MgB_2 hot-electron bolometer mixers for THz heterodyne instruments

Evgenii Novoselov, Naichuan M. Zhang, Sergey Cherednichenko*,
Terahertz and Millimetre Wave Laboratory, Fysikgränd 3, Gothenburg, Sweden 412 98

ABSTRACT

In this work we present experimental investigation of the MgB_2 hot-electron bolometer (HEB) for low noise mixing at terahertz frequencies. A dedicated MgB_2 thin film deposition system was designed and constructed based on Hybrid Physical-Chemical Deposition. Films as thin as 15nm have a superconducting transition at 35K, with a critical current density >10^7 A/cm^2 (at 4.2K) in bridges as narrow as 500nm, indicating on good connectivity in the film. The gain bandwidth (GBW) was measured by mixing of two THz sources. The GBW is proportional to the film thickness and it is at least 6GHz for 15nm thick devices. Performance of MgB_2 HEBs was compared to performance of one of the NbN HEB mixers made for the Herschel Space Observatory (one of the flight units), for which both the GBW and the Noise Bandwidth (NBW) was measured. MgB_2 HEB mixers show a GBW at least a factor of three broader compared to the NbN HEB measured in the same set-up.

Keywords: MgB_2, HEB, hot electron, THz, terahertz, HPCVD, superconducting MgB_2 film

1. INTRODUCTION

Terahertz (THz) frequency range is suitable for observation of molecular emission lines from interstellar medium, galaxies, or planets require heterodyne receivers with high spectral resolution [1]. In order to fulfill these stringent requirements, superconducting mixers are employed based either on Superconductor-Insulator-Superconductor (SIS) junctions or on superconducting hot-electron bolometers (HEB). Providing a times 1-to-3 quantum limit sensitivity, SIS mixers have an upper frequency cut-off frequency which for Nb-NbTiN type junction is at approximately 1.2-1.3THz.[2] Above this frequency, HEB mixers, based on NbN and NbTiN thin films, offer a much better sensitivity.[3] Selection of NbN and NbTiN for HEB mixers is motivated by a fast electron energy relaxation rate, τ which, to a large extend, determines the HEB mixer gain roll-off frequency, f_o : $f_o=1/\tau$. This roll-off frequency defined the maximum mixer gain bandwidth (GBW) if the intermediate frequency (IF) readout starts from zero (it is often not the case, hence the GBW is usually < f_o). The electron energy relaxation time is shorter for materials with a short electron-phonon interaction time (τ_{e-ph}) and a fast phonon escape from the film into the substrate (τ_{esc}). For the thinnest reported NbN and NbTiN films (3-5nm) the maximum GBW is about 2-4GHz, depending on the substrate, buffer layers, and (as a very important factor) on the measurement technique.[4] Ultimately, a large GBW results in a large noise bandwidth (NBW), defined here as an IF where the mixer (or the receiver) noise temperature increases by a factor of two from its value at low IFs. NBW is characterized by measuring the receiver noise temperature as a function of the IF. There are very few experimental reports on the Tr(IF) measurements for NbN HEB mixers covering from well below and up to above of f_o . Recent results which cover IFs from <1GHz to 5GHz show that the NBW of NbN HEB mixer receivers is about 3.5-4GHz (see also results further in this paper).[5] Observations of extra galactic sources at THz frequencies often require an IF bandwidth broader that that (see on an example of 1.9THz CII observation with the HIFI/Herschel[6]). Attempts to extend the GBW in NbN HEB mixers have not resulted in any repeatable improvements.

THz mixing in MgB_2 bolometers has been reported in 2007[7] . Later, a noise temperature as low as 700K was achieved at 1.6THz.[8] However, the gain bandwidth was approximately 2GHz and the noise bandwidth of 4GHz. The promise of a much wider GBW (8-10GHz, based on the measured electron-phonon interaction time and the phonon escape time [9]) has not been achieved. The utilized MgB_2 thin films, made by Molecular Beam Epitaxy, were 10-20nm thick with a superconducting transition temperature (T_c) 20-10K. The T_c in bulk MgB_2 is 39K. Therefore, there was a room for improvement in MgB_2 film T_c as well as even thinner films were required.

