Gain bandwidth of NbN Heterodyne Hot Electron Bolometer Superconducting Mixers made on thin SiO_2/Si_3N_4 membrane

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***Abstract*— We present results of the gain bandwidth investigation of NbN HEB mixers made on 1.4 μm thick SiO_2/Si_3N_4 stress-less membrane, and bulk-$Si/SiO_2/Si_3N_4$. We have found that the gain bandwidth of the devices made on these substrates is 0.6-0.9 GHz while on bare-Si it is 3.5 GHz. The final objective of this work is to process membrane based NbN HEB mixers for a 4x4 pixel heterodyne camera for 2.5 and 4.7 THz. SHAHIRA (Submm Heterodyne Array for HIgh speed Radio Astronomy) is a project supported by ESA.**

I. Introduction

Superconducting hot-electron bolometric (HEB) mixers have been demonstrated to be suitable devices for low noise and wide band heterodyne receivers at THz frequencies. Several international projects such as the Stratospheric Observatory for Infrared Astronomy (SOFIA) [1] and the Far Infrared and Submillimeter Space Telescope (Herschel) [2] will use HEB technology for atmospheric research and radio astronomy. Detection of submillimeter lines of OH (2.5 THz), HD (2.7 THz) and OI (4.7 THz) presents a high interest for radioastronomers [3]. It provides a strong motivation for the development of low-noise receivers for operation at THz frequencies. Depending on the RF coupling technique mixers are divided into two categories: waveguide mixers and quasi-optical mixers. As the RF frequency increases, machining of the waveguide mixers becomes more difficult. Therefore, quasi-optical mixers are more often used above 1 THz. In a quasi-optical heterodyne receiver the mixer (usually of a few m in size) is coupled to a planar antenna on a dielectric substrate. In order to minimize the back lobes, the substrates with high dielectric constants are selected ($silicon$, MgO). Moreover, for avoiding substrate modes and for beam collimation the substrate is clamped on the back of a spherical or an elliptical lens. In order to make an array out of lens antenna detectors two concepts have been proposed: a single lens for the whole antenna array, and an array of lenses with a single antenna on each lens (fly-eye technique). It has been discussed [4], [5] that scaling of both approaches to frequencies higher than 2 THz will be difficult. A few approaches suitable for scaling both in frequency and in number of pixels of the array have been discussed [6], [5], [7], where the HEB mixer is placed on an electrically thin substrate (membrane). Moreover, size of an antenna depends on dielectric constant, ϵ_r. For example, for a slot antenna the slot length is about 0.5 λ_e (effective wavelength), where $\lambda_e = \frac{\lambda_0}{\sqrt{\epsilon_{eff}}}$. The effective dielectric constant, ϵ_{eff}, on the dielectric/vacuum interface for the static case is $\sqrt{\frac{\epsilon_r+1}{2}}$. ϵ_r of the freestanding SiO_2/Si_3N_4 stress-less membrane is considered to be 1, since the wavelength at 2.5 THz, 2.7 THz and 4.7 THz is much larger than the membrane thickness when ϵ_r for bulk-Si equal 11.9. However, it remains unclear what will happen to the gain bandwidth when the HEB mixer is placed on such a membrane.

The first mixing experiments at millimeter-wave frequencies, employing superconducting thin films, were performed in 1990th [8]. Recently, technological development has mainly concentrated on NbN HEBs. The so called phonon-cooled NbN HEBs show very low noise (10-15 times the quantum limit) at 0.5-2.5 THz frequencies. The -3dB gain bandwidth achieved at the optimal operation point is about 3.7 GHz for the devices on crystalline quartz with MgO buffer layer [9], 4.5 GHz for MgO [10], 4 GHz on Si [11], 3.7 GHz on sapphire [12], 5.2 GHz on Si with MgO buffer layer and 2 nm thick NbN film [13].

In this paper we investigate the gain bandwidth of NbN mixer on freestanding SiO_2/Si_3N_4 stress-less membrane. SiO_2/Si_3N_4 is either a 1.4 μm membrane or a buffer layer between NbN film and bulk-Si substrate.

