Gain bandwidth of NbN HEB mixers on GaN buffer layer operating at 2 THz local oscillator frequency

S. Antipov[1]*, A. Trifonov[1], S. Krause[2], D. Meledin[2], V. Desmaris[2], V. Belitsky[2], and G. Gol'tsman[1]
[1] *Moscow State Pedagogical University, Moscow, 119992, Russia*
[2] *Group for Advanced Receiver Development, Chalmers University of Technology, SE-41296, Gothenburg, Sweden*
*Contact: sv_antipov@mail.ru

Abstract— In this paper, we present IF bandwidth measurement results of NbN HEB mixers, which are employing NbN thin films grown on a GaN buffer-layer. The HEB mixers were operated in the heterodyne regime at a bath temperature of approximately 4.5 K and with a local oscillator operating at a frequency of 2 THz. A quantum cascade laser served as the local oscillator and a reference synthesizer based on a BWO generator (130-160 GHz) and a semiconductor superlattice (SSL) frequency multiplier was used as a signal source. By changing the LO frequency it was possible to record the IF response or gain bandwidth of the HEB with a spectrum analyzer at the operation point, which yielded lowest noise temperature.

The gain bandwidth that was recorded in the heterodyne regime at 2 THz amounts to approximately 5 GHz and coincides well with a measurement that has been performed at elevated bath temperatures and lower LO frequency of 140 GHz. These findings strongly support that by using a GaN buffer-layer the phonon escape time of NbN HEBs can be significantly lower as compared to e.g. Si substrate, thus, providing higher gain bandwidth.

INTRODUCTION

The superconducting NbN hot electron bolometer (HEB) mixer continues to be a key technology for the heterodyne instruments operating at frequencies above 1 THz, offering high spectral resolution combined with record sensitivity at Terahertz frequencies [1, 2]. However, the intermediate frequency (IF) bandwidth of NbN HEB mixer still remains limited to typically 3-4 GHz for recent operational receivers [1, 3, 4]. The employment of on-substrate buffer-layers to promote the growth of high quality NbN films and better acoustic matching to facilitate the phonon escape are considered essential to overcome the IF limitation [5-6]. The latest progress in this direction has been achieved by fabrication of high-quality NbN ultra-thin films with the use of GaN buffer layer [7-8]. The study of IF bandwidth of NbN/GaN HEB mixers was performed under quasi-equilibrium conditions at $T \approx T_c$ using a direct measurement method when HEB mixer operates at elevated bath temperature, at low sub-THz LO frequency, and signal beating oscillations [9]. The impact of the improved NbN films on the RF and especially IF performance of HEB mixers at THz frequencies at low temperature and optimal LO power has not been demonstrated. In this paper, we present the gain IF bandwidth measurement of NbN/GaN HEB mixer operating at 2 THz LO frequency, and study the influence of the GaN buffer layer on IF bandwidth.

EXPERIMENT

A. *NbN/GaN HEB mixer*

The fabrication of submicrometer devices such as HEB mixers with bridge length of about 100-300 nm is a crucial and technologically challenging process. Thus, we produced independently two batches of HEB mixers with identical design at Chalmers and MSPU in order to exclude effects from fabrication related issues. In both cases, the mixers were fabricated starting from NbN thin films deposited at Chalmers by means of reactive DC magnetron sputtering on a GaN (0001) buffer-layer on sapphire and featured a single crystal structure due to the small lattice mismatch with high Tc of 12.5 K for 4.5 nm of thickness [9].The bolometer bridges with dimensions of 0.18 μm x 2.3 μm and the log-spiral antenna were defined by e-beam lithography and subsequent dry etching. The normal state resistance of the bolometer is close to 100 Ω.

B. *Experimental setup*

To record the IF output power of the HEB mixer, the heterodyne technique at $T \approx 4.5$ K was applied by mixing the THz radiation of LO and signal sources. The measurements were performed at the optimal level of the LO power at a fixed bias corresponding to the smallest noise temperature.

A 2 THz quantum cascade laser as a local oscillator and a signal source consisting of a reference synthesizer based on BWO generator (130-160 GHz) and a semiconductor superlattice (SSL) frequency multiplier operating at the 13th SSL harmonic were used as LO and signal source, respectively.

