Broadband MgB_2 Hot-Electron Bolometer THz Mixers operating up to 20K

Evgenii Novoselov and Sergey Cherednichenko

***Abstract*— We discuss performance of submicron size hot-electron bolometer (HEB) mixers made from thin MgB_2 superconducting films. With a superconducting transition temperature of ~30K, such THz mixers can operate with high sensitivity at temperatures up to 20K. Due to very small dimensions local oscillator (LO) power requirements are rather low. In the intermediate frequency (IF) band of 1-3GHz the double sideband receiver noise temperature is 1600K at 10K operation temperature, 2000K at 15K, 2500-3000K at 20K. The gain bandwidth of such devices is 6GHz and the noise bandwidth is estimated to be 6-8GHz**

***Index Terms*— hot-electron bolometer, HPCVD, magnesium diboride, superconductivity, thin film.**

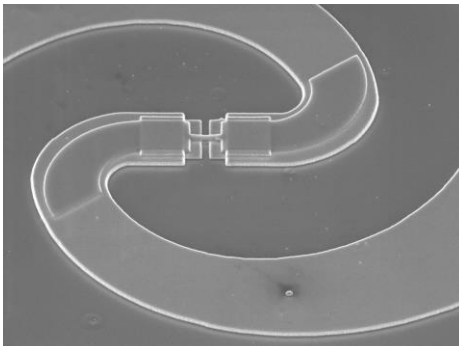

Fig. 1. A HEB mixer with a spiral antenna. The SEM image is obtained from a sample similar to the one discussed here. Gold spiral antenna is the light grey area.

I. INTRODUCTION

Utilization of bolometers as mixers in the submillimeter (or terahertz, THz) range has been suggested back in 1960s [1]. However only after fast electron energy relaxation was discovered in Nb-based superconducting films (hot-electron phenomenon) [2], bolometric mixers found wide applications in high spectral resolution radio astronomical instruments: on the ground (SMTO [3], APEX [4]), airborne (SOFIA [5]) and space borne (Herschel [6]) observatories. The choice for NbN was motivated by the fast electron-phonon interaction (10 ps) [7], ability to fabricate very thin films (5nm) [8], and a convenient critical temperature, T_c (16K in bulk, or 9-11 K in thin films). NbN HEB mixers operate in the 2-4K temperature range, cooled (in most cases) by liquid helium. A high response rate results in ~2GHz Gain Bandwidth (GBW) [9], which has also been reported by several groups. Sensitivity of NbN HEB mixers (in the units of the double sideband (DSB) receiver noise temperature) is ~700-1000K (~10 times the quantum limit) as it has been experimentally obtained for frequencies ranging from 1THz to 5THz [10,11]. The noise temperature increases towards higher intermediate frequencies (IF) and it doubles its value at about 4GHz. This figure sets the so called Noise Bandwidth (NBW) $T_r(IF)= T_r(0)\times(1+(f_{IF}/NBW)^2)$ (here, f_{IF} is the intermediate frequency, $T_r(0)$ is the noise temperature at $f_{IF}=0$) [12]. Though, for some applications these values for the GBW and the NBW are sufficient, importance for THz mixers with a broader IF bandwidth has been emphasized: e.g. for broadband molecular line surveys, observations of extragalactic sources, pressure and Doppler broadened lines. Furthermore, necessity of LHe for cooling of NbN HEB mixers severely limits operation time of Space missions, as well as observation campaigns for ground based instruments.

In 2007 a rather broad GBW was demonstrated in HEB mixers based on 20nm superconducting magnesium diboride (MgB_2) films [13]. Such films were made using molecular beam epitaxy [14]. Moreover, already first results showed a low noise temperature in such devices (10 000K) at THz frequencies. Phonon transmission through the MgB_2/substrate interface was estimated to be much better than through the NbN/substrate interface. Therefore, prospects for a GBW of up to 8-10GHz were discussed. Later, the noise performance was improved down to 700K (at 1.6THz [15]). However, that figure of merit was achieved for films with a T_c of 8-10K. Degradation of the critical temperature from 39K in bulk down to 20-25K for 20nm films, and then to 10K for 10nm films, resulted in an increased electron-phonon interaction time, and hence in a reduced GBW (2-3.5GHz). New deposition methods were required in order to produce a high quality thin MgB_2 film. On the other hand, MgB_2 films as thin as 10nm with a T_c above 30K were reported deposited with a Hybrid Physical Chemical Vapor Deposition technique [16]. First MgB_2 HEB mixers made with this technique were reported with a greatly improved GBW of 8GHz [17,18]. Very recently, similar approach was shown in [9], where a 6GHz GBW and a noise temperature of 3000K were obtained. Those devices were made with the photo-lithography technique and hence they were 1-5μm across. Due to the large size and the large T_c, such devices required a rather high LO power, hindering from accurate characterization at

This work was supported by the European Research Council (ERC).

