NbN FILM DEVELOPMENT FOR PHONON-COOLED HEB DEVICES

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ABSTRACT - Superconducting Hot-electron Bolometric (HEB) mixers employing thin films of NbN have become the devices of choice for heterodyne detection at terahertz frequencies. HEB mixers are inherently insensitive to the bandgap frequency of the superconducting material used in the device, in contrast to SIS mixers. We have developed a fabrication process for thin NbN films at the National Institute of Standards and Technology in Boulder, CO. A two-fold approach can be taken. The first is to maximize the critical temperature of the superconducting device by growing thicker films at the expense of IF bandwidth, whereas the second approach focuses on maximizing the IF bandwidth at the expense of the critical temperature. So far, we have developed a film-deposition process utilizing our DC reactive magnetron sputtering chamber. By current-biasing the RF plasma in a mixture of Ar and N_2, while using a Nb target, we can control the film stoichiometry and produce films with thicknesses of 5 nm. The films are deposited on MgO substrates that are heated to about 800 °C during deposition. A typical critical temperature (T_c) is about 10 K and the transition width is very small (0.5 K). The films are evaluated by measuring their superconducting characteristics as well as their thickness and surface roughness by means of AFM analysis.

Phonon-cooled HEB devices are fabricated from the films to study their performance as HEB mixers. The device fabrication process at UMass/Amherst involves lift-off lithography of the antenna (gold), and Reactive ion etching (RIE) or wet etching of the NbN. The I-V characteristics and noise temperatures of the devices were measured in order to determine their quality for PHEB applications.

I. INTRODUCTION

Heterodyne detection is the most sensitive spectroscopic technique over a broad frequency range that produces high spectral resolution in the THz region. A technological challenge is therefore to develop heterodyne receivers with the best possible sensitivity and bandwidth that are still compatible with such constraints as operating temperature and power available from existing local-oscillator (LO) sources. Hot-electron bolometric (HEB) detectors, with a thin film superconductor (NbN) as the active medium, have been under development for the last decade. NbN HEB detectors have demonstrated an increase in sensitivity of an order of magnitude and a decrease in LO power requirement by three orders of magnitude 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. A two fold approach can be taken for the development of HEB technology. The first is to maximize the critical temperature of the superconducting device by growing thicker films at the expense of IF bandwidth, whereas the second approach focuses on maximizing the IF bandwidth at the expense of the critical temperature. Here, we concentrate first on maximizing the critical temperature at the expense of the bandwidth. To conduct the investigation, we have developed a film-deposition process utilizing our dc reactive magnetron sputtering chamber. Then, PHEB devices were fabricated from the films. Preliminary results of the noise temperature measurements are presented.

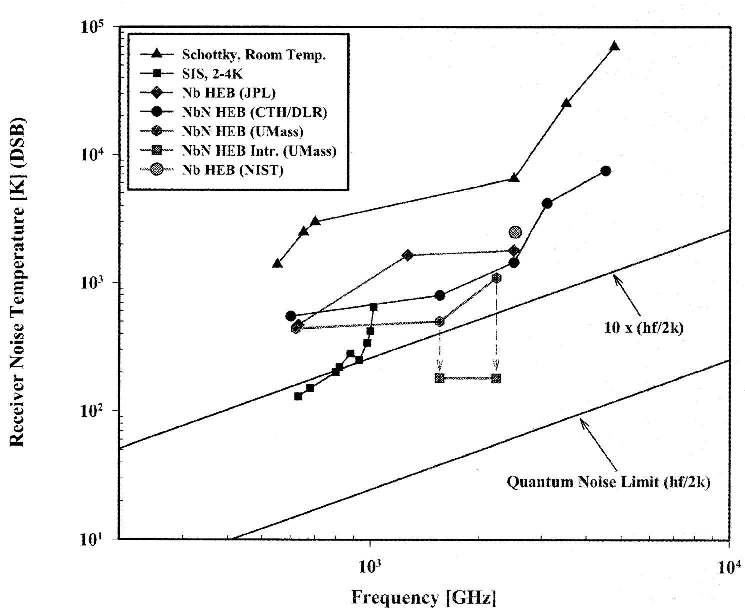


FIG. 1. Noise temperatures vs. frequency for receivers in the terahertz regime [1]-[6].

