MgB_2 thin film terahertz mixers

S.Cherednichenko*, V.Drakinskiy

Abstract— **Thin film (20 nm) MgB_2 bolometric devices were made on silicon substrates. The performance of the devices as THz mixers was investigated with respect to the gain bandwidth and the noise temperature. For the given film thickness the 3 dB gain roll-off frequency is 2.5 GHz, which is much higher than for the NbN HEB mixers of the same thickness. Corrected DSB mixer noise temperature is ≈2000 K at 2 GHz IF. The noise bandwidth was measured in the IF range of 2-5 GHz.**

Index Terms— **MgB_2, mixer, THz, electron-phonon interaction.**

I. Introduction

Superconducting hot-electron bolometer mixers have been under intensive investigation after early publications in 1990^{th} [1, 2]. Due to fast electron temperature relaxation rate the resistance modulation in some superconducting films can be done up to GHz range without responsivity degradation. In clean films ($ql>1$, where q is the phonon wavelength, and l is the electron mean free path), where electron diffusion coefficient D_e is large the electron temperature relaxation occurs via electron diffusion from the bolometer to the contact pads. Here, if bolometer is shorter than the electron diffusion length ($\sim(D_e\tau)^{0.5}$, where τ is the time of electron inelastic scattering, which at LHe temperatures occurs mostly on the phonons, $\tau_{e\text{-}ph}$), the bolometer response time is proportional to the bolometer length. E.g. for Nb, $(D_e\tau_{e\text{-}ph})^{0.5}\sim1$ µm. It provides the mixer gain bandwidth of the order of 6 GHz [3]. Besides the bolometer length limitation the quality of the superconductor-normal metal contact has to be very good in order to achieve good electron transmission. Electron-phonon interaction time in Nb films is of the order of 1 ns [4]. On contrary, in superconducting films with much shorter electron-phonon interaction time (e.g. in NbN $\tau_{e\text{-}ph}\approx10$ps at 10 K [5]) the electrons scatter on phonons prior they get a chance to diffuse to the contact pads. In this case the phonons serve as the heat sink. If the phonon heat capacitance is not much higher than the electron heat capacitance, the phonon escape time τ_{esc} from the film to the substrate becomes important. A number of radioastronomical instruments have been equipped with such thin film NbN HEB mixers: HIFI 1.4-1.9 THz band (Herschel Space observatory); TELIS, SOFIA, Receiver Lab Telescope in Chile (SAO), APEX. A DSB noise temperature of about 450 K has been achieved for 500-700 GHz, 700 K at 1.6THz and 1100 K at 2.5 THz [6, 7, 8], 6400 K at 5.2 THz [9]. NbN films technology is able to provide films as thin as 3 nm with T_c about 9K. Currently, the bottle- neck of the hot electrons' relaxation process is the phonon escape from the NbN film into the substrate. The mixer gain bandwidth of about 2 GHz for the NbN HEB mixers on crystalline quartz [10], 4.5 GHz on MgO [11], 3.5 GHz on Si [12].During the past years there was a continuous search for new materials. For example, Al, Ta, NbTiN, YBaCuO films have been tried. In this paper we report on successful implementation of THz bolometric mixers made of thin superconducting MgB_2 films.

Manuscript received May 15, 2006. The authors are with the Department of Microtechnology and Nanoscience, MC2, Chalmers University of Technology, SE-412 96, Gothenburg, Sweden.
(Corresponding author: S.Cherednichenko, e-mail: serguei.cherednichenko@mc2.chalmers. se).

A. DC characterization of MgB_2 microbridges.

The MgB_2 bolometers were lithographically made as 2x1 μm^2 bridges in a feed point of a planar spiral antenna [8]. The nominal film thickness is 20 nm with a T_c of about 25 K. The normal state resistivity of thicker MgB_2 films has been quoted to be in the range from 4-8 µOhm·cm [13,14] (which is factor of 5 higher than normal state resistivity of bulk samples [15]) to 20-80 µOhm·cm [16]. The RF resistivity in MgB_2 films is defined by the π-band ($2\Delta\approx kT_c$=1.7 meV). At 1.6THz the photon energy is 6meV.

