Reduction of phonon escape time for NbN hot electron bolometers by using GaN buffer-layers

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Abstract— **In this paper, we investigated the influence of the GaN buffer-layer on the phonon escape time of phonon-cooled hot electron bolometers based on NbN material and compared our findings to conventionally employed Si substrate. The presented experimental setup and operation of the HEB close to the critical temperature of the NbN film allowed for the extraction of phonon escape time in a simplified manner. Two independent experiments were performed at GARD/Chalmers and MSPU on a similar experimental setup at frequencies of approximately 180 and 140 GHz, respectively, and have shown reproducible and consistent results. By fitting the normalized IF measurement data to the heat balance equations, the escape time as fitting parameter has been deduced and amounts to 45 ps for the HEB based on Si substrate as in contrast to a significantly reduced escape time of 18 ps for the HEB utilizing the GaN buffer-layer under the assumption that no additional electron diffusion has taken place. This study indicates a high phonon transmissivity of the NbN-to-GaN interface and a prospective increase of IF bandwidth for HEB made of NbN on GaN buffer layers, which is desirable for future THz HEB heterodyne receivers.**

Introduction

Up to now, phonon-cooled hot electron bolometer (HEB) mixer based on NbN material provide ultimate noise performance in the terahertz frequency range and outcompete any other technology [1]. However, due to their physical working principle, they inherently possess a roll-off of their gain bandwidth, which can be associated with the cooling rate of "hot" electrons [2]. Consequently, the usable IF band of state-of-the-art receivers still remains limited to typically 0.2-5 GHz [3], [4], [5], which may not be sufficient for spectroscopic observations of distant, fast moving objects due to spectral line broadening and restricts the efficient use of observation time. In recent years, the prospective use of MgB_2 with high critical temperature (Tc) of 39 K for HEB mixer applications has become a promising candidate to boost the IF bandwidth performance due to its fast thermal relaxation time. However, the reported noise temperatures are still inferior to the best NbN HEB mixers and local oscillator (LO) power requirements are more demanding [6] [7].

Two major heat relaxation mechanisms have been identified, namely the electron-phonon interaction and the subsequent phonon escape to the underlying substrate [2], [8]. The superconducting and material properties of the NbN film determine the electron-phonon interaction, whereas the phonon transmissivity between NbN film and substrate mainly defines the rate of phonons escaping. The latter can be improved by reducing the thickness of the NbN film as well as increasing the acoustic matching in order to facilitate the phonon-escape cooling [9]. Despite advances in the reliable fabrication of NbN films with thicknesses ranging from 3.5 to 5 nm, approaching the coherence length of NbN unavoidably manifests in the suppression of its superconducting properties [10]. Thus, buffer-layers with similar crystal structure to NbN such as MgO [10] or 3C-SiC [11], [12] have been employed to promote the growth of single-crystal films with improved superconducting properties. Although, MgO is highly hydrophobic and complicates the fabrication of the delicate HEB device, it has yielded a larger (up to 3.7 GHz) gain bandwidth of the HEB when used on quartz substrates (2 GHz gain bandwidth) [13]. Moreover, it has recently been reported the possibility to grow epitaxial ultra-thin NbN with high critical temperature (Tc) by using a hexagonal GaN (0002) buffer-layer [14], [15]. Yet, the impact on the IF performance of the superior material properties of the films grown on GaN buffer-layers of the HEB made out of them, has not been demonstrated. We believe though that the use of this buffer-layer may also increase the phonon transmissivity between the NbN film and the substrate as the escape of phonons at the interface is not hindered by defects or lattice mismatch, as seen in Fig 1, which depicts the structural and crystallographic features of ultra-thin NbN on GaN [14]. This should have positive effects on the thermal conductance [16].