*serguei@chalmers.se; phone +46317728499; www.chalmers.se

Very promising results in thin MgB_2 film deposition were achieved with Hybrid Physcial-Chemical Deposition (HPCVD)[10] . Thin films made with HPCVD had higher T_c compared to films of the same thicknesses made of e.g. with MBE. First results for HEB mixers made of such films showed a GBW up to 8GHz (15nm thick, T_c=33K). The receiver noise temperature was rather high, of about 4000K at 600GHz.11

In order to investigate limits for MgB_2 HEB mixers we have built our own deposition system based on the HPCVD method. The goal is to obtain films as thin as 7-10nm with a T_c >30K. Furthermore, various techniques for HEB contacts have to be explored in order to reduce the contact resistance which appears when the contacts are made with the break of vacuum.

2. MgB_2 FILMS DEPOSITION

MgB_2 films were deposited in the home build HPCVD system, which is similar to described in [12]. It consists of three major sections: the gas supply unit, the reactor, and the pumping system (see Figure 1, left). The gas Mass Flow Controllers (MFCs) control supply of H_2, H_2+B_2H_6 (5%), and N_2. Pure hydrogen is used as a reducing gas (400 sccm), and 5% diborane (1-10 sccm) supplies boron from thermal decomposition of diborane. The reactor is a water cooled 200mm vacuum chamber which contains a heater (the lower section of the heater is shown in Figure 1, right-top). The heater's top section (Figure 1, right-low) has a groove where several pieces of Mg are placed (4-6g in total). The SiC substrate is placed in the central part of the heater, where the temperature is approximately 50 degrees below the peripheral part. At the deposition pressure of 20Torr the given mass of Mg suffices for about 4 min deposition time. Slower Mg evaporation rate results in the reduce Mg partial pressure and hence in formation of other phases of MgB_x.

.

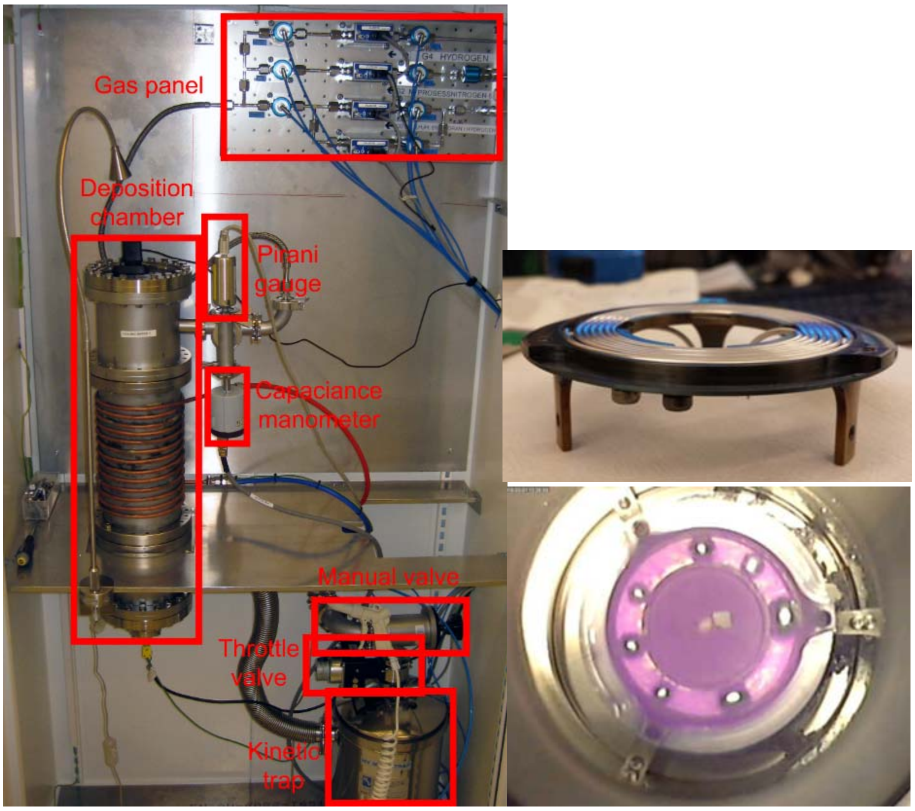

Figure 1. Photograph of the MgB_2 HPCVD system at Chalmers University of Technology. (left) General view with the main sections indicated. (top-right) The heater, with the top part removed. The coaxial heating cable is visible. (lower-right) The top view of the heater during deposition. The Mg pieces are melted and formed shiny bolls. A 5mmx5mm SiC substrate is seen slightly off centered (to the right).

