of the noise temperature as a function of frequency for different types of detectors operating in the terahertz regime.

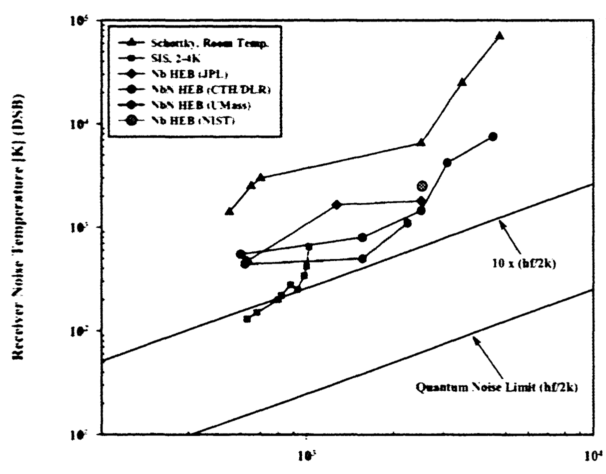


FIG. 1. Noise temperatures vs. frequency for receivers in the terahertz regime [1]-[7].

A two-fold approach can be taken in developing HEB technology. One approach focuses on minimizing receiver noise temperature and maximizing IF bandwidth at the expense of operational temperature (4 K). The NbN superconducting films have lower critical temperature (T_c). The other approach focuses on maximizing the operational temperature (6-10 K) at the expense of possibly higher noise temperature and narrower bandwidth, allowing the use of newly developed crycoolers. Here, we have concentrated on maximizing the critical temperature at the expense of bandwidth. We have developed an NbN film-deposition process utilizing our dc reactive magnetron sputtering chamber. After characterizing the superconducting films, we fabricated phonon-cooled HEB devices and studied their performance.

II. FILM DEPOSITION

NbN thin films were deposited using dc reactive sputtering from a Nb target in an atmosphere of nitrogen and argon . The deposition chamber was cryopumped down to a base pressure of 1.5×10^{-5} Pa. The total pressure is controlled with a variable throttle valve on the cryopump and is measured with a capacitance manometer. Ultra high purity (UHP) grade argon and zero-grade nitrogen were introduced into the chamber and their flow was controlled by needle valves. The partial pressure of nitrogen was determined simply by subtracting the initial Ar pressure from the total pressure of the mixture. The Nb sputtering target of 75 mm diameter was specified to have a purity of 99.95 %. The sample-to-target distance in our system is 10 cm. Crystalline MgO substrates, with (100) orientation, were cleaned in ambient temperature HF solution, followed by rinsing in organic solvents with ultrasonic agitation. The substrate was glued to a vacuum compatible heater block with silver paint and baked under a radiant heater for an hour prior to mounting in the deposition chamber.

The deposition sequence starts with cleaning of the target by sputtering Nb typically for five minutes onto a dummy sample in an atmosphere of pure Ar. In the next step nitrogen is added and pre-sputtering continues for another five minutes, while equilibrium is reached with regard to the nitrogen content at the target surface.

As discussed at length in the literature [8], a feedback mechanism exists in the magnetron plasma during reactive sputtering of NbN. When the plasma is voltage or power biased, the feedback is positive, leading the target surface to be either completely covered with nitride or completely free of nitride. The plasma current-voltage (I-V) characteristic in this condition is hysteretic, and control of the stoichiometry of sputtered films is problematic.

The resulting films are either nitrogen or niobium-rich, depending on the state of the target surface. However, under current bias the feedback is negative and the plasma I-V curve is single-valued, although it includes a region of negative differential resistance. Therefore, all NbN films described in this paper were grown with the plasma current-biased. FIG.2 shows the I-V curves for different pressures and gas compositions for our sputtering chamber. We have noticed a drift in the I-V characteristics over time, which was remedied by readjusting the deposition parameters.

During pre-sputtering, the MgO substrate was heated to 800 °C and actively stabilized at that temperature. Substrate temperature was monitored using a thermocouple embedded in the body of the heater block. Experience with identical heater blocks used for high-temperature laser ablation of YBCO films indicates that a significant temperature gradient (probably 20 to 50 °C) exists between the thermocouple and the surface of the substrate. Once the films were deposited, the sample was cooled to ambient temperature in nitrogen at 1atmosphere background pressure.