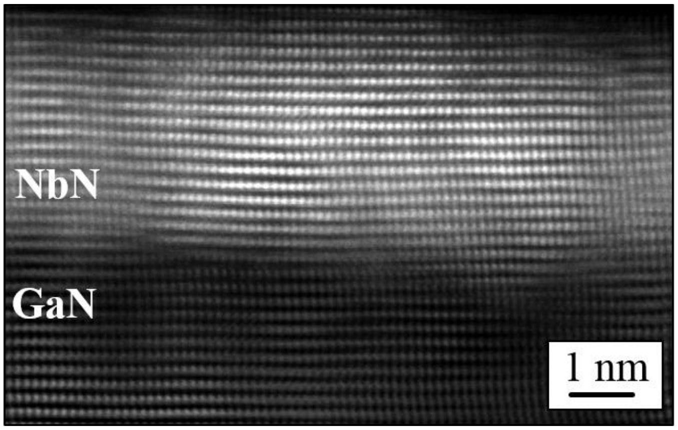

Fig. 1 HAADF/STEM image of the interface of NbN and the GaN buffer-layer. The low defect interface as well as the lattice match, which promotes an epitaxial growth of NbN, favors the phonon transmissivity [16].
(Credit to Dr. E. Pippel at MPI of Microstructure Physics, Halle/Saale, Germany)

Furthermore, the acoustic matching between a thin superconducting film to a substrate can be evaluated for isotropic and semi-infinite media by using Snell's law [9]. This theory has been applied for NbN and various substrates in order to calculate the acoustic matching coefficient for transverse phonons η_t, which depends upon the material properties such as the transverse acoustic velocity and density of the material, respectively, as seen in Table 1 for substrates to grow NbN onto. However, the accuracy of this model due to certain simplifications should be taken with caution as it predicts lower than experimentally observed escape times [8] and thus shall be seen as a more general trend.

TABLE I
MATERIAL PROPERTIES FOR NbN AND VARIOUS SUBSTRATES

material	acoustic wave speed (transverse, [100]) [m/s]	density [g/cm3]	reference
NbN (cubic)	4381[1]	8.47	[17], [18], [19], [20]
Si (100)	5840	2.33	[21]
SiO_2 glass	4000	2.2	[22]
SiC (3C, cubic)	4100	3.17	[23]
MgO (cubic)	6060	3.58	[24], [25]
Sapphire (c-axis)	6450	3.99	[9]
AlN (wurtzite)	6220	3.26	[23]
GaN (wurtzite)	4130	6.15	[23]

Generally, it can be stated that substrates with sound velocities smaller and densities greater than the one of the superconducting film are favorable for good acoustic matching and also prohibit the trapping of phonons as well as total internal reflection at the interface [9]. Fig. 2 illustrates the acoustic matching of transverse phonons between NbN and various substrates, computed on the basis of Kaplan's theory [9]. Transversal phonons are dominating in the electron scatter process in disordered films such as ultra-thin NbN [26].

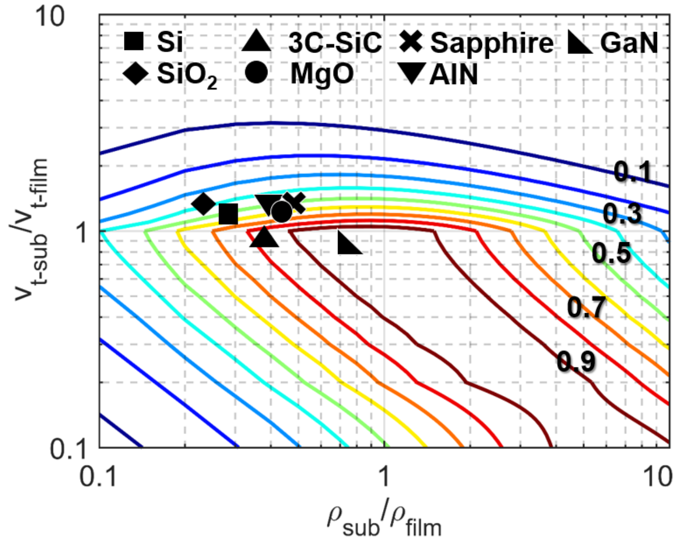

Fig. 2 Transversal acoustic matching coefficient of the NbN film and various substrates. Typically used substrates only provide a poor acoustic match, whereas the relatively heavy GaN may significantly increase the phonon transmissivity due to the good acoustic match to NbN.