II. FILM AND DEVICE FABRICATION

NbN Films

NbN thin films were prepared by reactive sputtering from a Nb target in a nitrogen/argon atmosphere. The deposition chamber is cryopumped and achieves a base pressure of 1.5 x 10^{-5} Pa. Total pressure is controlled with a variable throttle valve on the cryopump and is measured with a capacitance manometer. UHP grade argon and zero-grade nitrogen are introduced into the chamber and their flow is controlled by needle valves. The partial pressure of nitrogen is determined simply by subtracting the initial Ar pressure from the total pressure of the mixture. The 75 mm diameter Nb sputtering target 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, are cleaned in ambient temperature HF, 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 onto a dummy sample in an atmosphere of pure Ar, typically for five minutes. 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 [7], 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 films come out 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, though 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.

While pre-sputtering, the MgO substrate was heated to 800°C and actively stabilized at that temperature. Substrate temperature was monitored by 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

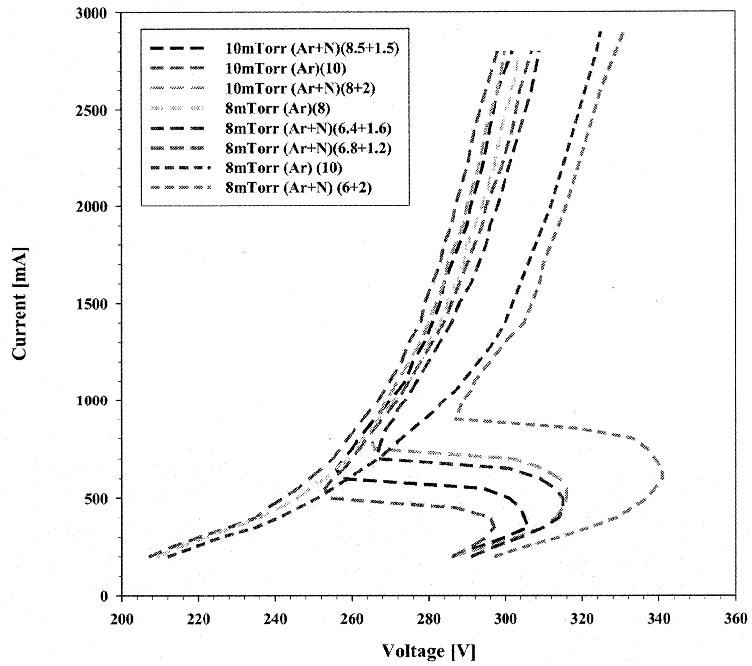


FIG. 2. I-V characteristics of the sputtering plasma.

deposited, the sample was cooled to ambient temperature in 1 atmosphere nitrogen background pressure.

Our highest critical temperature samples (T_c=11.2 K, ΔT_c=0.2 K) were obtained in a 15% N_2, 85% Ar mixture, at 1.33 Pa total pressure, an applied current of 1.2 A, and resulting voltage of about 275 V. Film thickness is measured with a commercial atomic force microscope (AFM). Typical deposition rates are around 0.25 nm/s. For the series of samples described here, a constant film thickness of 5 nm was desired. Accordingly, the deposition time for each film was adjusted under the assumption that deposition rate is proportional to power. Two optimization studies for maximizing critical temperature as a function of the plasma current and substrate temperature are shown in FIG.3.

Quasi-optical Design

The next step is 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 THz radiation into the device. A twin-slot antenna was photo-etched in a 200 nm gold layer that had been e-beam evaporated over the NbN film. Af-

