Study of MgB_2 HEB mixers vs the LO frequency and the bath temperature

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Abstract— **We investigate the noise and the gain of MgB_2 Hot-Electron Bolometer (HEB) mixers at 1.63THz LO. The critical temperature of the HEB was 22K and the film thickness was 20nm. At 4.2K and 12K bath temperatures the lowest obtained receiver noise temperatures are 1700K and 2100K, respectively, with a noise bandwidth of about 4.6GHz. The gain bandwidth is about 3GHz in both cases.**

I. INTRODUCTION

During the last decade superconducting Hot-Electron Bolometer (HEB) mixers have gain a lot of interest for high spectral resolution radio astronomy [1]. A low noise temperature (800 K-1500 K) at Local Oscillator (LO) frequencies from 1 THz to 4.7 THz combined with an IF bandwidth of 3-6GHz can now be obtained in many research groups. One of the most recent achievements of HEB mixers is a 4.7THz receiver on SOFIA [2]. Most of those HEB mixers utilize 3-10nm NbN films with a Tc of 8-11 K. NbTiN HEB mixers can provide a sensitivity similar to those made of NbN, however the IF bandwidth is smaller.

More recently, superconducting MgB_2 films have been suggested [3] as an alternative to both NbN and NbTiN. A *Tc* of 40K, a short electron-phonon interaction time, and progress in thin film depositions looked all promising for better performance HEB mixers.

The goals of our study of MgB_2 HEB mixers are twofold. First, we aim for a gain/ noise bandwidth larger compared to the above mentioned NbN and NbTiN HEB mixers. Previous studies of MgB_2 thin films suggest that a gain bandwidth of at least 8GHz can be achieved for films thinner than 15nm with a *Tc* >25-30K. Recent publications quoted an achieved gain bandwidth of 2-3GHz for 10nm MgB_2 films with a *Tc* of 9K and 20nm films with a *Tc* of 20K. For 10nm films with a Tc of 15K a gain bandwidth of 3.4GHz and a noise bandwidth of 6-7GHz was reported in [4]. The latest publication reported a gain bandwidth >8GHz for films 15nm thick with a *Tc* of 33K [5]. Therefore, there is a clear indication that with thinner films and higher Tc's the gain bandwidth can be pushed even further.

The second aim is to increase the operation temperature of HEB mixers to temperatures >15-20K where compact cryo coolers exist. Compared to NbN HEB mixers, which require either LHe or bulkier 4K cryo coolers, MgB_2 HEB mixers would allow for a much longer life time of space borne THz observatories.

Previously, we reported a 600K Double Sideband Noise Temperature for HEB mixers made of an MgB_2 film with a Tc about 8K at 600GHz LO and 1150K at 1.63THz LO. In [6] a 700K and a 1400K DSB noise temperatures have also been obtained for similar films at 1.63THz and 2.55THz LOs, respectively. A DSB *Tr* of 1800K was also reported for a device with a *Tc* of 15K. Yet it remained unclear what noise temperature can be achieved if the *Tc* will increase even further. From the basic theory of HEB mixers it follows that the output noise temperature is proportional to the *Tc*. In [6], a *Tr* of 3900K was reported for devices 15nm thick and a Tc of 33K at 0.6 THz LO. So, will the noise temperature of MgB_2 HEB mixers increase so much that it will make devices with a *Tc* of >20-30K useless for radio astronomy? This is the main question which we attempt to resolve with the presented investigation.

Currently, the highest Tc of our MgB_2 films is about 22-24K for 20nm. Below, we present an investigation of the noise temperature, the noise and the gain bandwidth, at 1.63 THz LO at both 4.2K and 12K bath temperature for a device made of such film.

II. METHODS

The MgB_2 thin film was deposited on a heated c-cut Al_2O_3 substrate using Molecular Beam Epitaxy (MBE). The film thickness was controlled by the deposition time, and it was about 20nm. A 20nm gold film was deposited in-situ after the film cooled down. We consider that in-situ deposition of the gold film provides both a lower MgB_2 to Au contact resistance and a protection from the MgB_2 oxidation during the film storage and initial steps of the HEB fabrication process.

