Low noise MgB_2 terahertz hot-electron bolometer mixers

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We report on low noise terahertz bolometric mixers made of MgB_2 superconducting thin films. For a 10-nm-thick MgB_2 film, the lowest mixer noise temperature was 600 K at 600 GHz. For 30 to 10-nm-thick films, the mixer gain bandwidth is an inverse function of the film thickness, reaching 3.4 GHz for the 10-nm film. As the critical temperature of the film decreases, the gain bandwidth also decreases, indicating the importance of high quality thin films for large gain bandwidth mixers. The results indicate the prospect of achieving a mixer gain bandwidth as large as 10-8 GHz for 3 to 5-nm-thick MgB_2 films. © *2012 American Institute of Physics*. [doi:10.1063/1.3678027]

Superconducting NbN hot-electron bolometer (HEB)[1] mixers are widely used for high resolution terahertz radio astronomy.[2] Such mixers have superior performance over other types of mixers (e.g., SIS, Schottky diodes)[2] at frequencies higher than 1.2 THz.[3–5] A large RF bandwidth, a low noise temperature, and low LO power requirements determined the choice of NbN HEB mixers for the Herschel space observatory.[6,7] In contrast to SIS mixers, the useful IF bandwidth of NbN HEB mixers is practically limited to 3-5 GHz,[8] as the noise temperature rises drastically at higher intermediate frequencies. The reason for this is that the HEB mixer gain rolls off as the IF exceeds the mixer's 3 dB gain bandwidth (GBW). The GBW is determined by two consequent processes in the electron energy relaxation: the electron-phonon interaction and the phonon energy relaxation. The second process mainly occurs via acoustic phonon escape into the substrate. The electron-phonon interaction time is usually a function of the temperature. For HEB mixers, the relevant electron temperature is the critical temperature of the superconducting film, T_c, to which the electrons are heated by a combination of the LO power and the dc bias current. In NbN thin films, the electron-phonon interaction time is approximately $\tau_{e\text{-}ph} \approx 12$ ps at 10 K.[9,10] The phonon escape time is on the order of $\tau_{esc} \approx 40$ ps for NbN films as thin as 3–4 nm.[8] Further reduction of the film thickness leads to a drastic reduction of the superconducting critical temperature, T_c, which acts towards a reduction of the GBW.[11] Therefore, increasing the GBW of phonon cooled NbN HEB mixers beyond the presently achieved 3–4 GHz seems to be unrealistic. A possible method to extend the GBW up to 6.5 GHz for NbN-based HEB mixers was discussed in Ref. 12, where electron diffusion from the bolometer into the contact pads was observed.

In this paper, we discuss an alternative material for THz HEB mixers, MgB_2 thin films. Earlier,[13] it was experimentally shown that due to the good acoustic match of MgB_2 films to Si substrates, a 2 GHz GBW can be obtained using 20 nm MgB_2 films. Such a GBW corresponds to approximately 5-nm-thick NbN films.[14] It has been discussed that the GBW of MgB_2 HEB mixers can be superior to that of NbN HEB mixers if very thin MgB_2 films are used. However, the reported mixer noise temperature was 11 000 K, which was caused by a high bolometer-antenna impedance mismatch.

In thin superconducting films, the phonon escape time[15] is $\tau_{esc} = 4\,d/\alpha u$, where α is the film-substrate phonon transmission coefficient and u is the speed of sound in the film. Therefore, to maximize the GBW, the film thickness d has to be as small as possible. c-Al_2O_3 substrates provide a much better lattice match to MgB_2 in comparison with silicon, resulting in higher critical temperatures for thin films. Therefore, such substrates were chosen for the devices discussed in this paper.