The MgB_2 deposition rate is adjusted with the diborane flow. As a measure of the deposited material we use a product of the diborane flow and the deposition time. The diborane flow was open when the thermocouple (attached to the lower surface of the heater) showed 700 degreed Celsius. Mg melted typically at 680 degrees, which could be observed via camera through the top window of the reactor. After deposition, the substrate was quickly cooled to the room temperature in the hydrogen atmosphere.

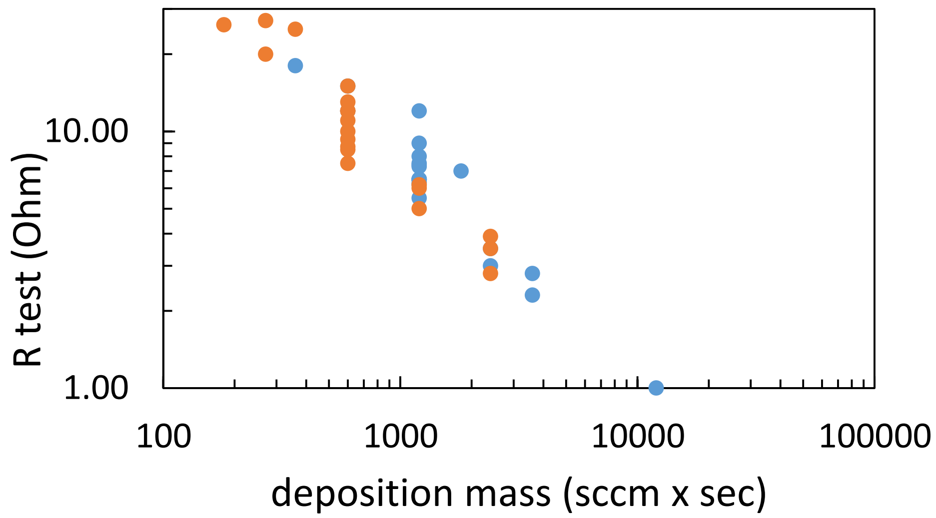

Figure 2. MgB_2 film resistance on a test wafer (SiC) versus deposition mass (the B2H6+H2 gas mass flow times the deposition time).

Resistance of the deposited film was measured immediately after the reactor was opened. This resistance was found to be inversely proportional to the deposition mass (the flow times the time) over two decades, which indicates on a good connectivity of the obtained film. For thick films the critical temperature was 40-41K. The thinnest film thickness was approximately 15nm, as it was measured with an Atomic Force Microscope. This film had a T_c of 35K, with a 2K transition width. The critical current density in the 500nm wide bridges was 1.6×10^7 A/cm^2 for 15 nm films and about 7×10^7 A/cm^2 for 30nm films.

HEB mixers were fabricated using a standard lithography process. After MgB_2 film deposition, a 20nm gold layer was deposited in a different machine. Approach for in-situ Au contacts deposition is under investigation and it will be presented elsewhere. The HEB mixers are nano bridges (from 500nmx500nm to 2µmx2µm) integrated with logarithmic spiral antennas, designed to cover a frequency range from 300GHz to 2THz. After fabrication, HEB were diced to individual devices.

For both the GBW and the noise temperature measurements, HEB mixer chips were attached to the back of either a 5mm or 12mm diameter Si lens. For the GBW measurements, a room temperature bias-T and a broadband microwave amplifier (0.1-20GHz) were used to bias the mixer and amplify the IF signal, which was then measured with a spectrum analyzer. The amplification of the entire IF chain (except for the mixer unit) was removed in order to obtain the IF response of the HEB mixer itself. Two 400GHz (and later, two 700GHz) sources were used (as an LO source and a Signal source) where the signal source frequency was tuned to cover the IF range from 0.1GHz to 10GHz. Power variation of the Signal Source were measured with the same HEB device in the direct detection mode. The GBW was measured for each device at many bias points, at several LO power levels, and at bath temperatures from 4.2K to 30K. At all bias points the GBW was the same for a given HEB mixers, which is different what was observed for NbN HEB mixers.

