MgB2 Hot-Electron Bolometer Mixers at Terahertz Frequencies

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MgB_2 Hot-Electron Bolometer Mixers at Terahertz Frequencies

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***Abstract*—In this paper we compare the performance of MgB_2 Hot-Electron Bolometer Mixers operating at Local Oscillator frequencies of 0.6 THz and 1.63 THz. The minimum noise temperatures that were obtained are 700 K and 1150 K for 0.6 THz and 1.63THz respectively. The receiver noise bandwidth is of the order of 2.2-3GHz for 10nm thick HEB devices with a Tc of 8.5K. Sub-micrometer size HEBs were also fabricated with no degradation of the initial film quality when a 20nm MgB_2 film with a Tc of 22K was used. In the direct detection mode, the maximum voltage responsivity is in the range of 1-2kV/W at 1.63THz and the optimal bias current is around 1/4-1/3 of the Ic at 4.2K.**

Index Terms—*Terahertz detector, Hot-Electron Bolometer, HEB mixer, MgB_2, thin film.*

I. Introduction

The part of the electromagnetic wave spectrum of 0.1-10 THz (3 mm – 30 µm) is frequently addressed as the terahertz (THz) range [1]. Despite difficulties to build components and systems for these frequencies, THz heterodyne receivers play important roles in astronomical and atmospheric science applications. [2]. As an example, the Herschel Space Observatory [3] with an overall frequency coverage of 60-670 µm allowed observation of star-formation activities, physics and chemistry of the interstellar medium, spectroscopic and photometric study of comets, asteroids and outer planet atmospheres and their satellites [4].

Several types of devices are used as mixer elements for heterodyne detection: Schottky diodes, SIS junctions, hot-electron bolometers (HEBs). In contrast to Schottky diode mixers, HEBs have much lower noise temperature and three orders of magnitude lower LO power requirements [5, 6]. HEBs could be used at higher frequencies than SIS mixers (1.3THz upper limit). Typically, phonon-cooled HEBs are made from ultrathin films of NbN [7], but novel materials could be implemented for HEB fabrication to improve their parameters. Magnesium diboride (MgB_2) discovered in 2001 [8] has the highest critical temperature (T_c = 39 K) among intermetallic compounds. Recent progress in MgB_2 thin film deposition [9], [10] opens new prospects in fabrication of superconducting electronic devices: hot-electron bolometers (HEB) [11], superconducting single-photon detectors (SSPD) [12], superconducting quantum interference devices (SQUID) [13], etc., because of its high T_c and short electron-phonon relaxation time.

Recently, low noise THz HEB mixers were demonstrated based on thin MgB_2 superconducting films deposited on c-Al_2O_3 substrates using molecular-beam epitaxy [14], [15]. A mixer noise temperature of 600K with a 3.4 GHz gain bandwidth was measured at 2K and an LO frequency of 600 GHz. Apart from Al_2O_3 , SiC substrates have been shown to result in very high quality MgB_2 superconducting films with a critical temperature in excess of 36K for thicknesses down to 10 nm [16]. In this work, devices were made from films as thin as 15nm, where GBW from 5GHz to 7GHz (depending on the bias point) have been achieved.

In our paper, we present experimental investigation of the noise and the conversion gain for MgB_2 HEB mixer on Al_2O_3 substrates at both 1.63THz and 0.6THz.

II. Device Fabrication and Experimental Set-up

HEB devices discussed in this paper were made of thin MgB_2 films on c-cut sapphire substrates. The lattice structure of this substrate matches very well with the lattice of MgB_2, hence providing high quality thin films. Recently, SiC has been shown to be a better option for this application [10], which we will address later in our research.

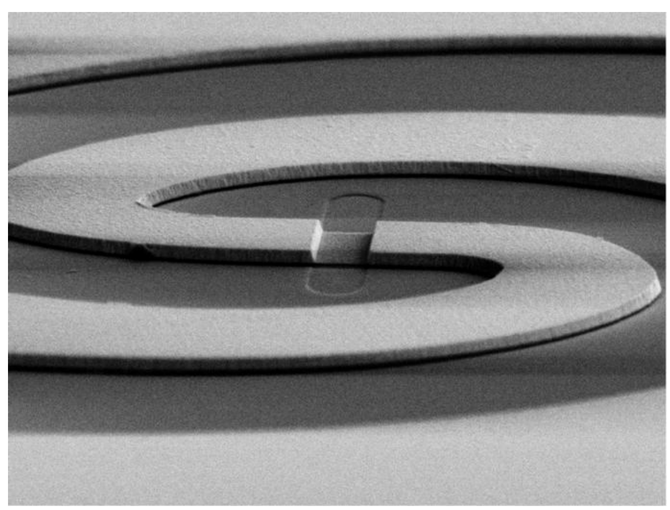

Fig. 1. Scanning Electron Microscope (SEM) image of a spiral antenna (light grey) integrated HEB (visible in the slot at the spiral center) mixer. The substrate is dark grey.