Our highest critical temperature samples (T_c=11.2 K, ΔT_c=0.2 K) were obtained in a mixture of 15 % N_2, 85 % Ar, at 1.33 Pa total pressure, an applied current of 1.2 A, and resulting voltage of about 275 V. Film thickness was measured using a commercial atomic force

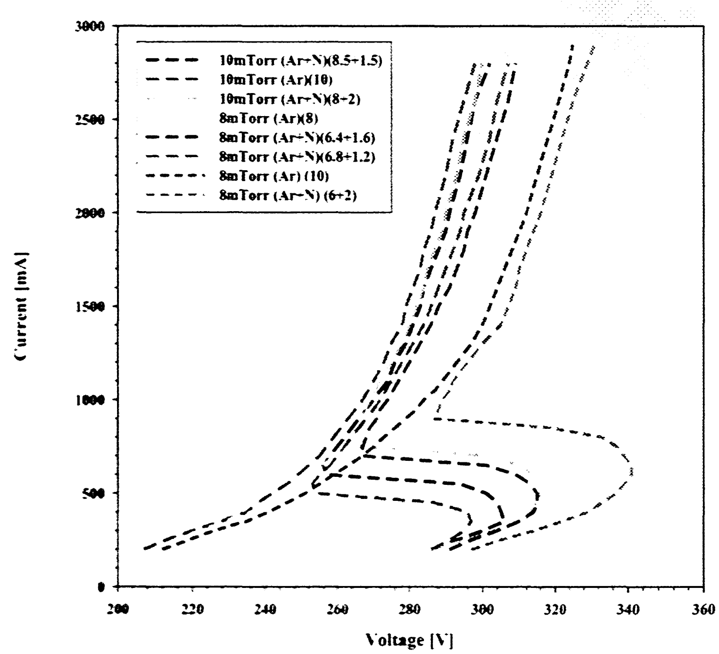
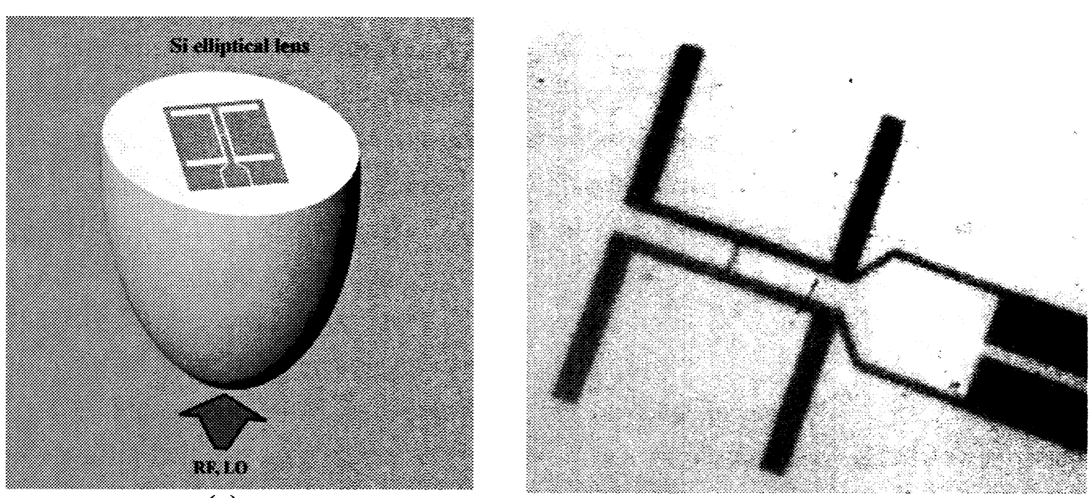


FIG. 2. I-V characteristics of the sputtering plasma.

microscope (AFM). Typical deposition rates are around 0.25 nm s. For the series of samples described here, a uniform film thickness of 5 nm was desired. The deposition time for each film was adjusted based on the assumption that the deposition rate is proportional to power, which in turn depends on the plasma current.