For the mixer noise temperature measurements, a cold Low Noise Amplifier (0.1-5GHz, 35-25dB gain, 5-7K noise temperature) was used as a first IF amplification stage. One more LNA was used at room temperature and a tunable 50MHz filter set the IF band. The IF power was measured with a power meter. A standard 300K/77K Y-factor method was used for the receiver noise temperature measurements. As an LO source, a FIR gas laser was used at 690GHz. A high output power of the laser allowed us to pump the mixer to the resistive state starting from a 10K bath temperature. Only HEB made of 15nm films were used for the noise temperature measurements. At this stage, no corrections for optical loss (e.g. the beam splitter, the cryostat window, IR filters, etc.) were applied to the obtained receiver noise temperature.

3. RESULTS

The GBW was measured for MgB_2 HEB made of 45nm (E2-1), 35nm (E3-8, E3-2), and 15nm films (E6-7). The critical temperatures of the 45nm and 35nm thick films were >38K, hence such devices were heated up to 35K. The GBW was the same for all temperatures starting from 4.2K. The 15nm thick HEBs were heated up to 30K. Figure 3 shows IF response for four discussed mixers. The temperatures, at which those curves were measured are given in the legend together with the roll-off frequencies of the fitting curves $(1+(f_{if}/f_o)^2)^{-1}$.

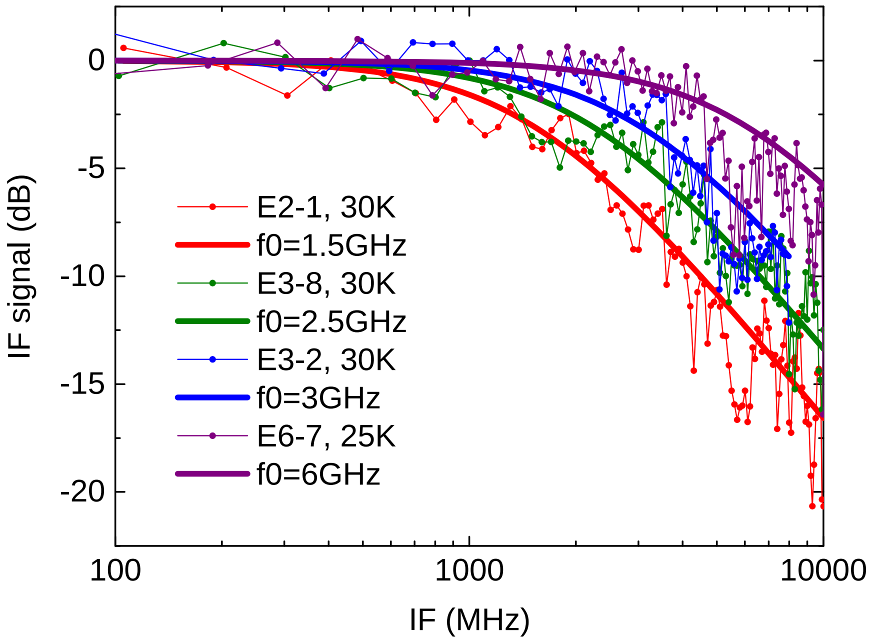

Figure 3. Normalized IF response of four MgB_2 HEB mixers as measured at 400GHz. The film thicknesses were: 45nm (E2-1), 35nm (E3-8 and E3-2), and 15nm films (E6-7). The mixers' temperatures and the gain roll-off frequencies are given in the legend.

The critical temperatures of the discussed mixers were close to each other. Therefore, the increase of the GBW for thinner films can be explained only by the reduction of the phonon escape time, which is proportional to the film thickness in the thin film limit (negligible temperature gradients across the film thickness).