MgB_2 films as thin as 10, 15, and 30 nm were grown using molecular-beam epitaxy.[16,17] Bolometers were lithographically made as ~100–500 μm^2 bridges at the feed point of either a planar spiral antenna (see Fig. 1) or a bow-tie antenna. The MgB_2 room temperature resistivity after fabrication ranged from 90 $\mu\Omega \times$ cm (30 nm film) to 200 $\mu\Omega \times$ cm (10 nm film). The sheet resistance ratio, R(300)/R(40), was approximately 1.3, which together with the high resistivity

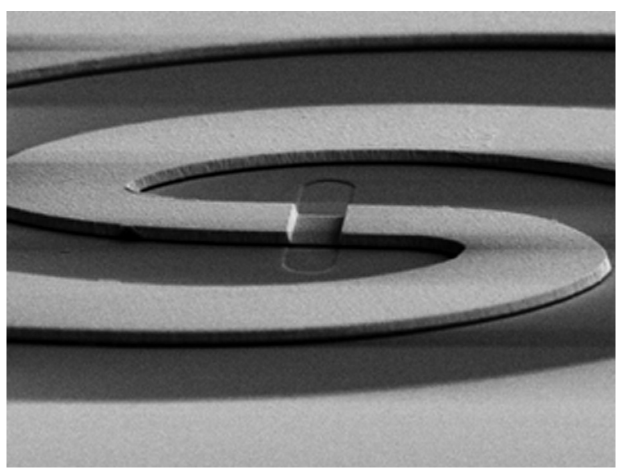

FIG. 1. A SEM image of a spiral-antenna-integrated MgB_2 HEB mixer. The antenna appears light gray. The HEB is between the spiral arms at the center.

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TABLE I. Gain bandwidth GBW, response time τ_Θ, film thickness d, and critical temperature T_c.

No.	GBW (GHz)	τ_θ (ps)	d (nm)	T_c (K)	ρ_{300} ($\mu\Omega \times$ cm)	$J_{c,4.2\,K}$ (MA/cm^2)
1	3.4	47	10	14	165	2.9
2	2.3	70	15	17	105	
3	1.3	130	30	24	90	9
4	1.5		10	8.5	190	0.5

indicates that our MgB_2 films are in the dirty limit.[18] The critical current density was in the range of $j_c = (0.2–10) \times 10^6$ A/cm^2. The critical temperature of the devices was 24, 17, and 14 K for the 30, 15, and 10 nm films (see Table I, samples 1-3). The devices were mounted on a Si lens and placed in a LHe cryostat with a base temperature of 4.2 K.

For gain bandwidth measurements, we used two backward wave oscillators (BWO) at approximately 600 GHz. The frequency of one BWO (the LO) was fixed, whereas the frequency of the other one (the signal) was tuned.

The optimal LO power for HEB mixers scales with the critical temperature and the bolometer size.[19] Furthermore, efficient coupling of the LO power to the HEB mixer occurs only at a condition of $hf > 2\Delta$, where hf is the photon energy and 2Δ is the superconductor energy gap. Therefore, for a mixing experiment at 600 GHz, we had to heat the mixers to approximately 7–9 K, which is still much lower than T_c. The bias voltage was optimized for the maximum IF signal, i.e., the mixer conversion gain. GBW measurements at higher bias voltages were also performed (though not discussed here), which confirmed the general tendency of HEB mixers to increase the GBW at high bias voltage conditions.

The results of the gain bandwidth measurements are given in Table I. In Figs. 2(a) and 2(b), we correlate the GBW data to the film thickness and the critical temperature for both MgB_2 mixers (from the discussed paper) and NbN mixers (from the literature). The open symbols in Fig. 2(a) (diamond and circle) correspond to MgB_2 sample #4. The solid lines in Figs. 2(a) and 2(b) are fits to the experimental data. For MgB_2 mixers, the fit is extrapolated to a film thickness of 3.5 nm.

At the thin film limit, the critical temperature decreases with the thickness, which mostly occurs due to a larger number of defects in the first layers of the film. A thorough optimization of the film deposition process is required to keep a high Tc in films that are just a few lattice constants thick. For a mixer made of a 10-nm-thick MgB_2 film, a 3.4 GHz GBW was obtained. To estimate the GBW for thinner MgB_2 film, we extrapolate the fit for GBW(d) in Fig. 2(a) using the same GBW vs. thickness dependence as for thicker films. For a 3.5 nm MgB_2 film, a GBW of 10 GHz seems to be quite feasible.