III. DEVICE FABRICATION

Our next step was to evaluate the films by fabricating phonon-cooled HEB mixer devices, and to measure the noise temperature and IF bandwidth of these devices. A quasi-optical coupling design was used to couple the terahertz radiation into the device. We fabricated devices at the terminals of a twin-slot antenna design and at the terminals of a much broader design utilizing the toothed self-complementary log-periodic antenna. The antennas were photo-etched in a 200 nm gold layer that had been e-beam evaporated over the NbN film. After the gold layer was lifted off, the NbN film was wet-etched or dry-etched to define a HEB device with length of 1 μm and width of 4 μm. The twin-slot antenna response is centered at 1.5 THz, with a bandwidth of 1 THz to 1.9 THz. FIG.3 shows a photograph of the HEB device at the terminals of the twin-slot antenna. Lastly, an elliptical Si lens was affixed to the backside of the substrate. The lens was positioned using lines that had been accurately scribed on the lens side of the substrate and then affixed with purified bee's wax.



(a) (b)

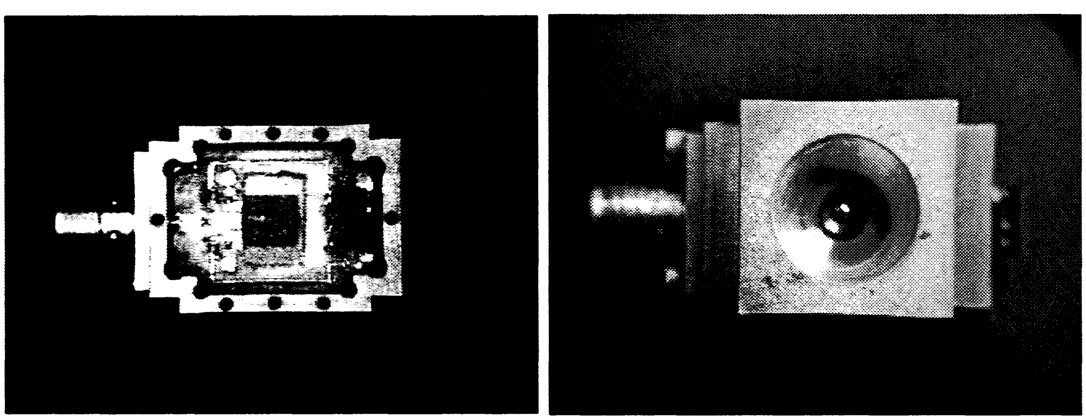
FIG.3. (a) a quasi-optical design illustration; (b) a photograph of the twin-slot antenna. The PHEB device in the center is too small to be seen.

IV. EXPERIMENTAL SETUP

The lens/substrate assembly was inserted into a mixer block, which also served as a bias tee. The mixer block (shown in FIG.4) was attached to a copper post, which was thermally anchored at its other end to the liquid helium reservoir of a commercial dewar. A heater controls the temperature of the mixer block. A cooled HEMT amplifier with a gain of 20 dB is used inside the dewar. This IF amplifier has a pass band from 1000 to 1800 MHz with a noise temperature of about 5 K. The contribution of the IF chain to the total double sideband receiver noise temperature is given by

$$T_{DSB.R} = \frac{Lc}{2}\left(T_{Device.out} + T_{IF}\right). \qquad (1)$$

The receiver noise temperature was measured with a CO_2 laser pumped far infrared (FIR) gas laser as the LO source. Mylar beam splitters with a thickness of 6 μm act as diplexer between the LO and a chopped hot/cold noise source. The LO radiation is focused by an off-axis paraboloid (OAP) mirror. FIG.5. shows an illustration of the experimental setup for noise temperature measurements.



(a) **(b)**

FIG.4. Photographs of the mixer block (a) front view; (b) back view.