For presented mixers, the IF signal varies only 9dB at the highest IF of 10GHz. Therefore, an error in the IF chain gain calibration of 1-2dB might result in a noticeable error in deduced value of the GBW. Therefore, as an ultimate calibration, we utilized an NbN HEB mixer. This mixer is one of the flight units delivered[13] by Chalmers University of Technology (in collaboration with Jet Propulsion laboratory (USA), and MSPU (Russian Federation)) for the HIFI instrument of the Herschel Space Observatory as a flight spare unit and for the HIFI Band 6 beam test. This unit was returned back to Chalmers after the successful integration of HIFI and the launch of the Herschel Observatory[14]. A remarkable note, after more than a decade after fabrication and integration (in year 2005), the HEB resistance was still the same within 1Ohm accuracy. The GBW of this mixer (still packed in the flight mixer) unit was now measured in the same set-up as the MgB_2 HEB mixers (the cryostat and the IF chain), except that the 690 GHz LO was used. Resulting IF response curves for the NbN HEB mixer are given in Figure 4. Two bias points were used: 1mV (the minimum noise temperature point), and 5mV at two LO power levels. At the optimal LO power, the GBW was also measured at a reduced bias of 0.5mV. At the minimum noise point (1mV) , which is also a maximum mixer gain point, the GBW was 1.6GHz. The GBW increases to 2.3GHz at the 5mV bias.

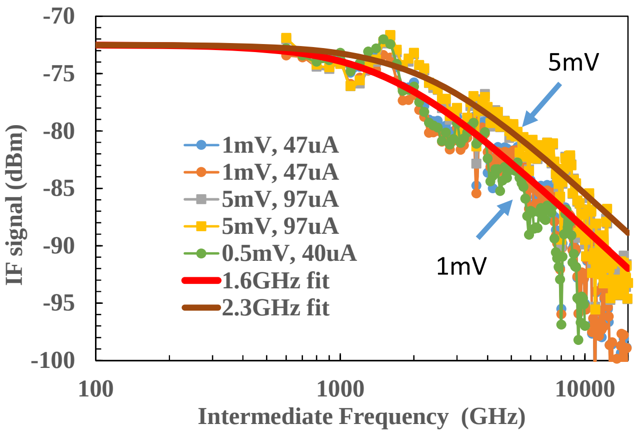

Figure 4. IF response of an NbN HEB mixer in the same set-up as for the MgB_2 HEB mixers. The minimum noise temperature (and the maximum mixer gain) is at about 1mV bias voltage. The NbN HEB mixer GBW increases at higher bias voltages, as it has been reported before.

Increase of the GBW at higher bias voltages is a typical property of NbN HEB mixers. However, previously we had observed a GBW of 3GHz for such mixers (not from this particular batch, though). The Noise Temperature was also measured across and IF band from 0.6GHz to 4GHz as it is shown in Figure 5. The LO was set at 1.63THz since the current NbN HEB mixer is integrated with a 1.6THz Double-Slot Antenna. The fitting curve defines the noise bandwidth, which is 3.5GHz in this case.

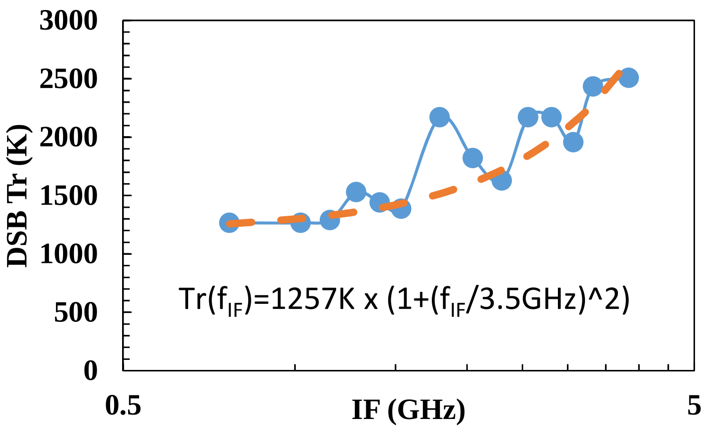

Figure 5. The measured DSB receiver noise temperature for the Herschel FM03 NbN HEB mixer at 1.63THz LO. No corrections for the optical loss were applied. Bias: 1mV, 47µA. The noise temperature is very similar to the one measured with the same sample prior to the delivery in 2005. A different IF LNA was used this time (0.1-5GHz) which allows for measurements from lower IFs. The mixer unit itself has a lower cut-off frequency at 500GHz (the built-in bias-T).