The THz radiation was coupled to the HEB mixer by an extended hemispherical Si lens. The mixer with the lens was cooled to 4.5 K in a cryostat with optical access through a 2 mm-thick high-density polyethylene (HDPE) window and a 200 μm thick Zitex G108 infrared filter mounted on the 77 K screen. The LO beam was diplexed into the signal path using a 12 μm thick Mylar beam splitter. The HEB mixer was IF-coupled to a 1-inch coplanar line with a subsequent transition to a coaxial cable which led the IF signal to a cryogenically cooled bias-T and HEMT low-noise amplifier with a bandwidth 0.4-12.0 GHz and a gain of about 30 dB. This was followed by a similar broadband room-temperature amplifier. The calibration of the IF chain was determined by measuring the portion of the RF white noise that went through the amplifier chain. The white Johnson noise in excess to the intrinsic noise of the first amplifier was produced by the very same HEB mixer driven in the normal state by additional heating to elevated bath temperature close to T≈Tc. The IF power versus intermediate frequency for HEB mixer was measured for constant optimal level of the LO power at a fixed bias conditions. While sweeping the signal source frequency, the IF output power level was measured with a spectrum analyzer.

Results and Discussion

In Fig. 1 we present the relative gain bandwidth of NbN/GaN HEB mixer (red star) that was measured for the 2 THz LO frequency for the optimal operation conditions (colored point in IVC) providing the highest IF signal to noise ratio. In addition, the gain bandwidth of NbN/Si HEB mixer (green circle) is depicted. Standing waves due to reflections between the HEB mixer and cryogenic LNA resulted in the resonance peaks in the IF dependence of the relative conversion efficiency. The peaks almost disappeared when we used the calibration procedure.

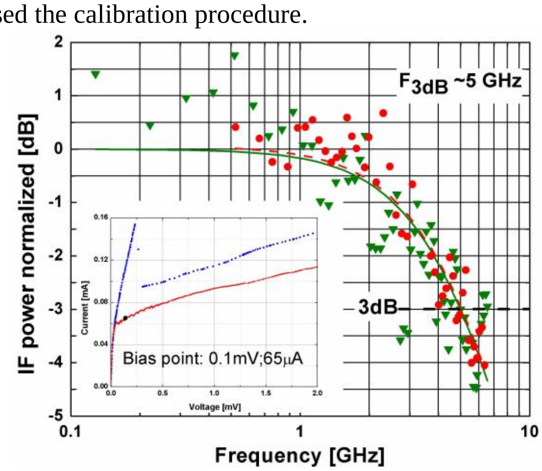

Fig. 1 Gain bandwidth in heterodyne regime at 2 THz at optimal pumping and bias conditions for NbN/GaN HEB mixer. The normalized IF power versus frequency shows a roll-off at approximately 5 GHz. Set of unpumped (blue) and optimally pumped (red) IVCs along with the operation point (0.1 mV; 65 μA) in dc voltage bias regime for NbN/GaN HEB mixer. Comparison of gain bandwidths of NbN/GaN HEB mixers in heterodyne regime at 2 THz (circles) vs elevated bath temperature regime at 140 GHz (triangles).

The normalization considerably enhanced the roll-off frequency determination accuracy of the IF bandwidth. We obtained the 3 dB roll-off frequency f_{3dB} by fitting our experimental IF dependence of the relative gain with single-pole Lorentzian. The gain bandwidth amounts to approximately 5 GHz for the NbN/GaN HEB at optimal pumping and bias conditions.

NbN/GaN HEB mixer shows a significant enhancement of IF roll-off frequency compared to commonly used Si substrate due to the reduction of phonon escape time (τ_{es}) for the NbN/GaN material combination. The typical NbN/Si HEB mixer with slightly large dimensions (5 nm × 0.3 μm × 3 μm) demonstrates of 3 dB roll-off frequency f_{3dB}≈3.4 GHz in heterodyne regime at 2 THz at optimal pumping and bias conditions.

When NbN/GaN HEB mixer operates at elevated bath temperatures close to the critical temperature of the NbN ultra-thin film, the contributions from electron-phonon processes and self-heating effects are relatively small, therefore IF roll-off will be governed by the phonon-escape. As the roll-off is similar for both the heterodyne and direct detection regime (Fig. 1), it may be concluded that in NbN/GaN HEBs the electron-phonon contribution is negligible compared to the phonon escape one. Thus, the IF bandwidth is determined mostly by the phonon escape, which seems to be significantly improved as compared to commonly used Si substrates. In [6], it was presented, that the improved phonon transparency is due to the good acoustic matching between NbN and GaN, as well as the improved low defect interface and enhanced superconducting properties of the NbN film.

Conclusions

The THz heterodyne measurements, which allowed the study the gain bandwidths of NbN/GaN HEB mixer at optimal bias condition, are presented. Utilizing a GaN buffer-layer has resulted in significant enhancement of gain bandwidth frequency of phonon-cooled HEB mixers based on NbN material compared to commonly used Si substrate. Matching of the gain bandwidth results at elevated bath temperature at 140 GHz and in heterodyne regime at 2 THz indicates the reduction of phonon escape time (τ_{es}) due to the GaN buffer layer.

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