For noise temperature measurements, a new batch of devices was made of a 10 nm film, with a bolometer size of $1 \times 3\ \mu m^2$ (see Table I, sample 4) integrated with the spiral antenna. Due to the circular polarization of the spiral antenna, it is not the best choice of an antenna to match to a linearly polarized LO source beam. However, it allows for mixer tests in a large frequency range. The critical tempera-

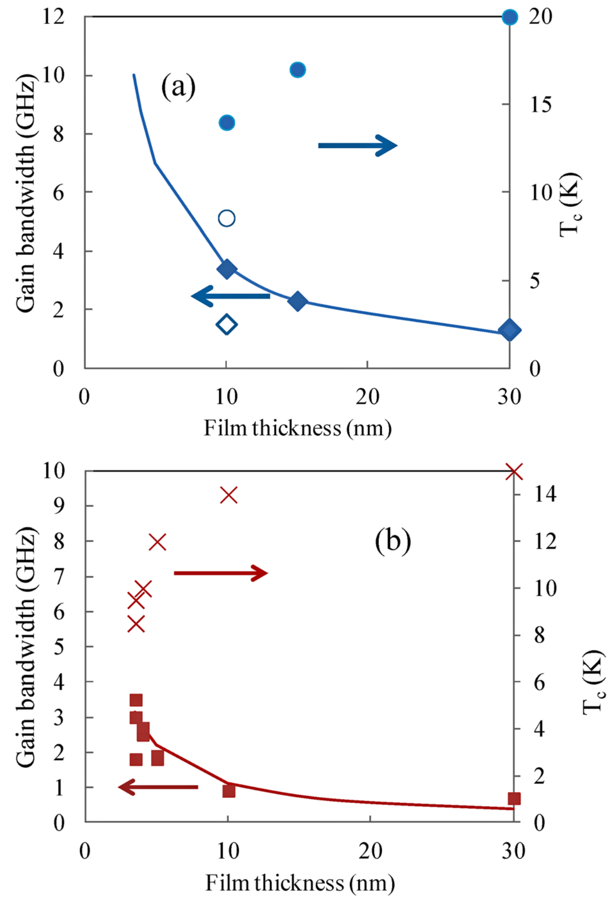

FIG. 2. (Color online) (a) The GBW (diamonds) and the T_c (circles) for MgB_2 HEB mixers versus the film thickness. The open symbols are for sample #4. (b) The GBW (squares) and the T_c (crosses) for NbN HEB mixers versus the film thickness (from Ref. 14).

ture of this batch turned out to be lower and was equal to 8.5 K (superconducting transition start) with a transition width of $\Delta T_c = 2.5$ K. We will further investigate the issue of small bolometers made of very thin MgB_2 films. However, at this stage, it also had a positive side in that it allowed us to perform noise measurements at frequencies as low as 300 GHz. Owing to the small energy gap, the LO power absorption from 300 GHz to 1.6 THz was the same, which was seen in the identical shape of the pumped IV-curves. The noise temperature was measured with a Y-factor technique using room temperature and LN-cooled black body sources. A 15 μm Mylar beam splitter was used to combine the signal from the black bodies and from the LO. The LO frequency was tuned away from the 550 GHz water vapor absorption line to minimize air absorption losses.

The IV-curves of sample #4 at 4.2 K with and without the LO power (at 600 GHz) are shown in Fig. 3. The receiver noise temperature has a broad minimum around a bias voltage of 1 mV and a current of 60 μA. The noise temperature versus IF in the range from 1 to 4.5 GHz and at a 600 GHz LO frequency is shown in Fig. 4. Correcting for the reflection losses at the silicon lens ($\sim$30%), the minimum receiver noise temperature (including noise contributions from the LNA, the IR filter, and beam splitter) is approximately 800 K. As we have discussed, the critical temperature of this batch was 8.5 K, i.e., much lower than for sample #1 (also

