Bandwidth Measurements of NbN HEB Devices with GaN Buffer Layers

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***Abstract*—Hot electron bolometers (HEBs) made of thin films of superconducting NbN are commonly used as far-infrared (THz) heterodyne detectors. The intermediate frequency (IF) bandwidth of a detector is limited by the rate of heat transfer away from the device. Detectors were fabricated from NbN on a GaN buffer layer, instead of a MgO buffer, in hopes of forming a closer acoustic match with the NbN and decreasing the phonon escape time. Acoustic matching has previously shown promising results with MgB_2 films on SiC. Devices on both GaN/Si and MgO/Si were tested with frequencies of 15-25 GHz near T_c = 13.3 K. Results yielded an IF bandwidth for NbN on GaN/Si of approximately 2.8 GHz and of approximately 1.8 GHz for NbN on MgO/Si. These results contrast with a recent publication that measured IF bandwidth of 7.5-8 GHz for NbN HEBs on GaN [1]. It is believed that smaller devices used in the aforementioned publication might result in electron diffusion through the contacts, decreasing the overall electron energy relaxation time. The larger devices used in this experiment show no significant bandwidth improvement of GaN over Si for application in THz HEB detectors.**

I. Introduction

NbN HEBs are used to perform THz spectroscopy in the far-infrared spectrum. This region contains spectral lines that describe the composition of star-forming regions in our and nearby galaxies. HEBs are the only mixer type which can work above 1.3 THz with low noise. NbN HEBs fabricated at JPL are typically deposited on a Si substrate with a MgO buffer. Such devices usually have an IF bandwidth under 3 GHz [2]. Detection of high-frequency lines around 5 THz (e.g., [OI] line @ 4.7 THz) requires an IF bandwidth of about 8 GHz, so measurements of such lines in one shot are not currently feasible [3]. Thus, HEB technology must be improved to increase the IF bandwidth.

To increase their IF bandwidth, devices must transfer heat more rapidly. When infrared radiation is incident on a device, electrons in the NbN film are heated. These electrons pass their heat to phonons in the NbN, which subsequently pass heat to phonons in the substrate. The time it takes for heat to leave the device, the phonon escape time, contributes significantly to the overall cooling time of an NbN HEB. The phonon escape time is proportional to the film's thickness. However, since any further reduction of the thickness in NbN HEB leads to device degradation, the only way to decrease the phonon escape time (= increase the IF bandwidth) is to improve the acoustic impedance matching on the interface between the device and substrate.

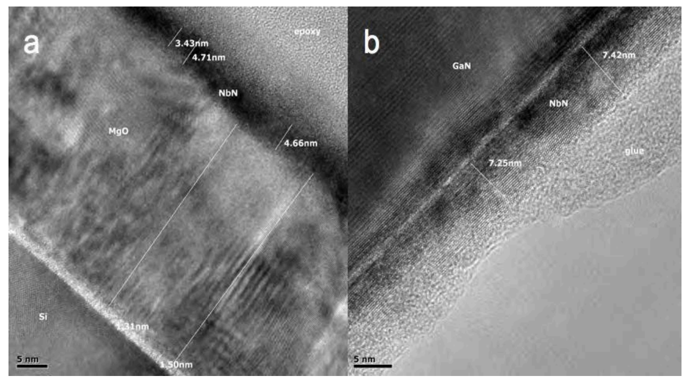

Fig. 1. TEM images of the two types of devices. (a) A device on MgO buffer. The Si substrate visible in the lower left is organized into a lattice, but the MgO buffer appears generally amorphous. The NbN film above the MgO is especially disorganized, with no clear lattice visible. Additionally, the film thickness varies by over a nanometer across the length of the image. (b) A device on GaN. Unlike the MgO buffer, the GaN buffer is neatly organized, and even the NbN film appears to be epitaxial. The NbN film thickness is also relatively constant across the length of the image.