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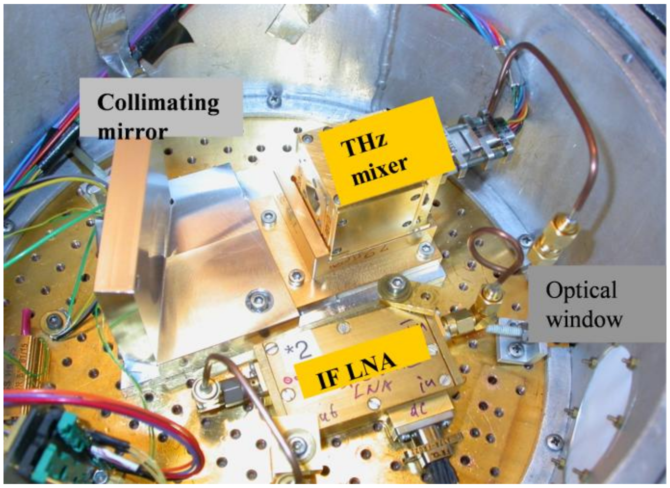

Fig. 2. Photograph of the interior of the test cryostat.

MgB_2 films were deposited with Molecular Beam Epitaxy (MBE) at a temperature of 300°C. Details of the deposition process have been published in [9]. MgB_2 films were covered with 20nm Au films in-situ. This method prevents MgB_2 films from degradation prior to and during the processing. Furthermore, it is expected to provide a lower contact resistance between the MgB_2 and the Au films. A low contact resistance is especially important considering the extremely high frequencies the devices are made for (>1THz).

Devices we discuss here were made from MgB_2 films deposited over a period of two years. Gradually, during process optimization, the critical temperature T_c of our ultra-thin films improved. Film smoothness, stresses, and other parameters have not been investigated and will not be discussed here.

HEBs were integrated with planar spiral antennas made of 300nm thick gold film deposited on top of the in-situ Au (Fig.1). The *in-situ* Au layer above the bolometer itself was etched by means of Ar Ion-Beam milling. After fabrication, the substrate was diced on individual chips, each including a spiral antenna integrated HEB and the two-point terminals,

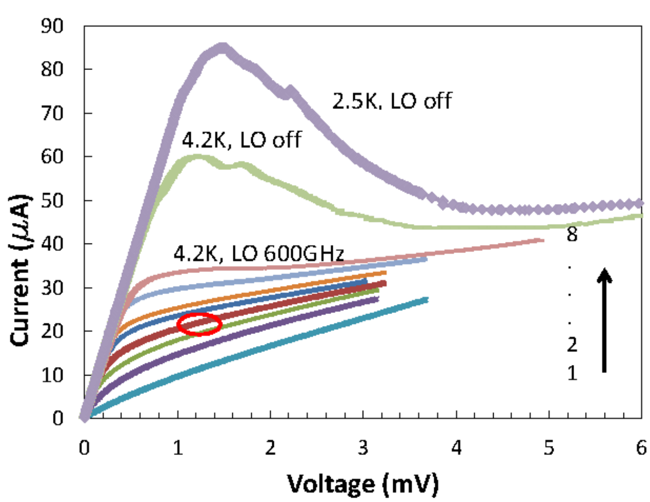

Fig. 3. I-V-curves of HEB mixer (10nm thick, T_C=8.5K) at 4.2K (with and without LO pumping at 600GHz) and at 2.5K (without LO). Eight pumped I-V curves are shown and they are labeled 1 through 8 in decreasing LO power.