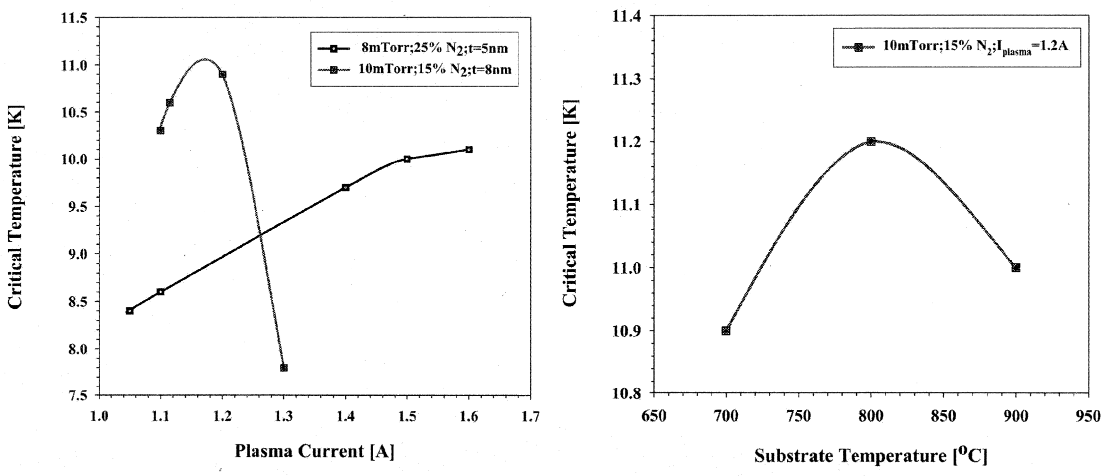
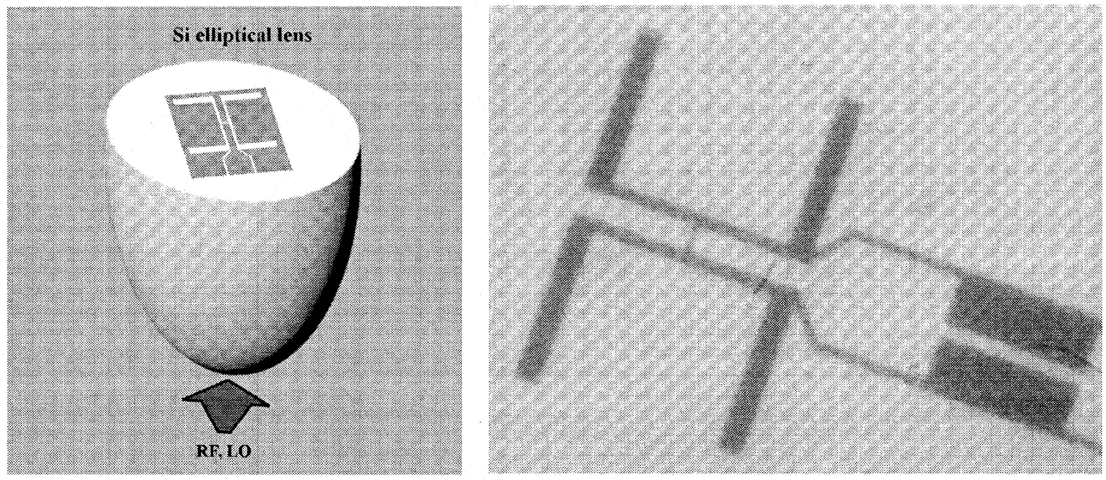


FIG.3. Optimizations of critical temperature as a function of substrate temperature and plasma current.

ter the gold layer was lifted off, the NbN film was wet-etched to define a HEB device with length of 1 μm and width of 4 μm. The antenna response is centered at 1.5 THz, with a bandwidth of 1 THz to 1.9 THz. FIG.4 shows a photograph of the HEB device at the terminals of a twin-slot antenna. Following device fabrication an elliptical Si lens was affixed to the backside of the substrate. The lens was positioned using lines which had been accurately scribed on the lens side of the substrate and then affixed with purified bee's wax. The lens/substrate assembly was inserted into a mixer block, which also served as a bias tee. A three-section filter prevents THz radiation from escaping out the IF port. Four devices were fabricated, and one of these was tested successfully.

III. EXPERIMENTAL SETUP

The integrated antenna/HEB device and lens are attached to a copper post, which is thermally anchored at the other end to the liquid helium reservoir of a commercial dewar. The antenna is connected to the IF and bias system via a semirigid coax line. A cooled HEMT amplifier is also used inside the dewar. This IF amplifier has a pass band from 1000 to 2000 MHz with a noise temperature of about 5 K. The receiver noise temperature is measured with a CO_2 laser pumped FIR gas laser as the LO source. Mylar beam splitters with a thickness of 6 μm act



(a) **(b)**

FIG.4. (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.

as diplexer between the LO and a chopped hot/cold noise source. The LO radiation is focused by a TPX lens.