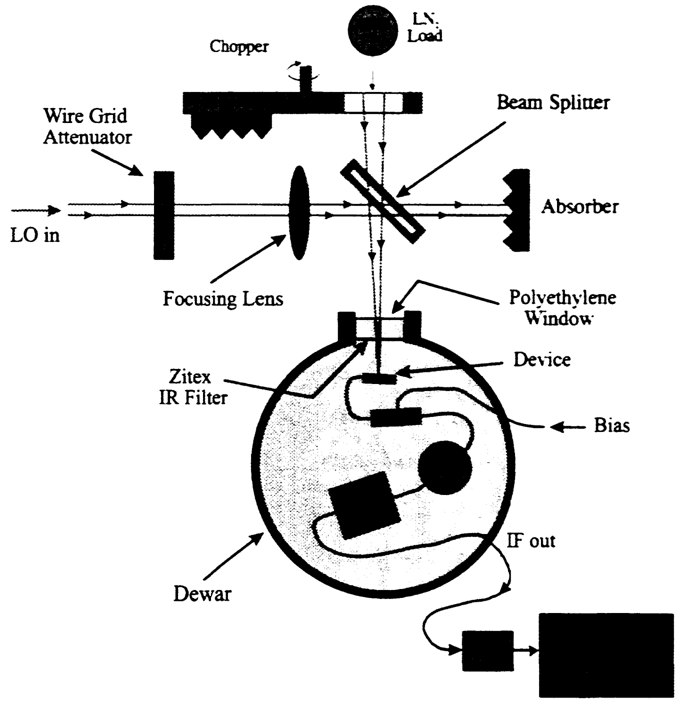
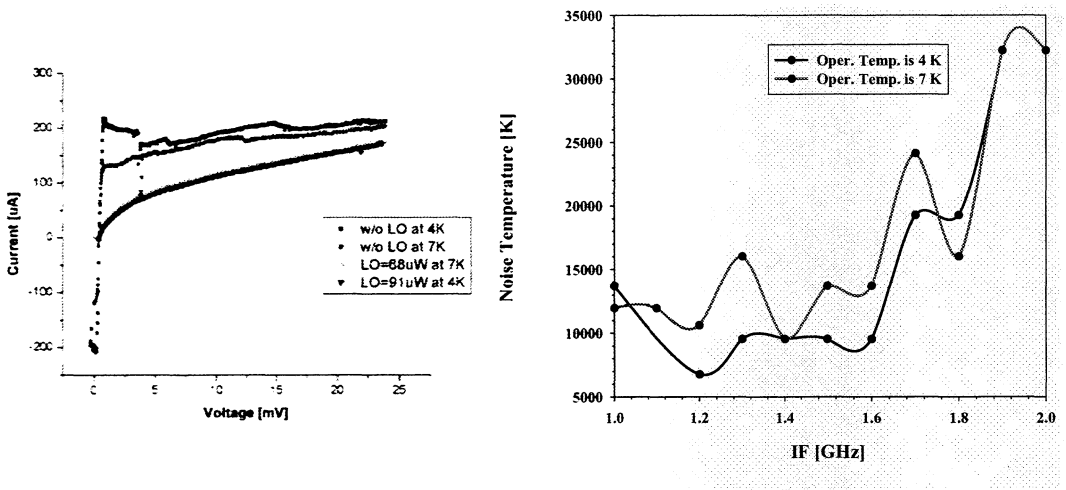


FIG.5. A diagram of the experimental setup for noise temperature measurements.

V. RESULTS AND DISCUSSION

The measured I-V curves for the devices resemble those of the best devices fabricated [4]. The LO power coupled to the devices here is an order of magnitude larger than for the best devices. The coupling losses are evidently more substantial for the devices produced here. The mismatch between the MgO substrate and the silicon lens and some optical misalignments are probably responsible for the higher LO power requirement and subsequently for the degraded noise temperature results. The best double-sideband receiver noise temperature measured at a wavelength of 184 μm (1.63 THz) is 3700 K. We also studied the dependence of noise temperature and IF bandwidth on the ambient temperature. FIG.6(a) shows the LO pumped I-V curves for one of the devices at two ambient temperatures (4 K and 7 K). The optimum pumped curves are identical for different temperatures and the LO power deceased by 1.3 dB for the elevated ambient temperature of 7 K. This results was expected from the principle of electrical substitution. The noise temperature performance was degraded slightly for the elevated ambient temperature (see FIG.6(b)). The noise tempera-



(a) **(b)**

FIG.6. (a) I-V characteristics of the device at two ambient temperatures; (b) noise temperature vs. IF at the two ambient temperatures.

ture results for this device are not the best; nevertheless, the behavior of the HEB at two different temperatures shows that the receiver noise temperature change is quite small. Since receiver noise temperatures of a few (10-20) times the quantum noise limit have been demonstrated for many devices operating at 4 K, our results show that the same performance should eventually also be possible at elevated temperatures. The IF bandwidth at 7 K with a 5 nm thick NbN film deposited on an MgO substrate is at least 2 GHz. These preliminary results are very encouraging.