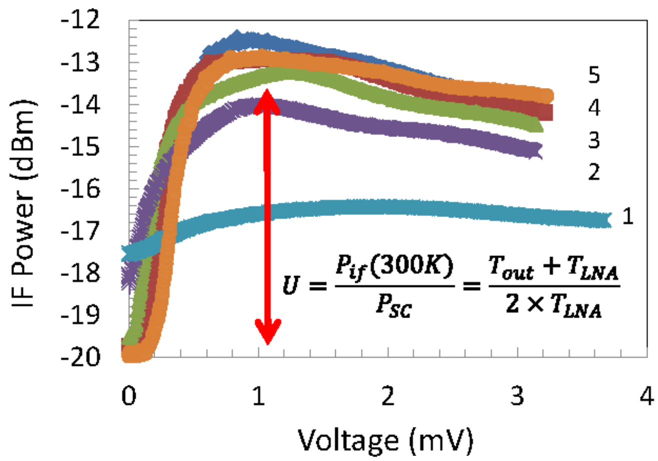

Fig. 4. P-V curves (1.6 GHz) measured at different LO power at 600GHz. The curves are labeled 1 through 5, corresponding to the numbered I-V curves shown in Fig.3. The equation explains the definition of the U-factor. Bath temperature is 4.2K.

used to bond the chip to the external (dc and IF (Intermediate Frequency)) circuits.

The HEB chip was clamped on the back side of a Si lens, and packaged in a mixer block with an SMA terminal. In the LHe cooled cryostat, a broadband bias-T and a broadband Low Noise Amplifier (LNA) followed the mixer block (Fig.2). Outside the cryostat, a pair of extra LNAs, a tunable IF filter (50MHz instantaneous bandwidth) and a microwave power meter formed the rest of the IF chain.

For the HEB mixer noise temperature measurements, a standard Y-factor technique was applied with two black body loads, at liquid nitrogen and room temperatures. Either a 12 μm or a 50 μm Mylar beam splitter was used to combine the Local Oscillator (LO) and the black body radiation, depending on the HEB size and the power of the LO. As LO sources, both a 0.6THz Backward Wave Oscillator (BWO) and a 1.63THz Far Infrared (FIR) gas laser were used. The losses in the beam splitter (0.1dB), the cryostat window (0.8dB), and the IR filter (0.6dB) were measured separately and used for the receiver noise temperature deduction. The Si lens reflection loss was accounted as 1dB [17, 18]. The LNA noise was not deducted from the noise temperature.

III. Results and Discussion

HEB mixers were tested at LO frequencies of 600GHz and 1.63THz. Considering previous publications [14, 15], the goal of the new experiments at 0.6 THz was to confirm the reproducibility of the earlier results. The new devices were also smaller in size (1μm×1μm vs 3μm×1.5μm reported earlier). However, we used MgB_2 films from the same film batch as before (10nm thick, T_c=8.8K). Current-Voltage (I-V) characteristics of the HEB mixer used for the noise temperature measurements are given in Fig.3. Despite an increase of the critical current upon cooling from 4.2K to 2.5K (achieved by reducing the LHe vapor pressure), the noise temperature improvement was quite small (about 10%). Therefore, all other tests were made at 4.2K. The lowest noise

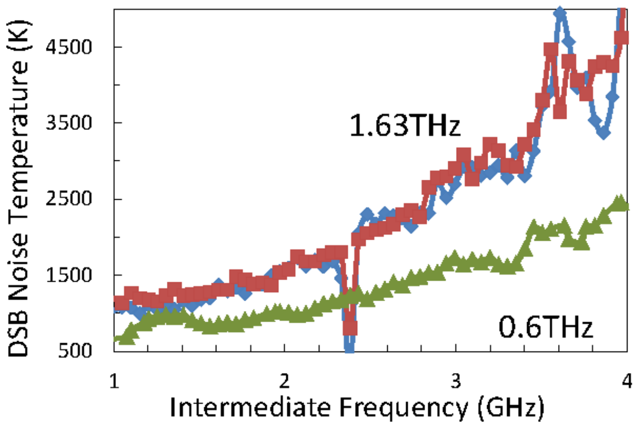

Fig. 5. The DSB noise temperature (corrected for the optical loss) at 0.6THz and 1.63THz LO frequencies for the device discussed in Fig.3 and Fig.4.

temperature was obtained at LO power and bias voltage corresponding to the red circle in Fig.3 (1mV, 20μA).

