Study of IF bandwidth of NbN hot electron bolometers on GaN buffer layer using a direct measurement method

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Abstract— **In this paper, we present a reliable measurement method to study the influence of the GaN buffer layer on phonon-escape time in comparison with commonly used Si substrates and, in consequence, on the IF bandwidth of HEBs. One of the key aspects is to operate the HEB mixer at elevated bath temperatures close to the critical temperature of the NbN ultra-thin film, where contributions from electron-phonon processes and self-heating effects are relatively small, therefore IF roll-off will be governed by the phonon-escape.**

Two independent experiments were performed at GARD and MSPU on a similar experimental setup at frequencies of approximately 180 and 140 GHz, respectively, and have shown reproducible and consistent results. The entire IF chain was characterized by S-parameter measurements. We compared the measurement results of epitaxial NbN grown onto GaN buffer-layer with Tc of 12.5 K (4.5 nm) with high quality polycrystalline NbN films on Si substrate with Tc of 10.5 K (5 nm) and observed a strong indication of an enhancement of phonon escape to the substrate by a factor of two for the NbN/GaN material combination.

INTRODUCTION

Utilizing the heterodyne receiver scheme at submillimetre and terahertz frequencies with high spectral resolution offers a great opportunity to study objects in the distant universe and helps understanding the processes taking place in the cold universe [1]. In order to observe these weak signals from Earth, highly sensitive receivers are required. Beyond approximately 1.2 THz, only hot electron bolometers based on NbN material provide ultimate noise performance and are the technology of choice where lowest noise is required. However, due to their physical working principle, they inherently possess a roll-off of their IF bandwidth, which can be associated with the cooling rate of "hot" electrons [2]. Two major relaxation processes have been identified in phonon cooled HEBs, namely the electron-phonon interaction and the subsequent phonon escape to the underlying substrate [2], [3]. Buffer-layers to promote the growth of high quality ultrathin–NbN films as well as to improve the acoustic matching have been considered essential to overcome their limited IF bandwidth, which only amounts to typically 3-4 GHz for recent operational receivers [4] [5] [6]. Even though improvements at the thin-film level have already been shown with the use of GaN buffer layers [7], the impact of the improved thin-films on mixer- and especially IF performance of HEBs made out of them has not been demonstrated yet. This study is aiming at determining the influence of the GaN substrate on escape time in comparison to conventional Si substrates, used to grow the NbN films onto.

EXPERIMENT

The measurement technique applied here is based on recording the IF output power of the HEB mixer, which is operated at elevated bath temperature close to the critical transition temperature (Tc) of the NbN ultra-thin film. In this operation mode, the inherent complex energy relaxation process of electrons is dominated by the escape of phonons to the substrate [2], [3]. Moreover, the raise of bath temperature has further implications such as the reduction of the energy gap of the superconducting material, thus being able to operate the mixer at lower LO frequencies, where measurement equipment and sufficiently high RF power is easily available. The characteristic escape time is proportional to the thickness of the NbN film and inversely proportional to the acoustic matching between the film and the substrate as well as the mean sound velocity of the film [8].

A. Ultra-thin NbN films

For this experiment, we prepared two high quality NbN films on Si substrate and GaN (0001) buffer-layer by means of reactive DC magnetron sputtering at elevated substrate holder temperatures. The film grown onto silicon at MSPU exhibited a poly-crystalline structure and a Tc of 10.5 K for 5 nm thickness. In contrast, the NbN film, which was deposited onto the GaN featured a single crystal structure due to the small lattice mismatch with high Tc of 12.5 K for 4.5 nm thickness.

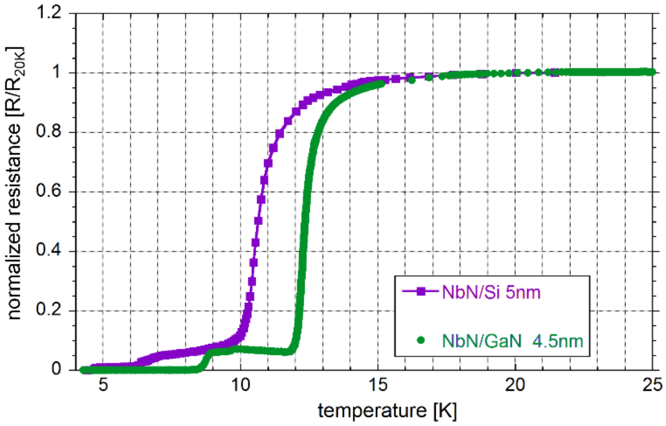

Fig. 1 Resistance versus temperature curve of the HEB bridges made of NbN, which was grown onto Si substrate (Tc=10.5 K) and GaN buffer-layer (Tc=12.5 K). The double transition is caused by the weakened superconductivity under the contact pads.

The electrical resistance versus temperature behaviour is shown in Fig. 1 and reflects the high quality of the NbN ultra-thin films, used to make the HEB from. The bolometer bridges with dimensions of 0.3x3 µm (fabricated at MSPU) and 0.2x2 µm (fabricated at GARD) and the log-spiral antenna was defined by e-beam lithography and subsequent dry etching.

B. *Experimental setup*

Two similar measurement systems were established at MSPU and GARD in order to cross-verify the measurement data of both laboratories.