IV. RESULTS AND DISCUSSION

The measured I-V curves are shown in FIG. 5. The top (black) curve was measured with no LO power applied, whereas the remaining curves were measured with different amounts of LO power applied at a wavelength of 184 μm (1.63 THz). The total receiver noise temperature, including the 6 μm thick mylar beam splitter, was about 6,000 K. The antenna and the lens were not optimally aligned in this preliminary experiment; therefore, we expect lower noise temperatures in future experiments. We base this on the excellent I-V curves (low critical current and a large reduction in the current at the resistive stage as shown in FIG. 5), which are similar to those of earlier devices that UMass/Amherst fabricated, and which had noise temperatures in the 500-1,000 K range. FIG.6 shows the measured IF frequency response. The 3 dB bandwidth is about 1.3 GHz, which is less than that for optimized films on MgO. Narrower bandwidths have typically been obtained in other laboratories for the first phase of a film growth program, so this is not too surprising. The preliminary results we have obtained so far are thus quite encouraging.

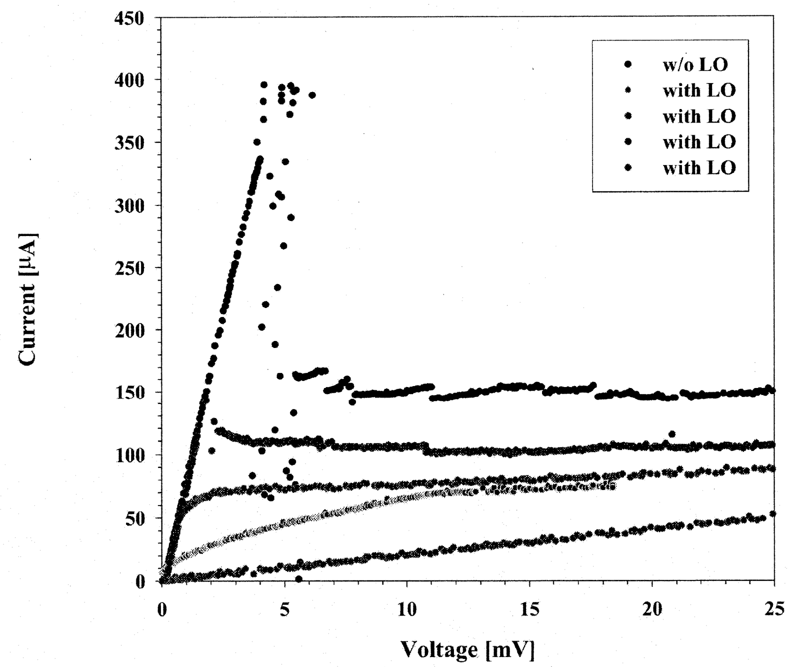


FIG.5. I-V characteristics of the device: the black curve was taken without LO power, showing the instability characteristics of an HEB device, whereas the blue through red curves were taken with increasing LO powers.

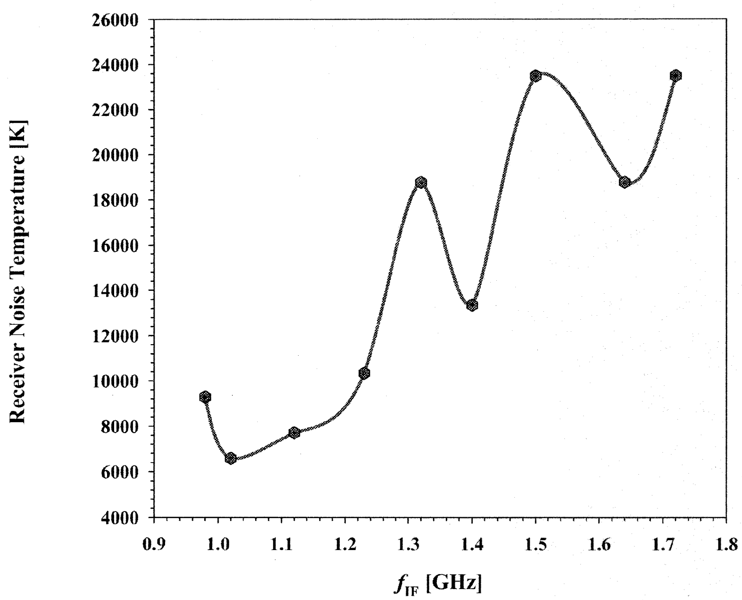


FIG.6. Noise temperature as a function of the IF frequency. The ripple in the frequency response is attributed to the IF filter circuitry.

ACKNOWLEDGMENTS

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