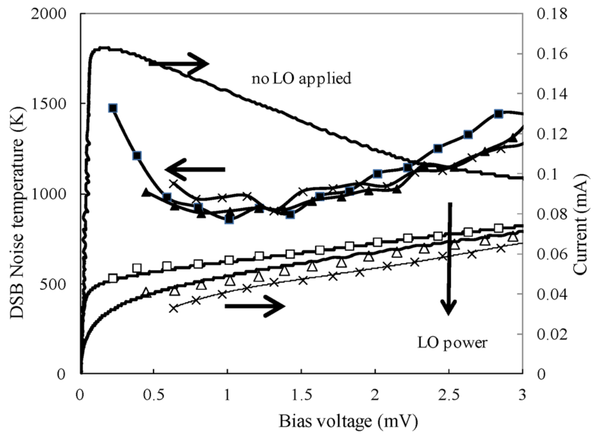

FIG. 3. (Color online) The IV-curves at various LO power levels (600 GHz), and the receiver DSB noise temperature vs. bias voltage for sample #4 at 4.2 K.

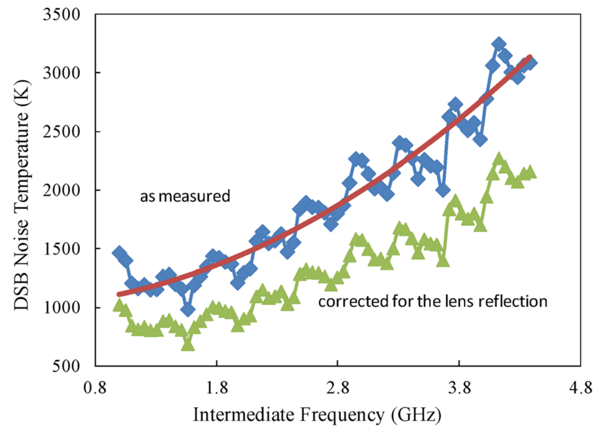

FIG. 4. (Color online) The receiver DSB noise temperature vs. IF for sample #4 at 4.2 K. The solid line is a fit for a 3 GHz receiver noise bandwidth.

made of a 10 nm film). For a bath temperature of 2 K (obtained by reducing the LHe vapor pressure), the critical current of sample #4 increases from 160 to 250 μA. To bring the mixer to the same bias point, the LO power had to be increased. At the same bias point, a 20% reduction of the receiver noise temperature was observed (~600 K). Indeed, as was discussed previously,[19] the HEB mixer gain is proportional to the LO power, which explains the general tendency of HEB mixers to show an improvement in performance for lower operation temperatures and/or higher critical temperatures. Further improvement of the mixer noise temperature is expected for devices with a higher Tc and a smaller ΔT_c.

As follows from Fig. 4, the noise bandwidth of device #4 is approximately 3 GHz. Using recorded values of the receiver output signal at 300 and 77 K input loads, we obtain the mixer conversion gain versus IF: $\Delta P = P_{300} - P_{77} = (300-77) \times G_m \times G_{IF}$, where G_m is the mixer gain (eventually including the RF losses) and G_{IF} is the IF chain gain. A GBW of 1.5 GHz was obtained using this method for device #4, which is a factor of 2 smaller than that of device #1. This reduction of the GBW we attribute to the reduction of the T_c, which leads to a reduction of the electron-phonon interaction rate. The T_c and the GBW for device #4 are shown in Fig. 2(a) with the open circle and the open diamond, respectively. A detailed discussion of all aspects of the MgB_2 HEB mixers is beyond the scope of this paper and will be given elsewhere. However, we can note that in metals, the electron-phonon interaction time is inversely proportional to the electron temperature (e.g., Ref. 20), which for the resistive state in HEB mixers, equals the critical temperature. This fact stresses the importance of a high T_c for thin MgB_2 films to minimize the electron energy relaxation time and, hence, to maximize the mixer's GBW.

In conclusion, we demonstrated a low noise THz HEB mixer based on thin MgB_2 superconducting films deposited on c-Al_2O_3 substrates using molecular-beam epitaxy. A receiver noise temperature of 600 K was measured at 2 K and 600 GHz. The GBW scales proportionally to the film thickness and reaches 3.4 GHz for a 10 nm film with a T_c of 14 K. From the obtained data, a GBW of 10–8 GHz is expected for mixers made of 3–5 nm films. Therefore, MgB_2 thin films appear very promising for low noise and wide GBW mixers for THz radio astronomy, as well as in other applications requiring broadband THz mixers.

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