The RF signal frequency of the HEB was chosen at 180 GHz (GARD) and 140 GHz (MSPU) and the signal was combined with the local oscillator signal (LO) through a waveguide hybrid (GARD) and beam splitter (at MSPU), respectively. The patterned chip was directly placed onto the waveguide opening, despite the resulting poor impedance match, the pumping of the mixer was easily achieved due to the raised bath temperature. The cooling of the mixer was achieved in a cryostat (GARD) to 4 K and subsequent temperature control of the mixer block by a resistive heater. At MSPU the device was cooled in a liquid helium Dewar and positioned carefully above the helium surface in order to control the temperature of the mixer. The current-voltage (IV) characteristic was recorded frequently during the measurement to exclude effects of drift of the operational point and to ensure constant conditions throughout the experiment. While sweeping the LO frequency, the IF output power level was measured with a spectrum analyzer in the frequency range of 0.2 to 7 GHz.

The entire IF chain including the LNA, bias T, coaxial cables, the mixer block and the HEB in its operating point was characterized by a S-parameter measurement and calibrated with gating and time domain reflectometry (TDR) techniques [9]. The recorded IF data was corrected with the deduced transfer response of the connected IF chain in the frequency band of interest.

RESULTS AND DISCUSSION

The measurement systems were verified by characterizing one particular HEB (NbN on Si with 0.3x3µm) in both laboratories. The recorded IF response, after de-embedding the IF transmission chain, are in very good accordance, as depicted in Fig. 2.

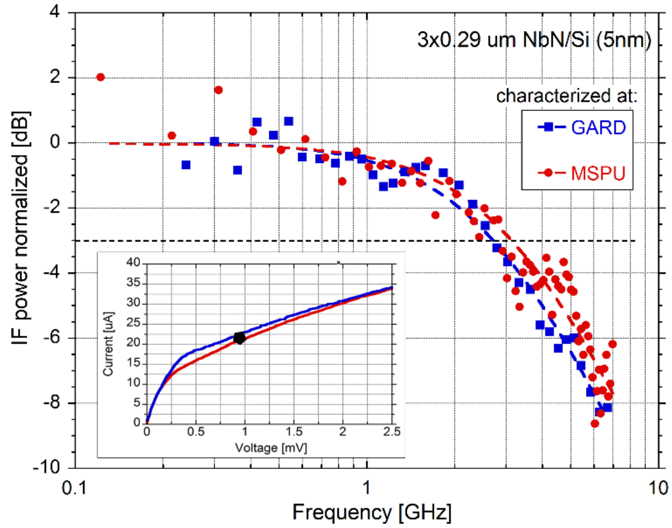

Fig. 2 Normalized recorded IF response for one particular NbN/Si HEB, which was characterized at MSPU (red) and at GARD (blue). The IF power versus frequency is similar and shows a roll-off at approximately 3 GHz. The operating point is indicated in the IVC in the lower left section.

Moreover, the effects on the response by changing bias point and LO power level were investigated and do not show a significant change in the IF roll-off (drop of power by 3 dB). This supports the assumption that the self-heating effect is small in this operation mode of the mixer and therefore, particularly suitable to investigate the influence of film and substrate on the phonon escape.

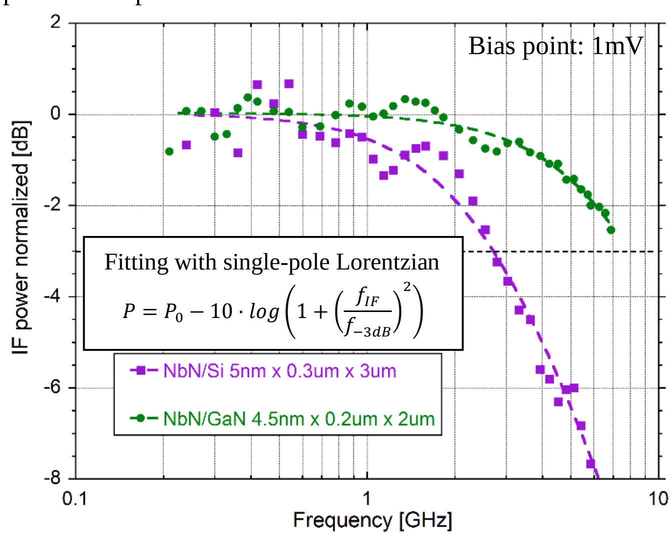

Fig. 3 Normalized recorded IF response for the HEB made of NbN/Si and NbN/GaN.

The 3-dB roll-off as indicated by the dashed line amounts to approximately 3 GHz for the NbN/Si HEB. However, the roll-off frequency, observed for two separately fabricated NbN/GaN HEBs, was significantly increased and amounts to 7.0-7.5 GHz at pumping and bias conditions similarly to the investigated NbN/Si as seen in Fig. 3.

CONCLUSION

It was presented a measurement technique, which allowed to study the effect of buffer-layers on the escape of phonons in phonon-cooled HEBs by operating the mixer at elevated bath temperatures close to the critical temperature of the NbN film, where the contribution of the electron-phonon interaction process and self-heating effect is comparably small. The HEB utilizing a GaN buffer-layer to promote high quality growth of NbN shows a significant enhancement of IF roll-off frequency compared to commonly used Si substrate. Thus, employing the GaN buffer-layer in future THz phonon-cooled HEB mixers based on NbN material may eventually help to overcome the limitation of their small IF bandwidth.

Further studies using this measurement setup will focus on differently sized bolometers to investigate the impact of bolometer area on IF bandwidth and more extensive studies on the effect of underlying buffer-layers.

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