In order to improve the power coupling to the PHEB device, we are experimenting with a different type of antenna. An illustration of the slot-ring antenna design currently under development is shown in FIG.7. Slot-ring antennas are well suited for use with terahertz PHEBs. A CPW stub filter, which presents an open circuit at the slot-ring, is used. The CPW will be fabricated with air bridges (well-known in MMIC technology at lower frequencies) in order to ensure that only the main CPW mode propagates. Although slot-ring antennas have been used successfully at much lower frequencies, they present a challenge at terahertz frequencies.

We also develop an InP HEMT MMIC cryogenic low-noise amplifier technology to be integrated with HEB receivers. An IF bandwidth of 1 to 10 GHz, together with a noise temperature less than 10 K, are now within reach. FIG.8 shows photographs of an MMIC design

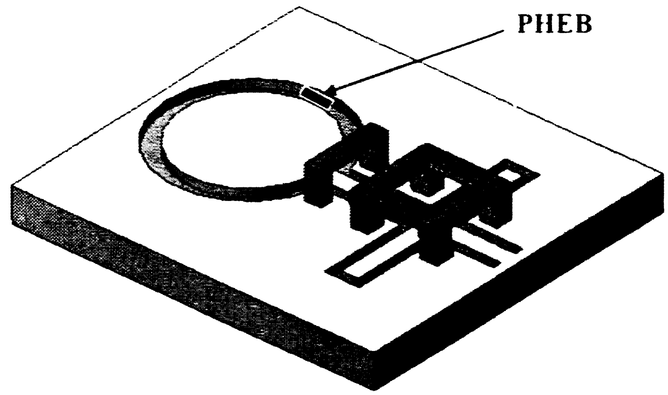


FIG.7. An illustration of a slot-ring antenna design with PHEB device.

under development at UMass. The MMIC chip was obtained courtesy of Dr. Sander Weinreb from JPL/CalTech. The amplifier noise temperature shown in FIG.8 includes contributions from the second stage (1.5 K-1.8 K approx.) and about 0.8-0.9 K from the isolator.

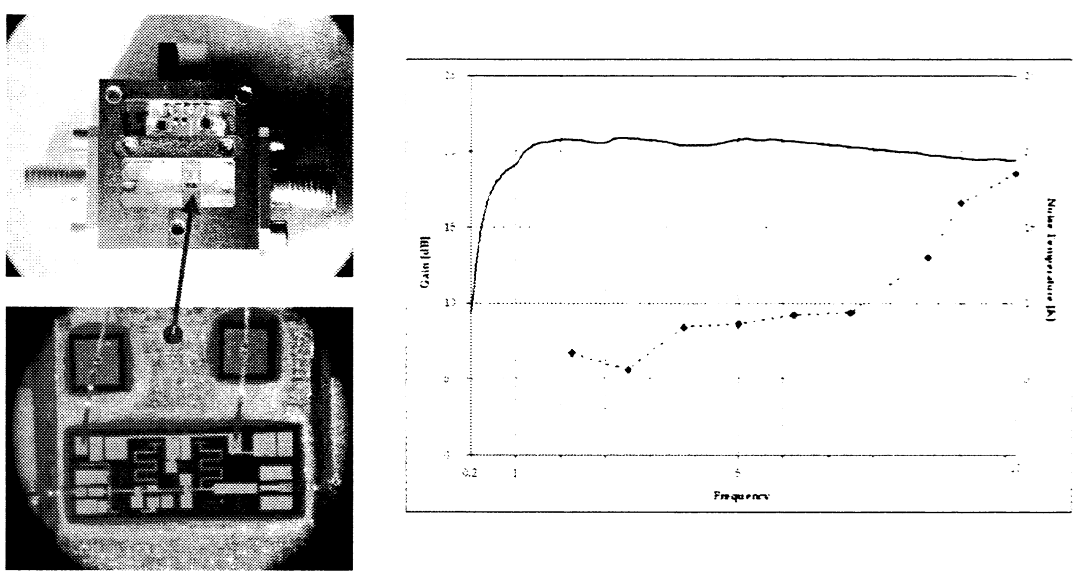


FIG.8. An InP HEMT MMIC cryogenic low-noise amplifier.

ACKNOWLEDGMENTS

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