Design of a wideband balanced waveguide HEB mixer employing a GaN buffer-layer for the 1-1.5 THz band

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Abstract— We present the design and implementation of a wideband balanced waveguide NbN HEB mixer employing a GaN substrate to be operated in the frequency range of 1 - 1.5 THz.

The balanced receiver scheme consisting of a 90˚ RF hybrid, a pair of NbN phonon-cooled HEB mixers and a 180˚ IF hybrid has major advantages over the single-ended configuration. Furthermore, the usually small IF bandwidth of phonon-cooled NbN HEB mixers has been addressed by employing a GaN substrate instead of a conventional Si or quartz substrate. It has recently been shown that using GaN substrate reduces the escape time of phonons from NbN bridge to the substrate and thus, prospectively enhances the overall cooling rate of hot electrons and yielding larger IF bandwidth. The mixer housing is implemented in a back-end configuration and has been fabricated by means of a micro-machining method, providing excellent control of the dimensions and smoothness of the all-metal waveguide components. The expected RF performance of the proposed HEB design as well as its fabrication and DC characterization are presented.

INTRODUCTION

Heterodyne instruments for high-resolution spectroscopy at the terahertz frequency range primarily employ Hot Electron Bolometer (HEB) mixers (Leisawitz, 2000), (Meledin, o.a., 2009) due to their superior sensitivity and low local oscillator power requirement when compared to the competing Schottky and SIS mixers. Despite the strong absorption by water vapor of the incident THz radiation, it is possible to observe astronomical objects from the ground in three frequency windows in the band of 1-1.5 THz containing several important CO transition lines (Pardo, Serabyn, & Cernicharo, 2001). The demand for a wide IF bandwidth is paramount for the efficient use of valuable observation time as well as for the study of distant objects with strong spectral line broadening.

The working principle of hot electron bolometer relies on the thermal energy exchange between "hot" electrons in the NbN film and the underlying substrate (Gershenzon, Gol'tsman, Gogidze, Elant'ev, Karasik, & Semenov, 1990). Thus, the IF roll off frequency and corresponding bandwidth of receivers in operation is limited to typically 3-4 GHz for NbN based HEB mixers using a conventional substrate such as Si (Il'in, Milostnaya, Verevkin, Gol'tsman, Gershenzon, & Sobolewski, 2000), (Pütz, Büchel, Jacobs, Schultz, Honingh, & Stutzki, 2014), SiN (Cherednichenko, o.a., 2007), quartz (Meledin, o.a., 2003) or sapphire (Kooi, o.a., 2007). Hereby, it is considered that the phonon escape from the film to the substrate plays a major role in limiting the IF bandwidth (Kooi, o.a., 2007). The employment of buffer-layers such as MgO (Miki, Uzawa, Kawakami, & Wang, 2001), (Meledin, o.a., 2003) and SiC (Dochev D. , o.a., 2011) were found to promote the epitaxial growth of NbN. Moreover, it has recently been shown that also the use of the hexagonal GaN (Krause, o.a., 2014), (Krause, o.a., 2016), (Krause, o.a., 2017) allows for high-quality single-crystal NbN films with improved superconducting properties and enhanced phonon escape time. This study investigates the possibility of using this promising GaN buffer-layer to be used in waveguide based NbN HEBs with prospectively increased IF bandwidth and low noise performance.

MIXER DESIGN

The balanced receiver scheme consists of a 90˚ RF hybrid, a pair of HEB mixers with desirably identical IV characteristics and a 180˚ IF hybrid, whereas one port is used to combine the resulting IF output of the mixers and the other to terminate the difference signal, in fact suppressing the LO AM noise and yielding higher receiver stability (Meledin, o.a., 2009). Despite the higher level of complexity, the major advantage is that all available LO power can be used as in contrast to, e.g., a beam splitter for LO and RF combination.

The full-metal RF hybrid, waveguides and mixer block were manufactured using a micromachining technique, where thick photoresist is used as a sacrificial mold (Desmaris, Meledin, Pavolotsky, Monje, & Belitsky, 2008). This technique provides excellent surface accuracy of below 15 nm and fulfils the high demands for THz waveguide components (Desmaris, Meledin, Dochev, Pavolotsky, & Belitsky, 2011).

A. Fullwave 3D simulation

The mixer design was optimized in the 3D fullwave FEM simulator HFSS in the frequency band between 900 GHz to 1600 GHz. Particular emphasis was put on a wideband design that would be able to cover 3 important frequency windows with a single receiver. The HEB impedance was assumed to be 90 Ohm and the E-probe was optimized accordingly to provide proper matching in the band of interest as illustrated in Fig. 1.