A group from Chalmers University and Moscow State Pedagogical University tested NbN devices made with a GaN buffer, instead of the typical MgO buffer [1]. The group measured an IF bandwidth of 7.5-8 GHz with a GaN buffer. They postulated that the increase in bandwidth was the result of improved acoustic impedance matching on the interface between the GaN and NbN [1]. However, the devices the group used were very small: 3 μm x 0.3 μm x 5 nm. At this device size, electron diffusion is a non-negligible cooling method that could increase the IF bandwidth. If the contacts in a device are too close together and do not have a significant superconducting gap impeding the diffusion, hot electrons diffuse out of the device through the contacts instead of passing their heat to phonons in the device. While this results in faster devices, past experience at JPL with Nb devices has shown that diffusion-cooled devices have higher noise temperatures and less sensitivity than phonon-cooled devices [4].

In this experiment, the bandwidth of larger GaN devices was measured to determine if electron diffusion was the cause of the increased bandwidth observed with small GaN devices.

II. Experimental Methods

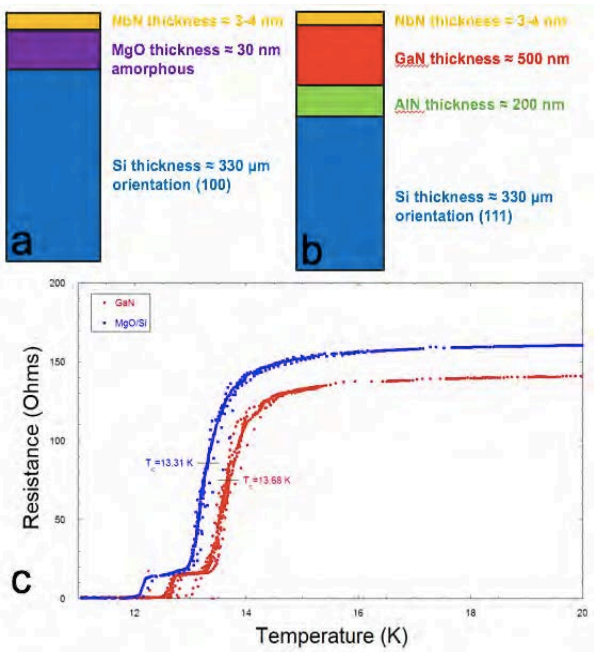

Fig. 2. (a) Diagram of the cross section of a device on MgO buffer. The NbN film is deposited on the MgO buffer, which rests on a Si substrate. (b) Diagram of a device on GaN buffer. NbN is deposited on a GaN buffer, and an AlN intermediate buffer between the GaN and Si substrate promotes epitaxial GaN growth. (c) Resistance vs. temperature curves for the two devices. The shape of the curve is similar for both devices, but the device on MgO has a higher resistance, and the device on GaN has a higher T_C.

Two types of NbN devices were fabricated: one with a MgO buffer and one with a GaN buffer. Both types of devices were 8 µm x 2 µm x 5 nm, almost an order of magnitude larger than the devices from another group mentioned above. The GaN wafer uses an intermediate buffer of AlN to promote epitaxial growth of GaN. The Transmission Electron Microscopy (TEM) images shown in Fig. 1 illustrate the difference in NbN structure caused by the two buffers. The MgO buffer and NbN film shown in Fig. 1a appear relatively amorphous, while the GaN buffer and NbN film in Fig. 1b look much better ordered into lattices.

Cross sections of the wafers used, including dimensions, are shown in Figs. 2a and 2b. R(T) curves of the HEB devices are displayed in Fig. 2c. The MgO device has a slightly higher resistance than the GaN device. The MgO device has T_C = 13.3 K, and the GaN device has T_C = 13.7 K. Otherwise, the two R(T) curves have similar structure. IV curves for the device on GaN are shown in Fig. 3. The curves were measured around T_C without pumping the device. Figure 4 is a photograph of a test device on a GaN buffer. The device itself is circled on the inset. The rest of the image shows the gold-plated circuit contact and the substrate.