It can be seen that all typically used substrates such as Si, quartz, sapphire and MgO provide a poor acoustic match to NbN, mainly because of their low density and high sound velocity as compared to the NbN material. However, GaN features a relatively high density and sound velocity comparable to NbN, which results in a good acoustic match. This in consequence may help to significantly increase the phonon transmissivity and in turn should lower the phonon escape time of HEBs. As the theory by Kaplan describes the acoustic matching of superconducting films to substrates, it should be taken with special attention for predicting escape times.

In this paper, we experimentally investigate the impact of the GaN buffer-layer on phonon escape in HEBs using a direct RF measurement method.

EXPERIMENT

The measurement technique applied in this study is based on the mixing of both low intensity LO and RF signal at an elevated temperature of the HEB close to the critical transition temperature of the NbN ultra-thin film. In this mode of operation, where the temperature dependent electron-phonon interaction is strong, the IF roll-off is dominated by the escape of phonons to the substrate [2], [8]. Moreover, the raise of physical temperature has further implications such as the reduction of the energy gap of the superconducting material. This lowers the photon energy, necessary to effectively break Cooper-pairs to quasi-particles and facilitates the pumping of the HEB, i.e., very little LO power is needed and the requirements on HEB alignment for maximum RF coupling can be relaxed. Moreover, the mixer can be operated at much lower frequencies, where measurement equipment and RF sources are easily available.

[1] Averaged data of the transverse acoustic velocity was used

A. Ultra-thin NbN films

As mentioned above the superconducting properties of the ultra-thin NbN film are of great importance for HEB's performance. We fabricated high quality films by means of reactive DC magnetron sputtering at elevated substrate temperatures. Poly-crystalline NbN with 5 nm thickness was grown onto bare Si substrate and exhibits a Tc of 10.5 K. The films grown on the GaN (0002) buffer-layer [12], [13] (approximately 2 µm buffer thickness), features an epitaxial crystal structure due to the small lattice mismatch with high Tc of 12.5 K at 4.5 nm film thickness[2].

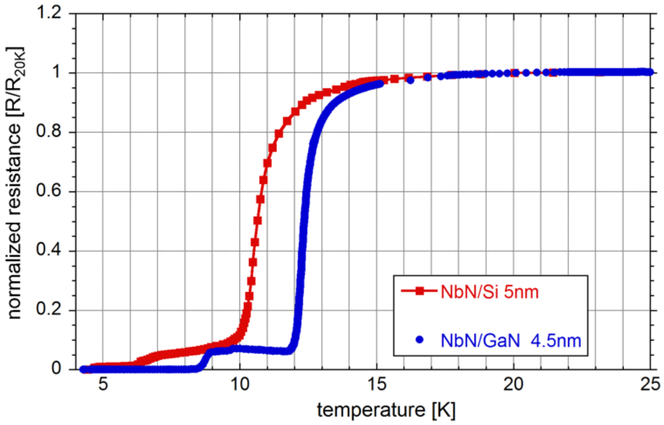

Fig. 3 Resistance versus temperature curve of the HEB bridges made of NbN, which was grown onto Si substrate (Tc=10.5 K) and GaN buffer-layer (Tc=12.5 K).

The electrical resistance versus temperature is shown in Fig. 3. The transition from the normal to the superconducting state is narrow, within 1-1.5 K, and reflects the high quality of the NbN ultra-thin films for prospective use for HEBs. The bolometer bridges of dimensions of 0.2 x 2 µm and 0.3 x 3 µm as well as the embedded spiral log antenna structure were defined by e-beam lithography and subsequent dry etching, as seen in Fig. 4. The contact pads were made by evaporation of Ti, as an adhesive layer, and Au without applying further cleaning steps. As the sputtered NbN on GaN films were stored at ambient atmosphere for up to one month until they were processed, they were likely to form a thin semiconductor-like native oxide [15].