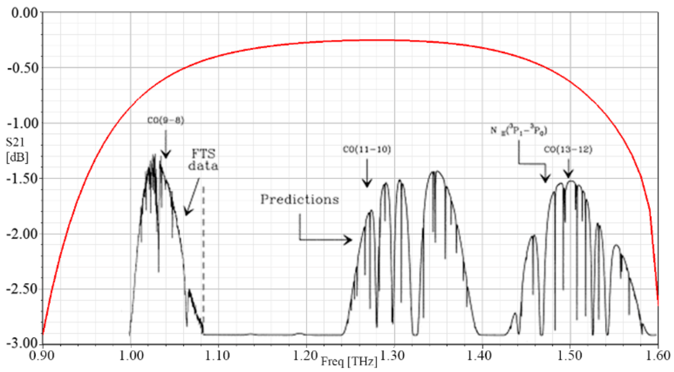

Fig. 1: Important absorption lines in three windows between 1 and 1.5 THz (Pardo, Serabyn, & Cernicharo, 2001). The red curve presents the expected coupling (S21) to the HEB bridge. The E-probe was optimized for a real impedance of 90 Ohm.

In order to facilitate the crucial alignment of the mixer chip, so called alignment notches were added to each side of the probe and should be used as an optical guide as well as limiting the maximum misalignment of the mixer chip inside the waveguide. Simulation indicates, as presented in Fig. 2, that the frequency band of 1.05-1.5 THz still can be covered even in the worst alignment scenario.

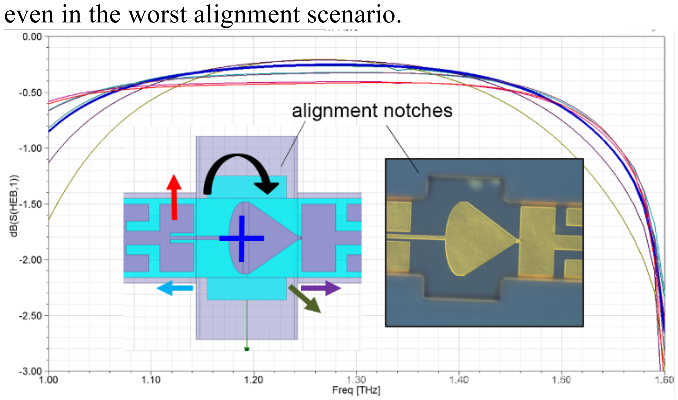

Fig. 2: Misalignment scenarios (worst case) and their effect on coupling efficiency. The frequency band from 1.05 to 1.5 THz can still be covered even in the case of the most unfavourable misalignment.

B. Fabrication

The fabrication of HEBs used for waveguide based applications is in general more challenging than for its quasi-optical counterpart, as the mixer chip eventually needs to be thinned down to be placed inside the waveguide without electrically loading the waveguide too much. This also implies that the NbN film with thickness of a few nanometer is at a higher risk of degradation during the thinning process. Thus, it is important to use high quality films exhibiting high critical temperature. We have grown epitaxial films with 4.5 nm thickness onto GaN buffer-layer with Tc of 12.5 K using reactive DC magnetron sputtering in a nitrogen/argon atmosphere at elevated temperatures (Krause, o.a., 2014).

E-beam lithography has been employed to define the RF structure as well as the bolometer and contact pads with great accuracy. All HEB chips have been characterized in an RT measurement prior to shaping the GaN membrane and crucial thinning down steps in order to track eventual degradation. A photoresist was used as an etch mask to pattern the 5.5 µm thin GaN buffer-layer into long membranes with the described alignment notches. In order to separate the devices from the remaining wafer, the bulk Si was removed from the backside by dry etching in SF6 chemistry. Subsequently, the mixer chips were placed in the mixer housing, carefully aligned and electrically contacted with a conductive adhesive (Dochev D. , Desmaris, Pavolotsky, Meledin, & Belitsky, 2011), (Meledin, o.a., 2009).

Results and Discussion

The electrical characterization of the HEB bridges revealed that the critical temperature of bolometers with bridge length as small as 200 nm shows very little degradation compared to the unprocessed NbN film. Moreover, they exhibited excellent uniformity both in their critical temperature and resistance.

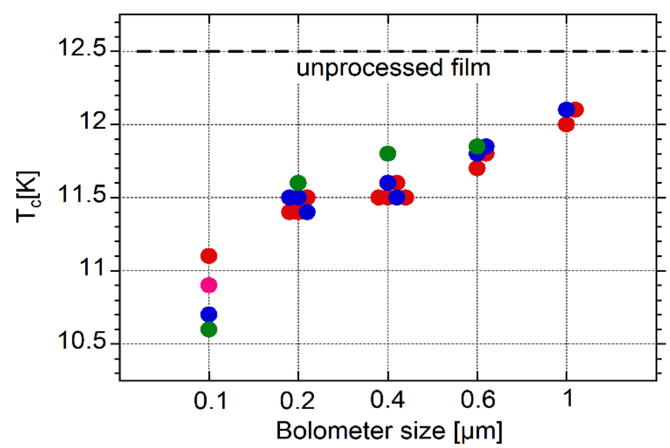

Fig. 3: Electrical characterization of the HEBs with different bridge dimensions in comparison with the unprocessed film prior patterning and thinning down of the membranes.