Fig.4 shows IF power P_{IF} vs bias voltage (P-V curves) for the corresponding I-V curves from Fig.3. A maximum of the *P-V* occurs at a bias voltage just below the voltage of the minimum noise temperature. The U-factor [19, 20], defined as a ratio of the P_{IF} with the mixer at the optimal point to the P_{IF} with the mixer in the superconducting state, has been shown to be a useful parameter with which to test the receiver. In the first state, P_{IF} is a sum of the mixer output noise ($k \times B \times T_{out}$), the IF amplifier noise ($k \times B \times T_{LNA}$), and the mixer response to the input load (294K in this case, $2 \times k \times B \times 294$K, the factor of 2 here occurs due to the Double Side Band nature of the receiver), k is the Boltzmann constant, and B is the bandwidth of the band pass filter at the output of the IF chain. In the second state, the HEB is in the superconducting state and does not produce any electrical noise. On the other hand, the HEB becomes a perfect short at microwave frequencies, which reflects the amplifier noise (hence, the factor of 2 in the formula for the U-factor, Fig.3). Therefore, a low U-factor means either a high IF amplifier noise or a low mixer output noise temperature. For a high sensitivity HEB mixer the dominant noise contribution is made by the electron temperature fluctuations, and which is much larger compared to the thermal noise (equal to the electron temperature in the HEB). More detailed discussion can be found in [21].

The measured DSB noise temperature spectrum across the 1-4 GHz IF band is shown in Fig.5. Similar to as reported earlier [14] the noise bandwidth is approximately 3GHz. The minimum noise temperature is 700K (1.1 GHz).

The LNA noise temperature was measured separately and is in the range of 2-3K. Therefore, from the 7dB U-factor (see Fig.4) we can obtain the mixer output noise temperature, which is approximately 25K. Given the (corrected for the optical loss) DSB noise temperature of 750K (at 1.6GHz, see Fig.5, 650K without the LNA noise contribution), the mixer gain can be calculated as -19dB, of which 1.5dB is the IF impedance mismatch loss ($Z=dV/dI$ = 170 Ohm is the IF impedance of the HEB mixer).

The accuracy of the mixer gain and the output noise calculations depends on the IF amplifier gain and noise stability versus the input impedance, which changes when the HEB mixer is switched from the operation point (Z= 170Ohm) to the superconducting state (Z=0). An isolator between the mixer and the amplifier would resolve this issue. However, a cryogenic broadband isolator was not available during the experiments. Our preliminary investigation shows that an error of up to 2dB can occur for T_{out} and G obtained from the U-factor if we disregard the LNA performance variation.

However, the superconducting state can be replaced by the normal state of the mixer. This state can be achieved when the mixer is heavily pumped with LO (curves 1 in Figs. 3 and 4). In this case the denominator in the U-factor becomes ($T_{LNA}+T_c$), since in the normal state the temperature fluctuation noise becomes much smaller than the thermal noise, where the effective temperature equals the electron temperature of the HEB. In this case, a mixer gain of -18.5dB and an output noise of 26K was obtained. This result is very close to that obtained from the U-factor.

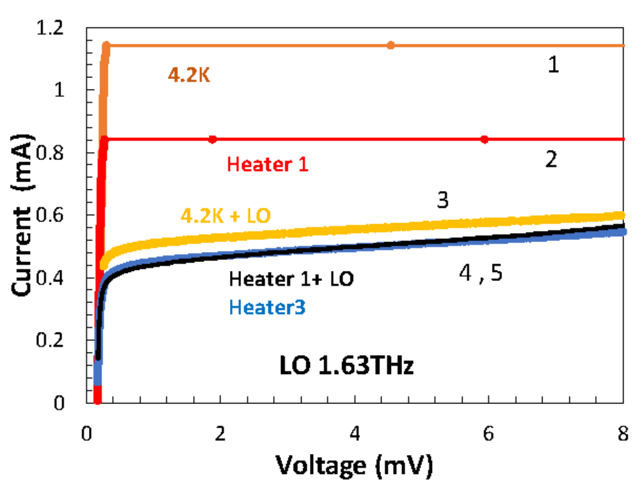

Fig. 6. The IV-curves of a HEB mixer made of 20nm film with a T_C of 22K. Curve 1: 4.2K no LO; Curve 2: Heating-1 no LO; Curve 3: 4.2K full LO power; Curve 4: Heating-1 with full LO power; Curve 5: No LO, the heating was increased untilcurve 5 coincided with curve 4.

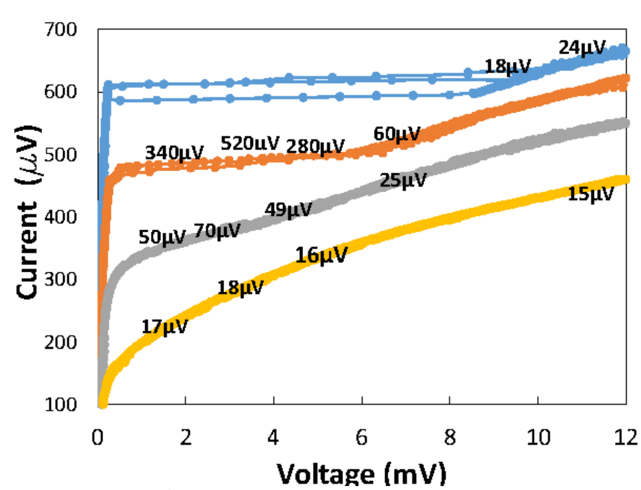

Fig. 7. IV-curves of the heated HEB Mixer (see Fig.6). The numbers in the field represent the voltage response at 1.63THz as measured with the lock-in amplifier.