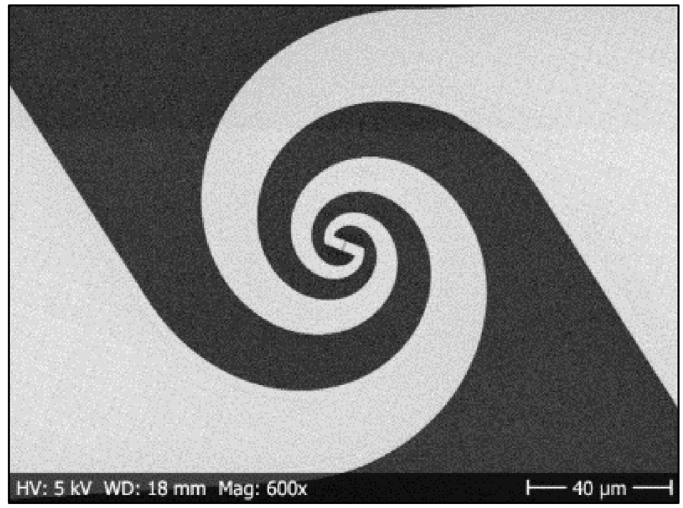

Fig. 4 SEM of the smallest HEB bridge with embedded spiral log antenna

B. Experimental setup

Two similar measurement systems were established at MSPU (Moscow, Russia) and GARD (Gothenburg, Sweden), in order to verify the consistency of the measurement data of both laboratories as depicted in Fig. 5. The specifics of each experimental setup used either at GARD and at MSPU are indicated in blue and red, respectively, as seen in Fig. 5.

The RF sources at MSPU consist of Backward Wave Oscillators (BWO) operating at 140 GHz, and the setup at GARD involved a VDI local oscillator source and a phase-locked YIG oscillator followed by a solid state multiplier signal source with a center frequency of 180 GHz. The RF signal was combined with the LO signal through a waveguide hybrid [27] and a beam splitter, at GARD and at MSPU, respectively. The patterned chip was directly placed onto the open end of a waveguide and despite the resulting poor impedance match, the pumping of the mixer was easily achieved due to the raised bath temperature and sufficient power of the LO/RF sources. The cooling of the mixer block was performed in a dry cryostat (at GARD) to 4 K and subsequently engaged 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 bath temperature of the mixer. was recorded frequently during the measurement to exclude effects of operational point drift and to ensure constant conditions throughout the experiment. The IF signal was amplified by a wideband LNA at room temperature and measured with a spectrum analyzer (using 5 MHz resolution bandwidth and averaging of data points for stable read out within 0.1 to 0.2 dB) up to 7 GHz by sweeping the LO frequency in small frequency steps (20-30 points per decade). Constant monitoring of the current-voltage characteristic (IVC) and subsequently adjusting the LO power level ensured identical pump conditions of the HEB in every frequency point. The signal power level was chosen low enough to not cause the IV characteristic of the HEB to alter, thus we estimate the signal power to be in the range of nW. Moreover, we assumed the

[2] Thickness derived from scaling the deposition time for a calibrated 5 nm film by means of HAADF/STEM presented in Fig. 1.

signal power to stay constant over the period of one measurement, which seemed reasonable as repeated measurements at certain frequencies resulted in identical read-outs of IF power level, hence the drift of the signal source output power was very low. The signal-to-noise ratio was in the order of 30-40 dB for frequencies approximately below 1 GHz and was still above 20 dB for the highest IF frequencies.