The HEB mixers were fabricated with e-beam lithography and lift-off processes. Thy substrate held 8 devices with bolometers of various dimensions, all survived during the processing and dicing. For the RF tests a device with a bolometer of 1µm wide and 200nm long was selected with a room temperature resistance of 305 Ohm, and a resistance just

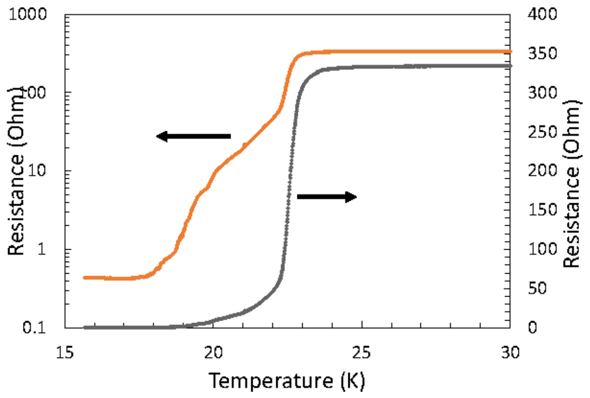

Fig. 1. Resistance vs Temperature (R-T) dependence for the discussed device both in the logarithmic and in the linear scales..

above the *Tc* of 330Ohm. The critical temperature was about 22-23K (see Fig.1). The critical current at 4.2K was about 1mA, which corresponds to the critical current density of 5×10^6 A/cm^2. The normal state resistivity of the MgB_2 film is about 3 mOhm×cm. Interestingly, the scatter of the normal state resistivity between the devices on the discussed substrate (from 0.3 to 7 mOhm×cm) is much larger than the scatter of Tc 's (from 22 K to 24K) or Jc (from 5×10^6 A/cm^2 to 13×10^6 A/cm^2). The presence of the double transition (Fig.1) suggest that the electrical contact between MgB_2 and Au is rather good.

The bolometer is integrated with a planar spiral antenna. For the RF tests, the HEB chip is attached to the back side of a 5mm diameter elliptical Si lens. A parabolic aluminium mirror is installed in the cryostat for the beam collimation. A bias-T and a Chalmers IF LNA (2-4GHz, T_N=3K) are installed on the same cold plate of the LHe cryostat. This bandwidth is given for the matching to 50 Ohm input impedance. However, a low noise and a high gain are obtained in the 1-4GHz bandwidth. At room temperature, the IF signal was further amplified and measured with a power meter. A tunable microwave filter (50MHz bandwidth) defined the IF frequency. For LO, a FIR gas laser was used at the 1.63THz CH_2F_2 line. The output power of the laser is about 1mW. A heater on top of the mixer block was used to bring up the mixer temperature above LHe. A thin plastic film was placed between the mixer block and the cryostat cold plate to minimize the LHe boiling rate during the "heated" tests. In order to measure the receiver noise temperature a Y-factor technique was used (293K/ 77K). The 293K/77K signal was alternated with a chopper at about 1Hz rate. The transmission loss of the cryostat window, the IR filters, and the air loss was used to calculate the "corrected" noise temperature. The IF chain noise was not subtracted. Therefore we keep the term "the receiver noise temperature". The noise data was also not corrected for the Si lens reflection loss.

The mixer gain was obtained using a U-factor method [6].

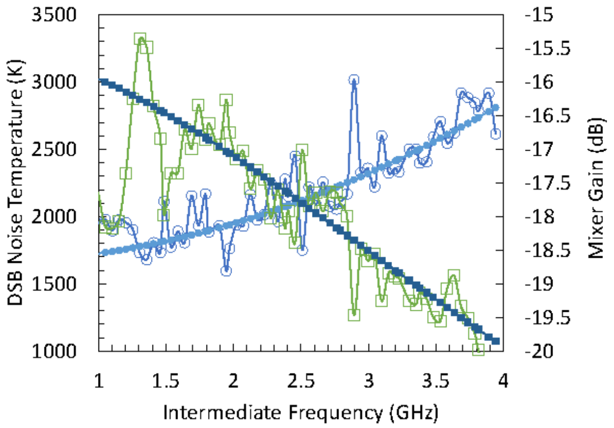

Fig. 2. The DSB receiver noise temperature (corrected for the optics loss) (circles) and the mixer gain (squares): measured (open) and fitted (filled). The LO was at 1.63 THz, and the bath temperature was 4.2K.