We should note that this is very similar to NbN HEB mixers made for SOFIA and which were tested with a similar cryogenic LNA.[5] Therefore, both the GBW and the NBW of the Herschel NbN HEB mixers can be considered as the state of the art. Herschel HIFI HEB mixers are optimized for a lower optimal LO power (HEBs are 2µm wide time 0.1 µm long), and hence have a 30% higher noise temperature compared to e.g. 4µm wide HEBs.[15,13] The IF cryo LNA, used this time, apparently has a worse input impedance matching to the HEB mixers in the 1-2GHz range, resulting in a spike at 1.7GHz. This one was not seen during the HIFI HEB mixer tests due to different LNAs, designed for a 2-5GHz band. Nevertheless, the obtained GBW matches rather well the NBW for the NbN HEB mixers, where a ratio NBW/GBW=1.5-2 has also been reported before. It means, that current MgB_2 HEB mixers have a GBW a factor 3 larger than the state of the art NbN HEB mixer.

We have not conducted an exact measurement of the LO power requirement for MgB_2 HEB mixers. However, comparison with the NbN HEB mixers shows that it is much higher than for NbN HEBs. Using a rather thick beam splitter (200 µm Mylar) we were able to pump an MgB_2 HEB mixer (similar to E6-7, Figure 3) with the 690GHz LO to a smooth IV only for a bath temperature of >20K. We will further optimize the LO coupling scheme, however, we were able to obtain the first noise temperature data for devices made of Chalmers MgB_2 films.

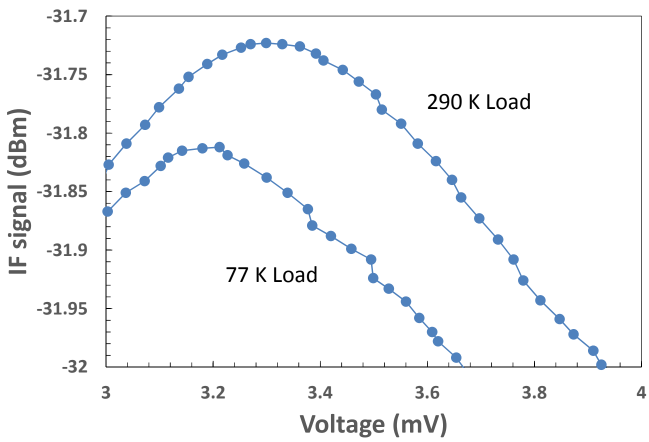

Figure 6. MgB_2 HEB mixer, made of a 15nm thick film. LO frequency is 690GHz. The measured IF response on both the Hot (290K) and the cold (77K) black body loads vs mixer bias voltage. The maximum Y-factor is 0.15dB, corresponding to a receiver noise temperature of 6100K. The mixer temperature is between 22K and 24K (based on comparing the IV to those measured in a dip stick at various temperatures). Correcting for the beam splitter loss, the noise temperature is 4300K.

The IF response (including the IF chain gain) on both the hot (290K) and the cold (77K) black body loads vs the mixer bias voltage is shown in Figure 6. At 3.5mV the Y-factor is 0.15dB, corresponding to a receiver noise temperature of approximately 6100K. The beam splitter reflection loss was measured to be 30% at 690GHz. Therefore, by correcting T_r just for the beam splitter loss we obtain a receiver noise temperature of approximately 4300K. Other optical losses might be also relevant to consider for a proper evaluation of the mixer. However, we will do that in our further investigation. The mixer temperature of about 23K is 1/3 from the HEB critical temperature. Therefore, a lower noise temperature should be expected at lower temperatures, which will be accessible for the tests after improvement of the LO coupling to the mixer.

4. CONCLUSION

MgB_2 HEB mixer technology is a young approach for THz wave detection, compared e.g. to NbN HEB mixers which were under an active investigation by many groups from at least 1995. Nevertheless, performance of HEB mixers made of low Tc MgB_2 films (e.g. 10K) is the same as for state of the art NbN HEB mixers. However, the goal is to obtain this low T_r in a much wider IF band, e.g. up to 8-10GHz. In this work we demonstrate that compared to the NbN HEB mixer (1.6GHz), the GBW for MgB_2 HEB (6GHz) is larger by a about factor of 3. The noise temperature for such MgB_2 devices (4300K) is about factor of 4 higher compared to the NbN HEB. It has been indicated in other publications,[11] that due to a fast MgB_2 film surface oxidation, in-situ contact fabrication might be required in order to reduce the THz signal coupling loss. Such effect has been observed in NbN HEB mixers, where more narrow devices show a high noise temperature, in particularly at higher LO frequencies (>1THz). This effect is expected to be much more critical for MgB_2 HEBs. Currently, we are working on a technique for in-situ gold contact deposition on thin MgB_2 films.