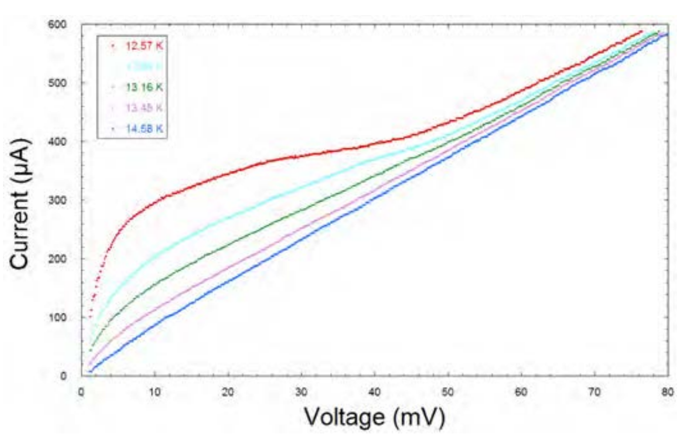

Fig. 3. IV curves near T_C for the device on GaN. The device was not pumped for these measurements.

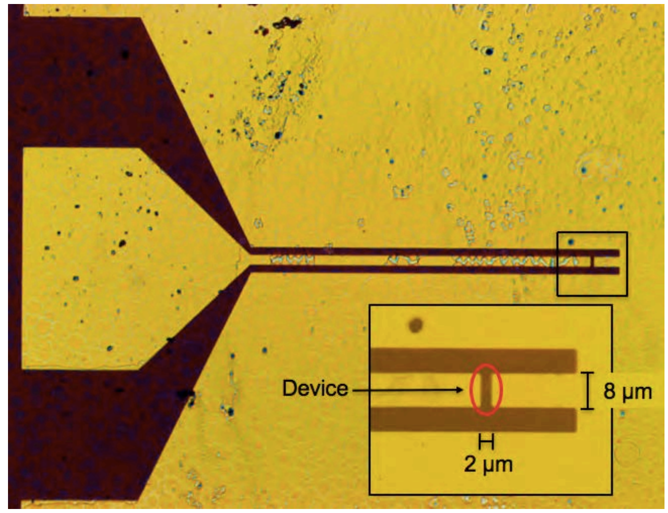

Fig. 4. Image of an HEB chip on GaN used for testing. The gold pentagon on the left is a dc/IF contact, and the HEB device is enlarged in the inset. All devices tested were 8 µm x 2 µm x 5 nm. Current flows to the right along the gold path in the center of the image and across the device into the ground plane.

The IF bandwidth of the devices was tested using microwave techniques. A block diagram of the experimental setup is shown in Fig. 5. The device was cooled below T_C, dc biased, and pumped with microwave radiation. One microwave source was fixed at 15 GHz, and another source was varied between 15-22 GHz. A 7 GHz low-pass filter set the upper limit on the measurable IF signals. The fixed and variable signals were combined and sent to the device at the end of a cryogenic dipstick in a LHe dewar. The device was positioned above the surface of the LHe at a temperature below T_C.

The device mixes the two microwave signals, and the resulting IF signal travels up the dipstick and through the low-pass filter. The IF signal passes through two amplifiers before being read by the spectrum analyzer.

III. Results and Analysis

Bandwidth measurement data of the device on MgO are shown in Fig. 6. Here, IF bandwidth is defined as the frequency at which the signal strength rolls off by 3 dB, signifying a 50% decrease in power. All data in this figure was collected at 12.60 K. The three curves were collected at 3 different bias points, marked on the IV curve in the lower left. The average IF bandwidth among the 3 curves is around 1.8 GHz. This value is expected; NbN devices with MgO buffers have been tested extensively and bandwidth is rarely above 3 GHz. Thus, the experimental setup is validated.

Figure 7 plots bandwidth measurements for the device on GaN. To account for the difference in T_C between the two buffers, data was collected at 12.90 K for GaN buffer, producing an IV curve like that for MgO buffer at 12.60 K. Again, data was collected at the 3 bias points marked on the IV