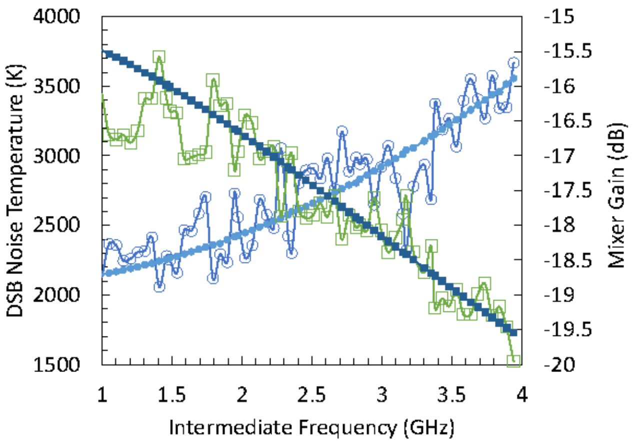

Fig. 3. The DSB receiver noise temperature (corrected for the optics loss) (circles) and the mixer gain (squares): measured (open) and fitted (filled). The LO was at 1.63 THz, and the bath temperature was 12 K.

III. RESULTS

The measured receiver noise temperature spectrum across the 1-4GHz IF band for the mixer temperature of 4.2K is presented in Fig. 2. At certain IFs the mixer response on the hot-cold load was unstable which resulted in errors in the noise temperature measurements (e.g. at 1.9GHz and 2.9GHz). The fitted line (solid circles) corresponds to a zero IF noise temperature of 1650K and a noise bandwidth of 4.7GHz.

Considering the LNA noise temperature (see above) the mixer gain was calculated using the Y-factor and the U-factor. The result is shown in Fig.2 (open squares). Higher ripples for IF < 1.8GHz correspond to the IFs with a high LNA return loss. The fitted curve corresponds to the zero IF mixer gain of -15.5dB and a gain bandwidth of 3 GHz.

At a bath temperature of about 12K the HEB critical current (without LO) is about halve of its value at 4.2K. The same noise and gain measurements as at 4.2K were conducted at 12K. Results are shown in Fig.3. The fitted zero IF noise and gain are 2050K and -15dB. The noise and the gain bandwidths are 4.6GHz and 2.9GHz, respectively.

In the presentation we will present experimental data at more temperatures, in particularly those closer to *Tc*. The LO power requirement will also be evaluated. We will discuss the obtained experimental results with regards to the material parameters and previously published data.

IV. CONCLUSIONS

For the first time we achieve a low receiver noise temperature for MgB_2 HEB mixers with a *Tc* >20K. Presently achieved performance of MgB_2 HEB mixers at 12K is already comparably to the performance of NbN HEB mixers at 4.2K.

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REFERENCES

[1] T. de Graauw, F.P. Helmich, T.G. Phillips, J. Stutzki, E. Caux, N. D. Whyborn, P. Dieleman, P. R. Roelfsema, H. Aarts, R. Assendorp, et al, “The Herschel-Heterodyne Instrument for the Far-Infrared (HIFI),” *Astronomy & Astrophysics*, vol. 518, pp. L6, 2010

[2] Ch.Risacher, R.Güsten, J.Stutzki, H.-W. Hübers, P. Pütz, ” The upGREAT Heterodyne Array Receivers for Far Infrared Astronomy”, in Proc. IRMMW Conference, Tuscon, Sept. 2014.

[3] S. Cherednichenko, V. Drakinskiy, K. Ueda, and M. Naito, “Terahertz mixing in MgB_2 microbolometers,” *Applied Physics Letters*, vol. 90, no. 2, pp. 023507-3, January 2007.

[4] S. Bevilacqua, S.Cherednichenko, V. Drakinskiy, J. Stake, H. Shibata and Y.Tokura, “Study of IF Bandwidth of MgB Phonon-Cooled Hot-Electron Bolometer Mixers ”, *IEEE Trans. Terahertz Sci. Technol.* vol. 3, no. 4, pp. 409-415, Jul. 2013

[5] D. Cunnane, J. H. Kawamura, M. A. Wolak, N. Acharya, T. Tan, X. X. Xi, and B. S. Karasik,”Characterization of MgB2 Superconducting Hot Electron Bolometers” *IEEE Appl. Supercond.* vol. 25, no. 3, p. 2300206, June 2015.

[6] E. Novoselov, S. Bevilacqua, S. Cherednichenko, H. Shibata, and Y. Tokura, “Noise measurements of the low T_c MgB_2 HEB mixer at 1.6THz and 2.6THz”, this conference