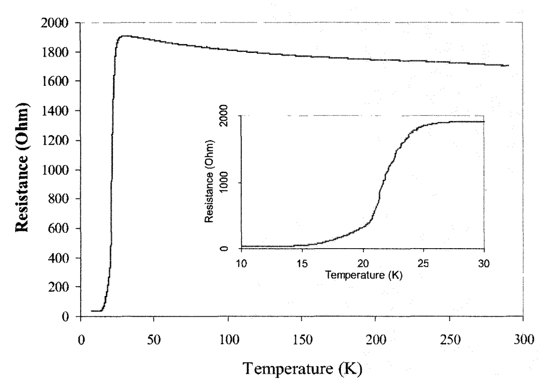

Fig. 1. Resistance versus temperature dependence for the MgB_2 mixer. The inset shows a close-up of the superconducting transition.

Therefore bolometer RF impedance at 1.6THz equals the normal resistance. The resistance of the MgB_2 microbridge versus temperature is shown in Fig. 1 (the inset zooms into the superconducting transition region). The transition is rather broad, ~4K with the middle of the transition at about 22 K. The broad superconducting transition and the long low temperature tail are probably due to the film nonhomogeneity.

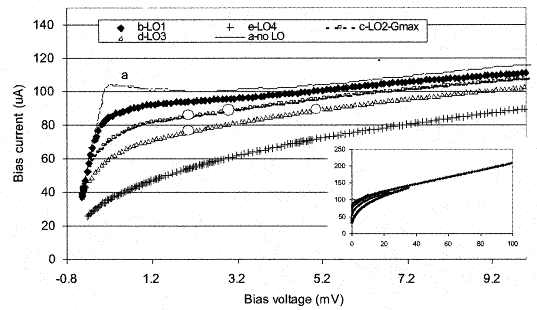

Fig. 2. Current- voltage (*IV*) curves of the MgB_2 mixer at 4.2 K bath temperature: without LO power (a) and with LO power applied (b-e). The maximum mixer gain was obtained for *IV*-c. The zero current corresponds to -0.8mV which is due to the thermal voltage on the bias lines. The curves are obtained with a bias voltage source. The inset shows the *IV*s on a larger scale.

The current –voltage (*IV*) characteristic at 4.2 K is shown in Fig. 2 (curve *a*) as obtained with a bias voltage source. The residual resistance is about 8 Ohm which corresponds to the value from the *R*(*T*) curve (Fig. 1). The critical current I_c is 105 μA, what for the given film dimensions results in the critical current density j_c=2.6·10^5 A/cm^2. Application of the THz Local Oscillator (LO) source (either at 0.6 THz or 1.6 THz) easily suppresses the critical current (Fig. 2, curves *b-e*). The dc resistance (U_0/I_0) on all bias points from Fig. 2 does not exceed 120 Ohm, which corresponds to the low temperature tail of the *R*(*T*)-curve. The maximum RF responsivity (recorded during the gain bandwidth measurements at 0.6 THz) corresponds to the *IV-c* and therefore does not coincide with the maximum *dR/dT*.

B. MgB_2 mixer gain bandwidth.

The time constant τ of the MgB_2 bolometer as a mixer was measured by mixing two 0.6 THz backward wave oscillators (BWO). One BWO was used as an LO while the other served as a signal source. The mixer chip was mounted on an elliptical silicon lens. The mixer unit was mounted on the cold plate of a LHe optical cryostat (4.2 K bath temperature). The IF output from the mixer unit was sent out of the cryostat to two broadband (0.1-12 GHz) room temperature amplifiers. Both IF frequency and IF power were measured with a broadband spectrum analyzer. In order to improve mixer matching to (rather long) IF line a 3dB attenuator was connected to the mixer unit output (in the cryostat) and another attenuator was connected to the IF output from the cryostat. The signal BWO power was much lower than the LO BWO power, and its frequency was constant during the measurements. First, the IF response was measured at the IF of about 0.5 GHz and the *IV*-curve (LO power) corresponding to the maximum IF response was found. During the mixer response measurements versus IF the LO BWO was frequency tuned while its power (as well as the mixer bias voltage) was kept constant. The bias points where the mixer response vs IF was measured are shown in Fig. 2 with circles. The experimental curves can be approximated with a single-pole Lorentzian $G(0)/[1+(2\pi f_{if}\tau)^2]$, where $G(0)$ is the IF response at zero frequency. For mixers it is more convenient to operate with a 3dB gain rol-off frequency $f_0=1/(2\pi\tau)$ which determines the mixer gain bandwidth. The maximum IF respons was observed at the LO power corresponding to the *IV-c* at the bias voltage 2-3 mV. At these points (2 mV, 84 μA; and 3mV, 87 μA) the mixer gain bandwidth is 2.3-2.5 GHz (Fig. 3). For higher LO power (2 mV, 77 μA) and for higher bias voltage (5mV, 90 μA) the gain bandwidth increases to correspondingly 3 GHz and 6 GHz.