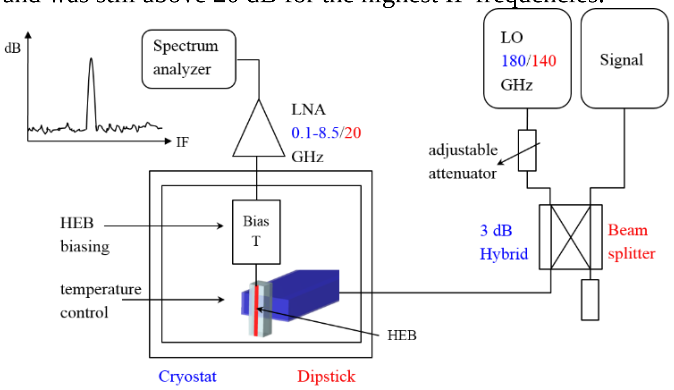

Fig. 5 Schematic of the measurement setup, the components indicated in blue were used at GARD, the red ones were part of the setup of MSPU. The IF signal was amplified by a LNA and measured by a spectrum analyzer. The frequency spectrum of interest was covered by sweeping the LO frequency in small steps and subsequent correction of measured data with the transfer behavior of the IF chain.

The calibration of the entire active IF chain, including cables to the spectrum analyzer, the operating LNA at room temperature as well as the bias T and connectors to the HEB at cryogenic temperatures, was performed by S-parameter measurements and utilizing the gating and time domain features of the VNA similarly to [28]. By not applying bias to the HEB, it was possible to utilize its superconducting state as a short calibration standard and helped to precisely pin-point the electrical length of the coaxial cables in the time domain. Moreover, using this calibration technique also allows measuring the HEB IF output impedance in its operating state under pumped conditions.

Results and Discussion

A. Calibration of the IF chain

The importance of proper wideband calibration shall be emphasized since it was found that the IF chain has an internal roll-off, which manifested itself as increasing insertion loss above approximately 3 GHz, as illustrated in Fig. 6. The IF transfer function in solid red presents a 2-port calibration at room temperature, whereas the blue dashed curve was generated from two 1-Port measurements according to [28] while the HEB mixer was at cryogenic temperatures.

The difference between both calibration techniques is caused by the effects of the cold coaxial cables for the latter calibration with lower coaxial cable resistance and thermal contraction in the dielectric material. The measurement data has been corrected with the cold calibration curve, which helped to improve the accuracy of the measurement data significantly. Furthermore, standing waves due to impedance mismatch with a frequency of approximately 50 MHz, which is equivalent to the electrical length of the whole IF chain, have been predicted by circuit simulations using the S-parameter data and were addressed by applying moving averages to smoothen the transfer response of the IF chain.

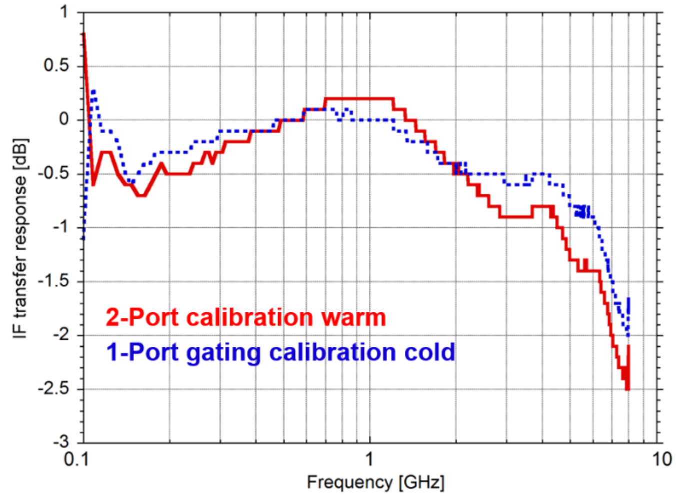

Fig. 6 Averaged system response derived from S-parameter measurements utilizing gating and TDR techniques [28]. The presented response is normalized, thus the actual gain of the amplifier is not visible although its gain variation is included.