We do not provide I-V characteristics of the mixer pumped with the 1.63 THz LO here, because those were the same as with the 600 GHz LO. This fact can be explained by a relatively low *Tc* of the devices, which results in a low energy gap, evidently with a characteristic frequency below 600GHz.

The minimum DSB noise temperature at 1.63THz LO was 1150K . The reason for a 50% increase in noise temperature compared to that measured at 600GHz is not clear at the moment. A contact resistance between the Au antenna and the MgB_2 bolometer might still exist despite the in-situ deposition of the Au layer. This could be the reason for an increase of optical loss at higher LO frequencies.

The same exercise with the U-factor, considering the noise temperature at 1.63THz, gives a mixer gain of -21dB. The fact that the U-factor is the same as for the 600GHz LO agrees with fact that the shape of the I-V curves during pumping with both LOs are the same.

We can note that for NbN HEB mixers (at 0.6THz and 1.63THz) the mixer conversion gain from -13dB to -14dB, and the mixer output noise from 40K to 60K was reported [20]

At 1.63THz the noise bandwidth is about 2.2-2.5GHz. Since the given noise temperature includes the contribution of the LNA, the LNA fraction increases by an increase of the optical or the mixer loss. Thereby, the receiver (the mixer + the LNA) noise bandwidth is reduced. A similar effect has also been observed for NbN HEB mixer [20].

Earlier we have shown that the noise bandwidth for MgB_2 HEB mixers increases when higher T_c MgB_2 films are used [15]. After optimization of the MgB_2 film deposition, the critical temperature increased to 20-25K. Using a 20nm MgB_2 film a set of devices was fabricated with a T_c of 22K. The I-V curves for one such device are given in Fig. 6. The bolometer dimensions are 1μm×0.4μm. With the total available power of the FIR laser (estimated as 100 μW in front of the cryostat), the mixer was pumped to an IV-curve which should be close to the optimum (curve 3 in Fig.6). However, for the noise temperature measurements with a thin beam splitter, the LO power at the cryostat will be greatly reduced. Therefore, the mixer has to be operated at a higher temperature. In Fig.6, curves 4 and 2 correspond to an increased temperature with and without LO pumping. For curve 5, LO was switched off and the mixer temperature was further increased until it overlapped with curve 4. As can be seen, curves 4 and 5 are identical. Therefore, at "Heater-1" the 1.63THz radiation has the same effect on the HEB as a rise in temperature.

In order to estimate which IV curve corresponds to the HEB maximum sensitivity to the THz radiation, a direct detection experiment was conducted. For a set of temperatures, the voltage response of the HEB on the amplitude modulated THz radiation was recorded (Fig.7). The FIR laser power was attenuated by 20dB, in order to reach the small signal limit (there was no visible effect of the laser on the I-V- curve). The laser radiation modulation was accomplished with a chopper (set on 20Hz). The voltage response of the HEB was measured with a lock-in amplifier. As can be seen in Fig.7, the maximum responsivity is achieved at a bias range of 2-4mV and 0.3-0.5mA, i.e. at a current which is about 1/4- 1/3 of the critical current at 4.2K. Considering the known optical losses, the maximum responsivity can now be calculated to be in a range of 1-2kV/W at 1.63THz. With this information, noise temperature measurements will have to be conducted in the near future.

IV. Conclusion

With this work we demonstrate that low noise performance can be repeatedly achieved for MgB_2 HEB mixers, both for 1 THz and for the above. The minimum noise temperatures obtained are 700K at 0.6THz and 1150K at 1.63THz LO frequencies. The noise bandwidth is of the order of 2.2-3GHz for devices 10nm thick with a Tc of 8.5K. For HEBs with a Tc of 22K we observe that the effect of the THz LO on the IV-curves is nearly the same as of HEB heating. The maximum direct detection responsivity is in the range of 1-2kV/W at 1.63THz and the optimal bias current is 1/4-1/3 of the Ic at 4.2K.

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