II. Device fabrication on membrane and measurement setup

The device fabrication are made of a 35 Å NbN film [14] on bulk-$Si/SiO_2/Si_3N_4$ substrate. The superconducting transition temperature and the room temperature sheet resistance of the film are 8.3 K and 660-700 Ω/square, respectively. The contact pads (80 nm Au) and the antenna (200 nm Au) are fabricated, using consecutive steps of electron beam lithography and lift-off process. The bolometer bridge is then covered by a SiO_2, which protects the NbN during ion milling. In the next step, Ar ion milling is used, to etch away the NbN film from the whole wafer, except from the bolometer bridge and under the antenna pads. The bolometers are 3.5 μm wide and 0.4 μm long. To make membrane we have removed Si_3N_4, SiO_2 layers and Si from the back side until reaching the SiO_2 membrane on the top face. The first step is done by Reactive Ion Etching. The second one is achieved by using of the Deep Reactive Ion Etch, DRIE, technique. The DRIE method is a time multiplexed system where isotropic etching is altered with a polymer depositing step, passivation. The passivation is performed with C_4F_8 plasma which deposits a Teflon like film on the wafer surface and trench wall. The following etching with SF_6 plasma etches areas parallel to the surface at a higher rate than trench walls thereby breaking through the bottom protective layer prior to the wall passivation etching the bottom silicon [15]. The superconducting critical temperature of the final device is 1 K lower than the initial. The measurement setup is shown

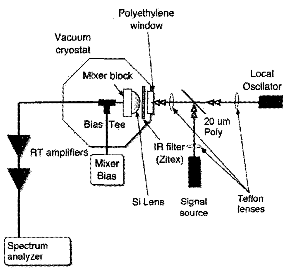

Fig. 1. Gain bandwidth measurement setup

in Figure 1. The HEB bandwidth was measured by detecting a mixing signal from two monochromatic sources (backward wave oscillators (BWO) for 600-700 GHz), one is used as a Local Oscillator (LO) and the other as a signal source. BWO RF power was combined by a 20 μm Polyethylene beam-splitter and arrived into a liquid-helium cooled vacuum cryostat through a window and an IR filter. The mixer block consisted of a silicon lens with a HEB clamped on the flat side of the lens. The mixer bath temperature was about 4.5 K. The signal source frequency was kept constant while the LO frequency was tuned in order to measure the IF signal at different IF. A bias-T was used to feed the bias to the mixer and to transmit the intermediate frequency signal to room temperature wideband amplifiers (0.1-20 GHz). The signal was amplitude and the frequency measured by a spectrum analyzer. The HEB bias point was controlled by the LO power and a DC voltage source. The DC parameters of the measured devices are shown in the Table I.

III. Measurements Results

For a single time constant bolometric mixer the mixer conversion gain $G(f_{IF})$ follows the intermediate frequency f_{IF} as:

$$G(f_{IF}) = \frac{G(0)}{1 + (\frac{f_{IF}}{f_{gain}})^2} \tag{1}$$

where f_{gain} is the 3dB cut-off frequency:

$$f_{gain} = \frac{1}{2\pi\tau_{mix}} \tag{2}$$

τ_{mix} is the mixer time constant, which differ from the electron cooling time τ_θ due to presence of the bias current:

$$\tau_{mix} = \frac{\tau_\theta}{1 - A} \tag{3}$$

where A is electro-thermal feedback and equals:

$$A = C_{dc} I_0^2 \frac{R_L - R_0}{R_L + R_0} \tag{4}$$

where I_0 is the bias current, R_0 is the bolometer resistance at the operating point, R_L is the IF load resistance. τ_{mix} can be longer or shorter of the τ_θ depending on the impedance of the mixers in that point.