B. Measurement verification

In order to verify the validity of the applied measurement method, one particular HEB (NbN/Si with 0.3 x 3 µm) has been characterized under similar bias and pump conditions at both laboratories, as seen in the inset, showing measured IV curves, in Fig. 7. The bias voltage was chosen to be 1 mV, where usually good noise performance of practical NbN HEB mixers is to be expected. The normalized IF power is in good agreement between the different setups, as depicted in Fig. 7. Instabilities associated with the low LO power level were not observed throughout the measurements since the IV curve was continuous and monotonous at elevated bath temperatures even without applying LO power. The HEB IF roll-off occurs at 3 GHz, which is characterized by 3 dB reduction in power as indicated by the dashed line.

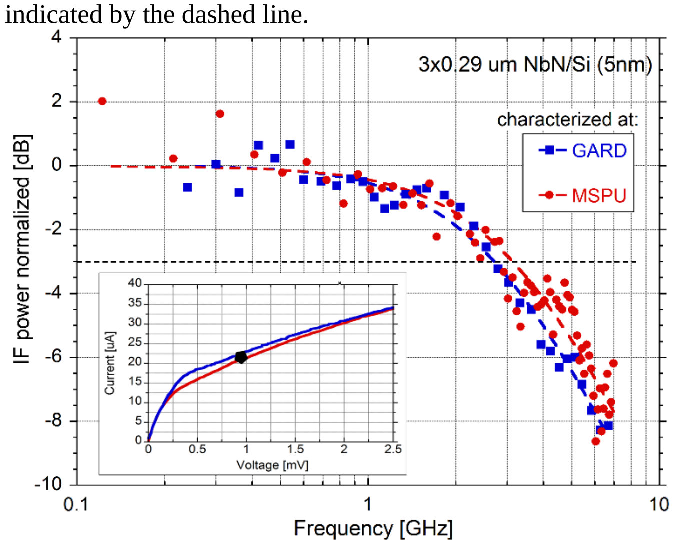

Fig. 7 Normalized recorded IF response for one particular NbN/Si HEB, which was characterized at MSPU (red) and at GARD (blue). The IF power versus

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.

We studied the effects on the IF response by changing the bias point and LO power. This is illustrated in Fig. 8 for the bias voltages of 0.5 mV, 1 mV and 1.5 mV under strong pumped conditions (LO2) and less pumping (LO1) at a constant bath temperature. Even though the absolute maximum IF power level varied from -70 dBm for the LO2 at 0.5 mV to -75 dBm for the LO1 at 1.5 mV, the normalized IF response shows only insignificant differences.

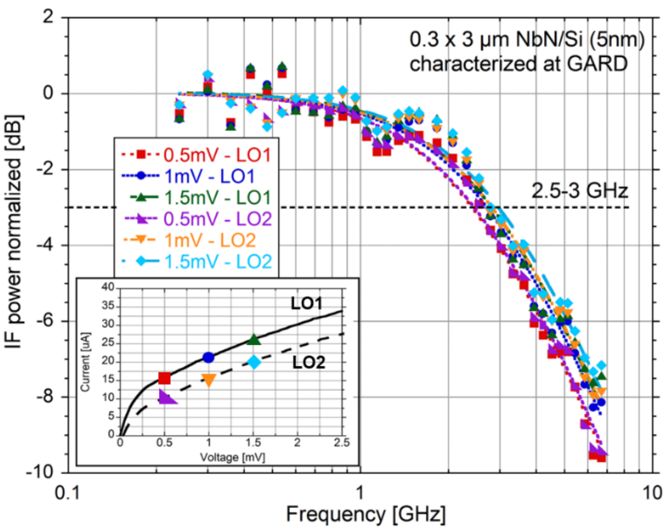

Fig. 8 Normalized IF response for three different bias voltages and pumping levels. The normalized IF response, however, is almost identical. The temperature was kept constant at 8.6 K, which was measured at the block with close vicinity to the actual HEB.