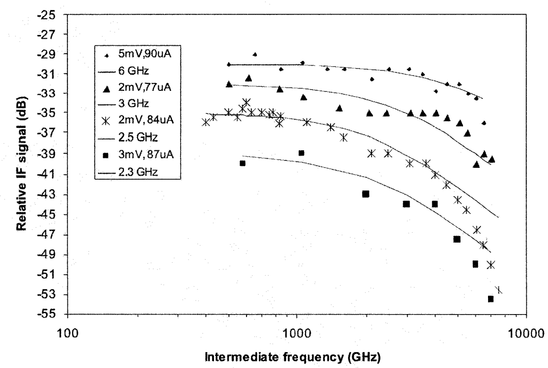

Fig. 3. Intermediate frequency response of the MgB_2 mixer at two different LO power levels and different bias voltages. The LO frequency is 600 GHz.

C. Mixer noise temperature.

The MgB_2 mixer noise temperature was measured at 1.63 THz LO frequency. An optically pumped FIR laser was used as the LO source. A 2-4.5 GHz low noise amplifier (LNA) with the noise temperature of 2 K and the gain of 32 dB was mounted on the LHe cryostat cold plate, next to the mixer unit. At room temperature the IF chain consisted of 58 dB extra amplification, 1-9 GHz tunable Yig-filter (50 MHz instantaneous bandwidth), and a low noise power meter. In the optical path, two Zitex (250 μm thick) IR filters were installed on the 4.2K and 77K cryostat shields. The cryostat window was sealed with a 1 mm Teflon slab. The system noise temperature was obtained by measuring the Y-factor at each IF frequency by chopping the 300K/77K RF input load. The calibration signal was combined with the LO beam with a Milar beam splitter. The mixer noise temperature T_m was then calculated by taking into account the known RF losses in the air, cryostat window and the IR filters. Finally, the T_m was corrected for the reflection between the mixer and the antenna which is caused by the impedance mismatch: $R=(Z_{ant}-Z_m)^2/(Z_{ant}+Z_m)^2$, where Z_{ant}=100 Ohm is the calculated antenna impedance, and Z_m is the MgB_2 mixer normal state resistance (≈2000 K). It results in R=0.18, i.e. about 7.5 dB. The resulting mixer double sideband noise temperature is shown in Fig. 4. The ripples are caused by a standing wave in the IF line between the mixer and the LNA since no isolator was used.

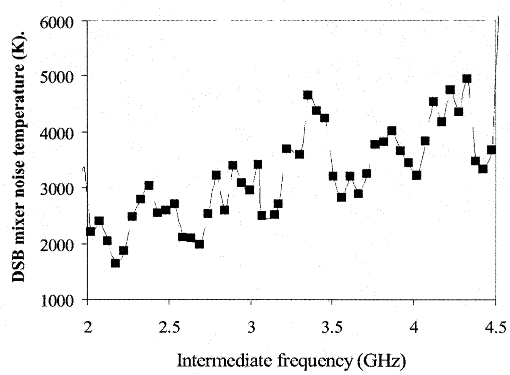

Fig. 4. Double sideband mixer noise temperature corrected for the bolometer-antenna mismatch (7.5 dB) as a function of the intermediate frequency (50 MHz instantaneous bandwidth).