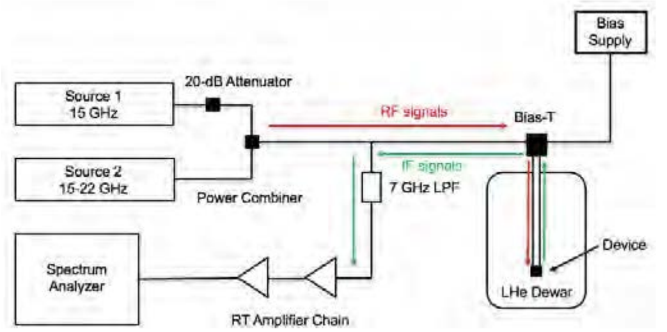

Fig. 5. The experimental setup. Signals originate from two generators: one is fixed at 15 GHz and attenuated, and the other is variable from 15-22 GHz. The signals are combined and travel to the device on the end of a dipstick in a LHe dewar. The device produces an IF signal which passes back up the dipstick, through a 7 GHz low-pass filter, and through a series of amplifiers. The signal is then read by the spectrum analyzer.

curve in the lower left. For these trials with GaN, the average bandwidth is about 2.8 GHz.

While the GaN device offers a 1 GHz improvement in bandwidth over the MgO device, it is far from the 7.5-8 GHz bandwidth measured by the group from Chalmers and Moscow State University. Thus, it appears that the large bandwidth observed in [1] may be due to electron diffusion, and not improved acoustic impedance matching. Although this group's diffusion-cooled devices exhibit a large bandwidth, previous results at JPL predict the devices' sensitivity is poor. GaN may not drastically increase IF bandwidth, but it may still be a viable buffer because it produces higher quality NbN films with well-organized lattice.

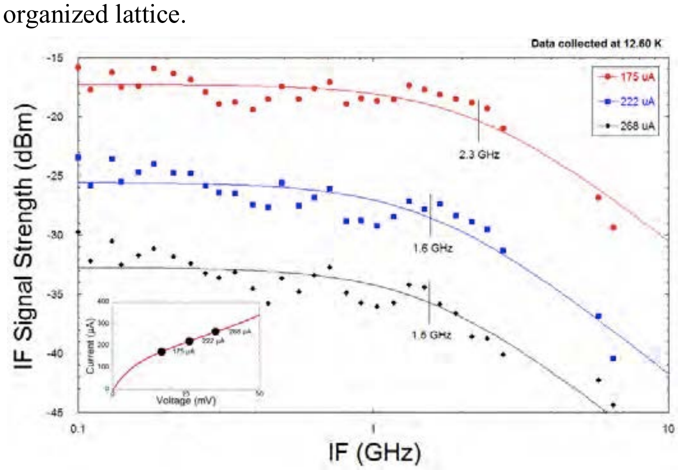

Fig. 6. Bandwidth measurements for the HEB device on MgO. All data was collected at 12.60 K. Each curve was collected at a different bias point, and the bias points are marked on the IV curve in the lower left inset.

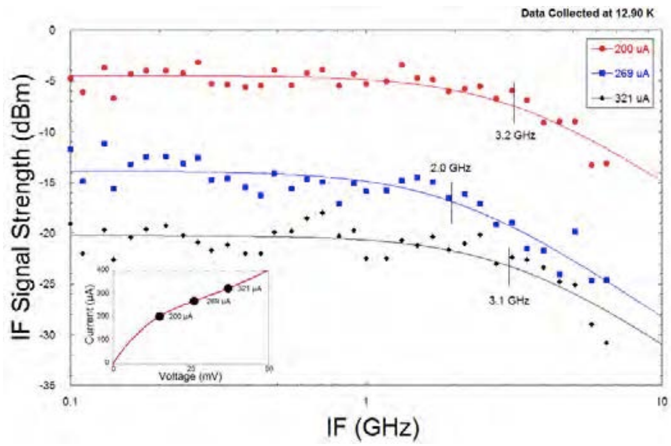

Fig. 7. Bandwidth measurements for the HEB device on GaN. This data was collected at 12.90 K, 0.3 K higher than the measurements for MgO buffer to account for the difference in T_C. Measurements were made at the three bias points marked on the IV curve in the lower left inset.

Conclusions

The IF bandwidth of NbN HEBs with GaN buffer layers was measured as almost 3 GHz, while the NbN device with MgO buffer has an IF bandwidth near 2 GHz. Thus, the large increase in bandwidth observed by another group when using GaN buffers cannot be confirmed. GaN produced well-ordered NbN films that may be useful for fabricating better quality NbN HEBs, but the increased acoustic impedance matching played little role in increasing IF bandwidth.

Acknowledgments

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