The observed small influence of the bias and pumping conditions on the IF roll-off of the HEB mixer is an evidence for only minor self-heating effects, which would have otherwise complicated the extraction of intrinsic relaxation times.

C. *Escape time of HEB made of NbN/Si and NbN/GaN*

Nebosis et al. [2] used heat-balance equations in the rigorous analysis of the performance of HEBs. Similarly, to our experiment, they operated the HEB at elevated temperatures, although in the detector mode. The solution of heat-balance equations was applied to fit our normalized IF power to the theoretical transfer function Ψ, Eq. (1).

$$\Psi(\omega) = \frac{(1+i\omega\tau_1)(1+i\omega\tau_2)}{1+i\omega\tau_3} \quad (1)$$

with $\tau_1^{-1}, \tau_2^{-1}, \tau_3^{-1}$ and Ω :

$$\tau_1^{-1}, \tau_2^{-1} = \frac{\Omega}{2}\left(1 \mp \sqrt{1-\frac{4\tau_{e-ph}^{-1}\tau_{esc}^{-1}}{\Omega^2}}\right)$$

$$\Omega = \left(1+\frac{c_e}{c_{ph}}\right)\cdot\tau_{e-ph}^{-1} + \tau_{esc}^{-1}$$

$$\tau_3^{-1} = \frac{c_e}{c_{ph}}\tau_{e-ph}^{-1} + \tau_{esc}^{-1}$$

In the temperature range of interest, the temperature dependent electron-phonon contribution $\tau_{\mathrm{e-ph}}$ and the ratio of the specific heat capacity of electrons c_e and phonons c_{ph}, can be estimated by the empirical formula Eq. (2) and (3), which are valid for thin NbN films [29], [30].

$$\tau_{\mathrm{e-ph}} = 500\cdot \mathrm{T}^{-1.6}\ (ps\cdot K) \quad (2)$$

$$c_{\mathrm{e}}/c_{\mathrm{ph}} = 18.77\cdot \mathrm{T}^{-2} \quad (3)$$

Applying Eq. (1-3) to the measured data of the NbN/Si HEB yields a fit for an escape time of τ_{esc}=45 ps, as depicted in Fig. 9a. This value is in a reasonable agreement with the literature [24] value of 38 ps for a slightly thinner film and 40 ps [30] and relates to a drop in recorded IF power by 3 dB at approximately 3 GHz. Making the same fit procedure for the roll-off frequency of the NbN/GaN HEB, we discovered that the IF frequency roll-off was significantly increased to 7.5-8 GHz at pumping and bias conditions similar to the investigated NbN/Si as depicted in Fig. 9b.