II. Conclusion.

The gain bandwidth of 2.5 GHz obtained with the MgB_2 bolometers is an order of magnitude larger than for any type of superconducting bolometric mixers at the given film thickness (20 nm). An electron-phonon time constant in MgB_2 films ~ps has been already reported [17]. However, in order to interpret our results a complete two temperature model [18] has to be applied which we will do in another paper. Dynamic resistance (*dV/dI*) at the maximum gain bias points is of the order of 300 Ohm, which is much higher than the IF line impedance (50 Ohm). This results in 3dB IF loss. Furthermore, it causes the observed IF ripples seen in Fig. 4.

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References:

1 E.M. Gershenzon, G.N. Gol'tsman, I.G. Gogidze, Y.P.Gousev, A.I. Elant'ev, B.S. Karasik, and A.D. Semenov, *Sov. Phys. Superconductivity*, **3**(10), 1582, 1990
2 D.E. Prober, Appl. Phys. Lett. **62**, 2119 (1993)
3 P.J.Burke, et al, Appl.Phys.Lett., **68**, 3344 (1996).
4 E.M.Gershenzon, M.E.Gershenzon, G.N.Gol'tsman, A.M.Lyul'kin, A.D.Semenov, and A.V.Sergeev, Sov.Phys.JETP 70(3), 505, (1990)
5 Y. Gousev, G. Goltsman, A. Semenov, and E. Gershenzon, J. Appl. Phys., **75**, 3695 (1994).
6 S. Cherednichenko, M. Kroug, P. Khosropanah, A. Adam, H. Merkel, E. Kollberg, D.Loudkov, B. Voronov, G. Gol'tsman, H.-W. Huebers, H. Richter, Physica C, vol.372.pp.427-431, Aug. 2002.
7 J.Kawamura, R.Blundell, C.E.Tong, G.Gol'tsman, E.Gershenzon, B.Voronov and S.Cherednichenko Applied Physics Letters, **70**(12), pp.1619-1621, 24 March,1997.
8 M.Kroug, S.Cherednichenko, H.Merkel, E.Kollberg, B.Voronov, G.Gol'tsman H.-W.Huebers, H.Richter, IEEE Trans. on Appl. Supercond. Vol.11, n.11, pp. 962-965, 2001
9 H.-W. Hübers, A. Semenov, H. Richter, M. Schwarz, B. Günther, K. Smirnov, G. Gol'tsman, and B. Voronov, in: *Millimeter and Submillimeter Detectors for Astronomy II*, J. Zmuidzinas, W. S. Holland, and S. Withington, eds., Proc. SPIE **5498**, pp. 579-586, 2004.
10 J.Kawamura, R.Blundell, C.-Y.E.Tong, G.Gol'tsman, E.Gershenzon, B.Voronov, and S.Cherednichenko, Appl.Phys.Lett. **70**, 1619 (1997).
11 S.Cherednichenko, M. Kroug, P.Yagoubov, H. Merkel, E. Kollberg, K.S. Yngvesson, B. Voronov and G. Gol'tsman, Proc. 11th Intl. Symp. Space Terahertz Technol., 219, (2000), Ann Arbor, MI, USA.
12 H.Ekström, E.Kollberg, P.Yagoubov, G. Gol'tsman, E. Gershenzon, and K.S. Yngvesson, Appl. Phys. Lett. **70**, 3296 (1997).
13 R.A.Kaindl, M.A.Carnahan, J.Orenstein, D.S.Chemla, H.M.Christen, H.-Y.Zhai, M.Paranthaman, and D.H.Lowndes, Phys.Rev.Lett., **88**, 027003-1 (2002).
14 B.B.Jin, P.Kuzel, F.Kadlec, T.Dahm, J.M.Redwing, A.V.Pogrebnyakov, X.X.Xi, and M.Klein, Appl. Phys.Lett., **87**, 092593 (2005).
15 T.Masui, and S.Tajima, Physica C, **385**, 91 (2003).
16 K.Ueda, and M.Naito, Appl.Phys.Lett., **79**, 2046 (2001).
17 Y.Xu, et al, Phys.Rev.Lett., **91**, 197004 (2003).
18 N.Perrin and C.Vanneste, Phys. Rev.B., **28**, 5150 (1983).