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TABLE I
MgB_2 HEB SIZE (WxL), RESISTANCE AT 295K AND 50K (R_{295} AND R_{50}), CRITICAL TEMPERATURE (T_C), AND CRITICAL CURRENT AT 4.2K (I_C).

#	WxL (nm^2)	R_{295} (Ω)	R_{50}(Ω)	T_c(K)	I_c at 4.2K (mA)
E8-2	300×300	52	41	32	0.75
E8-7	500×500	86	67	29	0.62

THz frequencies (output power of THz source is very limited).

In this work we present first results for submicron size MgB_2 HEB mixers made using the e-beam technique. 10nm MgB_2 films were deposited in a custom made HPCVD system, demonstrating a T_c of 35K. Devices as small as 300×300nm^2 and 500×500nm^2 were fabricated and characterized at 693GHz.

II. Device fabrication and experimental techniques

In order to obtain thin MgB_2 films with a high T_c (the goal is T_c>30K) we utilized our home built HPCVD system. The system design and the details of the deposition process have been described in [19]. For the samples discuss in this paper, a deposition pressure (H_2) of 20Torr was chosen since it provides a smooth surface, which is essential for submicron size HEBs. The diborane (5% of B_2H_6 in H_2) flow was 2sccm and the deposition time was 120s. Films on 10×10mm^2 SiC substrates were used for the HEB fabrication. The film thickness was 10nm as measured with a Transmission Electron Microscope (TEM). Previous measurements of the films thickness indicate that the given deposition parameters result in a 10-15nm thick MgB_2 film. The critical temperature on the witness substrate was 35K with a transition width of 1K. MgB_2 films on the 10mmx10mm substrates were covered with a 20nm thick gold layer (2nm Ti buffer) in a magnetron sputter with about 10min MgB_2 exposure to the air during the wafer transfer.

Our previous experience shows that the equivalent sheet resistance in microstructures is approximately a factor of 2-3 larger than the sheet resistance in the continuous film (35-40Ω/sqr at room temperature). The residual resistance ratio (RRR=R_{295}/R_{50}) for continuous films was 2 (for the discussed thickness), whereas RRR was 1.3 for the ready devices. HEB mixers are essentially microbridges at the feed point of a planar spiral antenna (see Fig.1). Antenna impedance is real (self complementary design) and it is ~90Ω. Microbridges were designed as squares with either a 300nm or 500nm side.

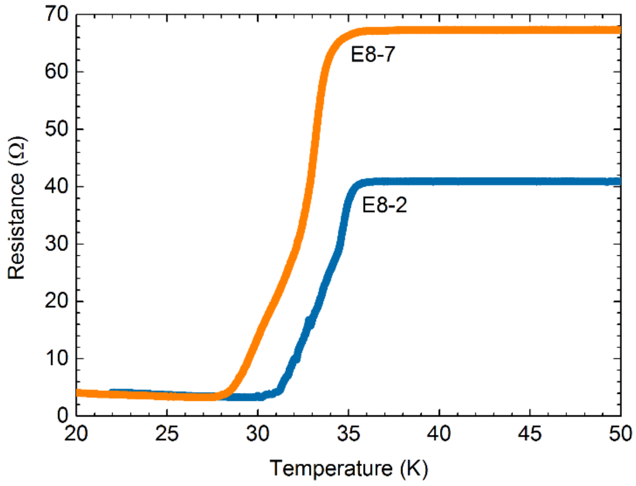

Fig. 2 R-T curves for samples E8-2 (blue) and E8-7 (orange).

Resulting devices had room temperature resistances in a range of 50-80Ω. Scattering of the resistance values we associate with some film non-uniformity on the microscale. Variation of R_{295} also correlates with the variation of the critical current. For the THz measurements one device 300x300nm^2 and one 500×500nm^2 were chosen. The critical temperatures were 32K and 29K, correspondingly. IV-curves of the devices were recorded in a dip-stick with a 5K interval. The critical current values in the mixer block (during THz characterization) were used to obtain the HEB actual temperature.

In order to measure the HEB mixer sensitivity, we mounted HEB chips in a mixer block. This block consisted of a 12mm elliptical Si lens and a coaxial contact to the HEB. This Si lens size was found to the near optimum for the THz beam coupling from the FIR gas laser, used as the LO source. The laser emission frequency was 693GHz. The mixer block was installed in a LHe optical cryostat with some thermal insulation from the cold plate. A heater was mounted on the mixer block to be able to rise its temperature. In the cryostat, a bias-T and a 1.5-4.5GHz Low Noise Amplifier (LNA) followed the mixer block. The noise temperature of the LNA was nominally about 2-3K, however the total IF chain noise is higher due to the loss in the bias-T. At room temperature the IF signal was further amplified by ~50dB, and measured with a microwave power meter. A tunable bandpass filter (1-9GHz, 50MHz bandwidth), installed just before the power meter controlled the IF frequency. A 12µm Milar film bean splitter combined the LO and the Signal (from the 295K and 78K black bodies). The receiver noise temperature was obtained from the measured Y-factor, and then corrected for a 1.3dB loss in the cryostat window and the IR filter, a 0.5dB loss in the beam splitter, and a 1dB loss on the Si lens surface (the Si lens did not have any antireflection coating). These optical corrections we also