REFERENCES

[1] P.Goldsmith and D.C.Lis, Trans. IEEE THz Sci.Technol. vol. 2, n. 4, Jul. 2012, p.383

[2] A. Karpov, D. A. Miller, J. A. Stern, B. Bumble, H. G. LeDuc, et al., "Low Noise 1 THz SIS Mixer for Stratospheric Observatory: Design and Characterization", IEEE Trans.Appl.Supercond., vol.21, n.3, June 2011, p.616

[3] W. Zhang,P. Khosropanah, J. R. Gao, E. L. Kollberg, K. S. Yngvesson, T. Bansal, R. Barends, and T. M. Klapwijk, Appl.Phys.Lett. 96, 111113 (2010)

[4] H. Ekström, E. Kollberg, P. Yagoubov, G. Gol'tsman, E. Gershenzon et al. " Gain and noise bandwidth of NbN hot-electron bolometric mixers", Appl. Phys. Lett. 70, 3296 (1997);

[5] C.Risacher, R.Güsten, J.Stutzki, H.-W.Hübers, D. Büchel et al., "First Supra-THz heterodyne Array Receivers for Astronomy With the SOFIA Observatory", Trans.IEEE THz Sci.Technol., v.6, n.2, pp.199-211, March, 2016.

[6] A. F. Loenen, P.P. Van der Werf, R.Güsten, R.Meijerink, F.P. Israel, et al.,"Excitation of the molecular gas in the nuclear region of M82" Astron. Astrophys., vol. 521, p. L2, 2010.

[7] S. Cherednichenko, V. Drakinskiy, et al, "Terahertz mixing in MgB_2 microbolometers", Appl. Phys. Lett., 90 (2) pp, (2007)

[8] E. Novoselov, S. Bevilacqua, S. Cherednichenko, K.Ueda, T.Naito "Effect of the Critical and Operational Temperatures on the Sensitivity of MgB_2 HEB Mixers", IEEE Trans. Terahertz Sic. Technol. vol. 6 (2) s. 238-277 (2016)

[9] S. Bevilacqua, S. Cherednichenko, V. Drakinskiy, H. Shibata, Y. Tokura . "Study of IF bandwidth of MgB_2 phonon-cooled hot-electron bolometer mixers" . IEEE Trans.THz Sci. Technol.. v.3, n.4,pp. 409-415, Jul. 2013

[10] D. Cunnane, J. Kawamura, B. Karasik, M. A. Wolak, and X. X. Xi, "Development of hot-electron THz bolometric mixers using MgB_2 thinfilms", Proc. of SPIE Vol. 9153, 91531Q.

[11] D. Cunnane, J. H. Kawamura, M. A. Wolak, N. Acharya, T. Tan, X. X. Xi, and B. S. Karasik,"Characterization of MgB_2 Superconducting Hot Electron Bolometers" IEEE Appl. Supercond. vol. 25, no. 3, p. 2300206, June 2015

[12] X.X. Xi, A.V. Pogrebnyakov, S.Y. Xu, K. Chen, Y. Cui, "MgB_2 thin films by hybrid physical–chemical vapor deposition", Physica C 456 (2007) 22–37

[13] S.Cherednichenko, V.Drakinskiy, T. Berg, P. Khosropanah, and E. Kollberg "Hot-electron bolometer terahertz mixers for the Herschel Space Observatory", Rev. Sci. Instrum. 79, 034501 (2008).

[14] De Graauw T, Helmich FP, Phillips TG, et al, "The Herschel-Heterodyne Instrument for the Far-Infrared (HIFI)", ASTRONOMY & ASTROPHYSICS Volume: 518 Article Number: L6 , pp.1-7. 2010.

[15] S. Cherednichenko, M. Kroug, P. Khosropanah, A. Adam, H. Merkel, E. Kollberg, D.Loudkov, B. Voronov, G. Gol'tsman, H.-W. Huebers, H. Richter, "1.6 THz HEB mixer for far infrared space telescope (Hershel)", Physica C, vol.372.pp.427-431, Aug. 2002.