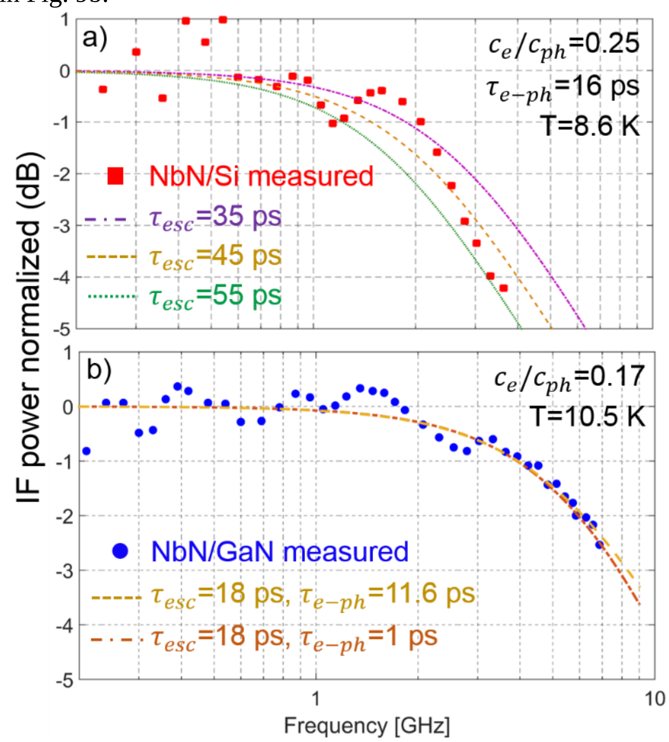

Fig. 9 Fitting of the theoretical response to the measurement data according to Eq. (1-3). The HEB on NbN/Si (upper figure) and NbN/GaN (lower) had identical dimensions of 0.3x3 µm and were operated at the bias voltage of 1 mV and similar pumping conditions. The influence of the fitting parameter τ_{esc} is shown and the best fit was achieved for τ_{esc} = 45 ps for the NbN/Si HEB. However, an escape time of only 18 ps was deduced for the NbN/GaN HEB. The minor contribution of τ_{e-ph} to the fitting is indicated in the lower figure, such as the theoretical response is hardly affected by changing τ_{e-ph} from 1 ps to 11.6 ps (from Eq. 2).

The electron-phonon contribution is negligibly small, according to our simulations (the dashed lines), as there is no difference in the theoretical fit when changing τ_{e-ph} from 11.6 ps (from Eq. (2)) to 1 ps. The associated escape time amounts to only 18 ps, which we believe is mainly attributed to the improved acoustic matching as discussed above. However, the presence of an additional diffusion channel cannot completely be ruled out as it has been observed in NbN mixers with bridge length of 0.19 µm [31]. We believe that the electron diffusion cooling channel should be largely suppressed in our experiment since the contact pads are not deposited in-situ, in contrast to the HEBs studied in [31], [32], and have not been cleaned prior to their deposition. Moreover, two independently fabricated devices with bridge length of 0.2 and 0.3 µm, utilizing the GaN buffer-layer, showed no noticeable difference in IF roll-off.

Furthermore, the higher critical temperature of the NbN film grown on GaN not only allows for a reduction of thickness of the NbN film, thus reducing the escape time, it also implies a higher electron temperature under pumped mixer conditions and lowered ratio of the specific heat capacity of electrons and phonons c_e/c_{ph} (Eq. 3), which in fact favors the IF response towards an extended roll-off (Eq. 1).

Conclusion

The HEBs utilizing a GaN buffer-layer to promote high quality growth of NbN were shown to significantly enhance the experimental 3-dB roll-off frequency of up to 8 GHz compared 3 GHz for commonly used Si substrate. We presented a direct 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 physical temperature close to the critical temperature of the NbN film, where the contribution of the electron-phonon interaction process and self-heating effect are sufficiently small.

Moreover, the escape time was used as a fitting parameter in a theoretical description of the response function of HEBs, which was derived from the heat-balance equations. The deduced escape time for the NbN/GaN HEB, was estimated to only 18 ps, as in contrast to 45 ps for NbN on Si, when considering that only phonon cooling has taken place. We associate the increased HEB mixer roll-off with the improved phonon transmissivity of film and substrate. Thus, employing the GaN buffer-layer in future THz phonon-cooled HEB mixers based on NbN material should help to overcome the limitation of their small IF bandwidth.

Acknowledgement

This work was partly supported by the Ministry of Education and Science of the Russian Federation, Contract No. 14.B25.31.0007. G.G. gratefully acknowledges the support from RFBR, contract #16-29-11779 and the State Task 1846 of the Ministry of Science and Education of Russian Federation. Moreover, this work was supported by the National Centre for Research and Development in the frame of projects INNOTECH-K2/IN2/85/182066/NCBR/13, and PBS/A3/2015.

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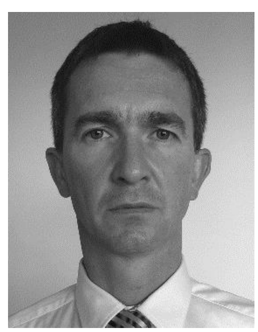

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