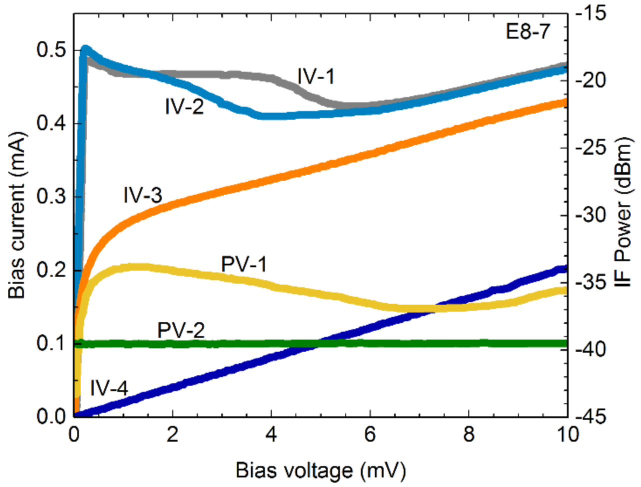

Fig. 3. Current-Voltage (IV) curves for the 500nmx500nm HEB: IV-1 -in the dip-tick at 10K; IV-2- in the mixer block; IV-3- under the optimal LO power (693GHz); IV-4- pumped by the LO into the normal state. IF Power-Voltage curves measured at 2GHz: PV-1 – corresponds to the optimal LO (IV-3); PV-2- corresponds to the normal state (IV-4).

utilized in our previous publications, hence a direct comparison with published results for larger HEB mixers can be done.

III. SENSITIVITY CHARACTERIZATION

MgB$_2$ HEB mixers were characterized in the receiver set-up as described in the previous section. The choice of the LO frequency (693GHz) was motivated by a higher output power of the utilized far-infrared (FIR) laser, as compared to other emission lines (e.g. 1.63THz). A factor of 10 smaller area of the discussed devices compared to those e.g. presented in [9], allowed to use a thinner beam splitter and hence to increase the measured Y-factor. Current–Voltage characteristics (IV-curves) of sample E8-7 are shown in Fig.3. By comparing the IVs measured in the dip-stick (IV-1) and in the cryostat (IV-2) we can estimate the sample temperature, 10K. The IV under the optimal LO power (the highest Y-factor) is IV-3. The measured microwave power P_{IF} from the receiver is a sum of the HEB output noise, the IF chain noise, and the down converted signal from the input load. The resulting P_{IF} (Fig.3, PV-1) varies with the HEB bias voltage with a maximum at about 0.5mV. The lowest receiver noise temperature is obtained at bias voltages slightly above the maximum on the PV-curve (1-2mV). Since the device area was very small then using a mirror (instead of the beam splitter) the LO source was able to pump the HEB into the normal state (IV-4). IV-4 is totally linear with a resistance of 50Ω, near beginning of the superconducting transition (see Fig.2). The IF power is also bias independent, indication that the HEB is in the normal state. As any normal conductor the output noise of the HEB in this state is just the Johnson noise, with a characteristic noise temperature equal the HEB electron temperature, hence 32K. How much the noise of the HEB at the best sensitivity point (IV-3) exceeds the noise in the normal state indicates on how well the HEB works and how low the IF LNA noise is.

The HEB receiver noise temperature across a 1.3-4.5GHz IF band is shown in Fig.4. For these measurements the cold load was periodically alternated with a hot load coated chopper. The scattering of the points is due to LO source instabilities, leading to Y-factor fluctuations. The noise temperature is approximately 2000K in the range from 1.5GHz to 3GHz.

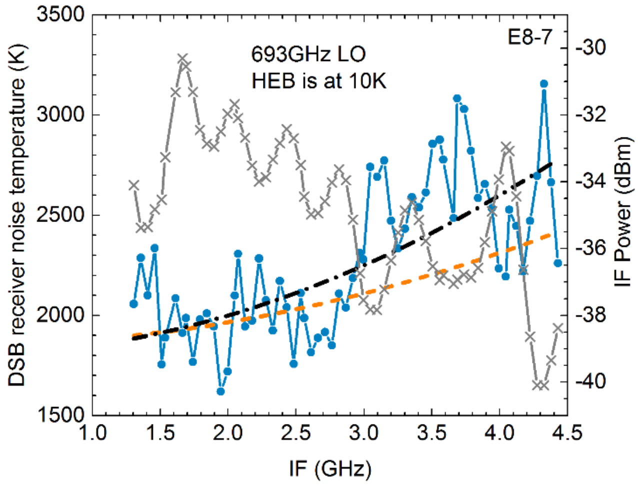

Fig. 4. The receiver noise temperature (circles) and the output power (crosses) (295K load) as a function of the IF. The HEB mixer was at 10K. The dashed and dashed-dotted lines are noise bandwidth fits for a 6GHz and an 8GHz noise bandwidth.