C_{dc} is the dc responsivity of the HEB and is defined as:

$$C_{dc} = \frac{\partial R}{\partial P} = \frac{\partial R}{\partial \theta}\frac{\partial \theta}{\partial P} = \frac{\partial R}{\partial \theta}\frac{1}{G_{th}} = \frac{\partial R}{\partial \theta}\frac{\tau_{e-ph}}{c_e V} \tag{5}$$

where G_{th} is the thermal conductance between electrons and phonons, V is the volume of the bolometer.

We investigated devices made on SiO_2/Si_3N_4 stress-less membrane, bulk-$Si/SiO_2/Si_3N_4$ and bare-Si.

Gain bandwidth of 3.5 nm thin NbN hot-electron mixers made on bare-Si was reported by many authors and averages 3.5-4 GHz. We used such device as a standard to calibrate the set-up. At the bias point where the lowest noise temperature can be expected, the IV-curves had negative differential resistance. It is can be when the signal and LO frequencies are not high enough so that f_{LO}, $f_s < 2\Delta/h$, (2Δ is the energy gap, h is the Plank constant). We used a heater to suppress the NbN superconducting energy gap and to get smooth IV-curve during this measurements. In fact, we increased the bath temperature of the device. As an indicator we used the HEB's critical current, which was suppressed by a factor of 2 after the heater was switched on. The results of the gain bandwidth measurements for the all measured devices are shown in Table II and Figures 2- 4.

The superconducting transition temperature of the devices on SiO_2/Si_3N_4 and bulk-$Si/SiO_2/Si_3N_4$ was lower than on bare-Si and the critical current in the cryostat was nearly half of the value in LHe. The mixer effective volume and $\frac{\partial R}{\partial \theta}$ are not known exactly. Therefore, all mixers were measured at several bias points and $\frac{\partial R}{\partial \theta}$ and the mixer volume were adjusted so the electron temperature relaxation time τ_θ is the same for a particular sample (indeed for a phonon cooled HEB the electron relaxation time shall be bias independent). The operation points correspond to the optimum noise performance of the devices which were chosen by analogy with devices are

TABLE I

THE PARAMETERS OF THE MEASURED DEVICES. FOR ALL DEVICES THE WIDTH WAS A=3.5 μM, LENGTH B=0.4 μM, FILM THICKNESS D=3.5 nM.

Device Id.		S001-16	S001-17	S001-4	S08-n
Resistance	R (Ω)	210	217	212	111
Critical current at 4.2K/and in the cryostat	I_C (μA)	105/55	115/49	100/52	380/320
Critical temperature	T_c (K)	7.2	7.5	7.2	8.3
Substrate		SiO_2/Si_3N_4		bulk-$Si/SiO_2/Si_3N_4$	bare-Si
Thickness of the substrate	D (μm)	1.4		400+1.4	350

TABLE II

SUMMARY OF THE MEASUREMENTS RESULTS FOR ALL DEVICES. DC RESISTANCE IN THE OPERATION POINT $R_0=\frac{U_0}{I_0}$, TEMPERATURE DERIVATIVE OF THE RESISTANCE $\frac{\partial R}{\partial \theta}$ ARE USED TO CALCULATE THE ELECTRO THERMAL FEEDBACK COEFFICIENT A. $\tau_{mix}=\frac{1}{2\pi f_{gain}}$ IS THE MIXER TIME CONSTANT OBTAINED FROM THE $3dB$ GAIN BANDWIDTH f_{gain}. τ_{θ} IS THE ELECTRON RELAXATION TIME OBTAINED AFTER CALIBRATION OF τ_{mix} FOR THE ELECTRO THERMAL FEEDBACK. THE MIXER EFFECTIVE VOLUME IS $2.3*10^{-3}$ μm^3.