Once etched, the HEB mixer chips were sorted, identified and one pair was subsequently placed inside the waveguide channel. The inspection under the SEM revealed the high quality of the mixer chips and compliance of the RF structure dimensions to the designed values. An enlarged view on the E-probe and RF structure as well as the alignment of the entire chip can be seen in Fig. 4.

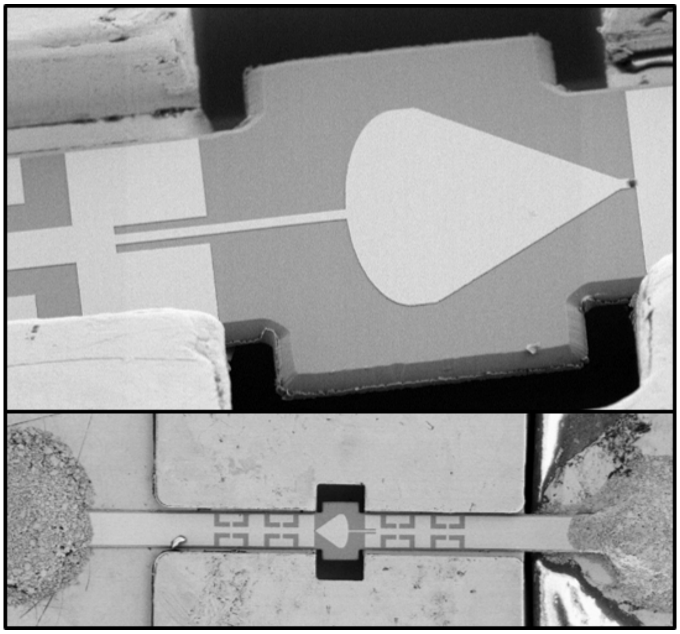

Fig. 4: SEM image of the aligned HEB mixer chip with electrical contacts and the enlarged view onto the E-probe and high impedance line for providing the DC bias.

The HEB mixer was cooled down in a cryostat to 4K and its critical current re-measured and compared to the values obtained before etching of the chip membrane. As depicted in Fig. 5, the critical current is largely identical and amounts to 135 µA for a device with 200 nm and 95 Ohm normal state resistance. The difference of the IV response beyond the critical current is due to different bias circuits.

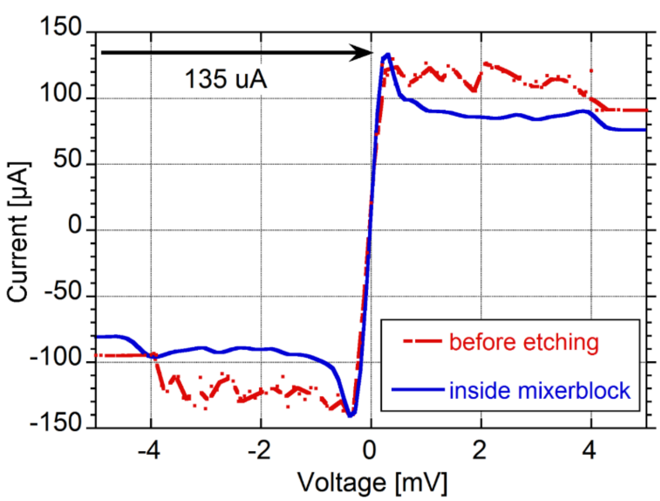

Fig. 5: IV curves of one particular HEB mixer with 200 nm bridge length before the membrane patterning and after patterning and mounting inside the waveguide channel. The critical current does not show any degradation

Conclusion

This manuscript presented the design, implementation and first DC characterization of a wideband balanced waveguide NbN HEB mixer using a GaN substrate. The latter is believed to increase the IF bandwidth as recent studies predict. The optimized E-probe and high-impedance line enable the wideband operation from approximately 1 to 1.6 THz as demonstrated by HFSS simulations, thus covering important absorptions lines in 3 different atmospheric windows with a single HEB mixer. Moreover, the balanced receiver scheme promises higher stability by employing balanced layout to suppress LO AM noise and replaces the inefficient beam splitter with its significant waste of LO power. The fabrication of the presented design was successfully implemented with only very little degradation of the NbN film's critical temperature from 12.5 K of the unprocessed film to 11.5 K for a HEB mixer with 200 nm bridge length. DC measurements have proven that even the most crucial process steps such as the GaN patterning and removal of bulk Si from the backside of the chip had not deteriorated the critical current of the HEB mixer.

Further studies will be focusing on an extended RF characterization including noise temperature and bandwidth measurements.

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