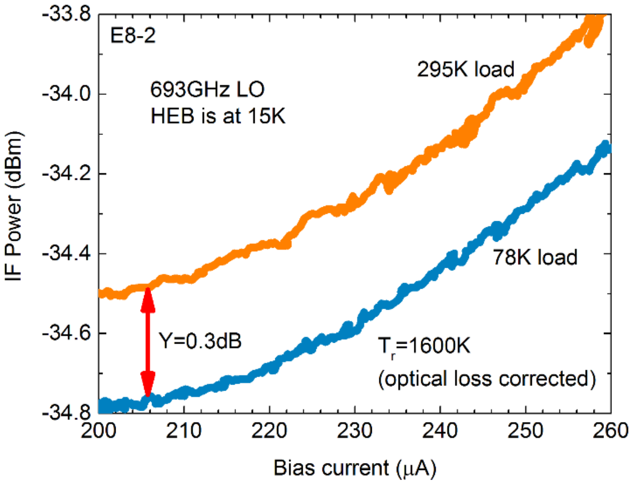

Fig. 5. IF response of sample E8-2 to the hot (295K) and the cold (78K) black body loads as a function of the bias current, I0. Variation of Io was achieved with a varying LO power. The bias voltage is 1mV, and the IF is 1.3GHz. The indicated noise temperature is corrected for the optical loss, as described in Section II. The HEB mixer was at 15K.

Recorded P_{IF} shows some falls of the receiver gain between 3GHz and 4GHz, and at 4.3GHz. It is also accompanied by a rise of the noise temperature (Fig.4). We interpret it as an LNA degradation. Two fitting curves (the dashed and dashed-dotted curves in Fig.4) are $T_r(IF)=T_r(0)(1+(f_{IF}/NBW)^2)$ with a NBW of 6 GHz and 8GHz, where $T_r(0)$ is the receiver noise temperature at zero IF.

In order to deal with LO source instabilities, the next sample (E8-2) was tested at a fixed IF (1.3GHz) and a fixed bias voltage (1mV). P_{IF} was recorded as function of the bias current. The later was achieved by varying the LO power both with the hot and the cold loads at the receiver input (Fig.5). For the 1mV bias point, the Y-factor was about the same from 200µA to 250µA. The resulting noise temperature is approximately 1600K (with the optical loss removed). During this test the mixer temperature was 15K.

IV. DISCUSSION

In the previous section we showed that a noise temperature of the order of 1600K can be achived at 15K operation of an MgB$_2$ HEB mixer. Such mixers had a submicron size and with a 1mW LO source a 15dB atennuation is required in order to obtain the optimal IV-curve if a mirror is used. It means approximately 30µW (referenced to the output of the LO source) for the LO power requirement for the discussed devices. With a 50µm thick Mylar beam splitter there was ~7-8dB margin. Such a beam splitter has a reflection coefficient of 0.5 at 693GHz which confirms the result obtained with the mirror. With the 50µm thick Mylar beam splitter the noise temperature is approximately ×1.5 higher than with the 12µm thick beam splitter. This factor is close to the one obtained from calculations of the thin film beam splitter [20].

Apparent problem with the utilized IF LNA prevented obtaning an accurate receiver noise temperature data in the whole range up to 4.5GHz. However, the noise bandwidth seems to be more than 6-8GHz. This is still narrower that expected for a 6GHz gain bandwidth obtained for devices made of similar films [9]. We believe that replacement of the LNA will solve this issue.

Another direction for improvements is optimization of the MgB_2 thin film deposition and the HEB fabrication techniques in a way to reduce the superconducting transition width. For batch E8 the transition width is approximately 4K with a double transition structure. Such feature appears only in our thinnest films. Considering a greatly reduced RRR in the micron size HEBs (1.3 against 2 for films, see also [19]), we conclude that there is a significant concentration of deffects in the film on the micrometer scale.

V. CONCLUSION

A receiver noise temperature of 1600K has been demonstrated for MgB_2 HEB mixers at 15K operation temperature and at a 693GHz LO. Devices were made from a 10nm thick film, similar to the one for which a 6GHz gain bandwidth has been obtained [9]. The noise bandwidth is currently in a range of 6-8GHz, limited by the IF amplifier.

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