Device Id.	Bias point	f_{gain},GHz	R_0, Ohm	$\frac{\partial R}{\partial \theta}$, Ohm/K	A^1	τ_{mix}, ps	τ_{θ}, ps
S001-16	1) 0.5mV, 24uA	0.92	20.8	200	0.31	173	119
	2) 0.5mV, 27uA	0.73	18.5	200	0.44	218	123
S001-17	3) 0.8mV, 28uA	0.95	28.6	200	0.25	168	126
S001-4	1) 0.5mV, 15uA	0.85	33	200	0.06	187	176
	2) 0.5mV, 19uA	0.73	26.3	200	0.15	218	186
	3) 0.5mV, 22uA	0.66	22.7	200	0.24	241	184
	4) 0.5mV, 25uA	0.57	20	200	0.35	279	182
S08-n	1) 1.1mV, 26uA	4.9	42.3	200	0.05	32	31
	2) 1.1mV, 41uA	3.7	27	200	0.312	43	23
	3) 1.45mV, 30uA	5.27	48	200	0.014	30	30

[1] $A=C_{dc}\, I_0^2\, \frac{R_L-R_0}{R_L+R_0}$

to be used for band 6 of HIFI instrument on the Herschel Space Observatory.

The measured $G(f_{IF})$ curve was approximated with a single polynomial curve (1) and f_{gain} was obtained minimizing the standard deviation of the experimental curve from the approximation. Then using the formulae (2) and (3) the electron relaxation time τ_{θ} was calculated. Comparing τ_{θ} of HEB on different substrates we analyze the effect of the membrane on the electron cooling rate.

The $\tau_{\theta} \propto (\tau_{e-ph}, \frac{C_e}{C_p}, \tau_{esc})$, where τ_{e-ph} (the electron-phonon interaction time), C_e and C_p (electron and phonon specific heat, respectively) are temperature dependent. Hot electrons, characterized by an electron temperature θ, close to T_c, are cooled by scattering with phonons and subsequent phonon transfer into the substrate. In thin NbN films the electron-phonon interaction time τ_{e-ph} has been investigated in [16], [8]:

$$\tau_{e-ph} \approx \frac{500}{\theta^{1.6}}[ps] \qquad (6)$$

The τ_{e-ph} is about 21 ps at 7.2 K and 17 ps at 8.3 K. It shows that $\frac{C_e}{C_p}$ and τ_{esc} make the capital contribution into τ_{θ}. Phonon escape time (τ_{esc}) is a characteristic time, which determines the heat transfer rate from phonons of the film to the substrate (the film thickness is much less than the phonon diffusion length) and depends on the film thickness, d, and the film/substrate acoustic match, α, [8], [17]:

$$\tau_{esc} \approx \frac{4d}{\alpha u} \qquad (7)$$

where u is the sound velocity in the film.

For NbN films on *silicon* and *sapphire* substrates τ_{esc} =7d (ps) [12], where d is in nm, on bulk MgO substrates τ_{esc} =5d (ps) [18], and on *crystal quartz* (SiO_2) τ_{esc} =10d (ps) [19]. For the NbN on SiO_2/Si_3N_4 membrane and on bulk-$Si/SiO_2/Si_3N_4$ has been obtained the phonon escape time 17d (ps) and 26d (ps), respectively. When it is considered that thickness of NbN film is the same for all devices, we can see from (7) the film/substrate acoustic match, α, can make the difference of τ_{esc} for different substrates, but after some calculations we can conclude that the acoustic mismatch can not explain the large difference of the phonon transmission for Si, *sapphire*, MgO on one side and specially Si_3N_4 on the other side. The acoustic mismatch approach is valid under conditions of specular phonon reflection. However, when the phonon wavelength becomes comparable with the defects on the substrate surface a fraction of diffusive scattered phonons increases. As a result, the phonon transmission through the film/substrate interface decreases. Typical specification for the substrates surface roughness is 0.1-1nm and as is well known, *silicon*, *sapphire* and MgO have better surface quality comparing to SiO_2 and Si_3N_4 that also confirmed by superconductor transition temperature for the ultrathin NbN films, which is lower for SiO_2 and Si_3N_4 than on other substrates.

IV. CONCLUSION

We have measured different devices made on bare-Si, 1.4 μm thick SiO_2/Si_3N_4 stress-less membrane and bulk-$Si/SiO_2/Si_3N_4$. We have found that gain bandwidth of the devices made on two last substrates are narrower than on bare-Si and it is not wider than 1 GHz. One reason is: T_c of NbN

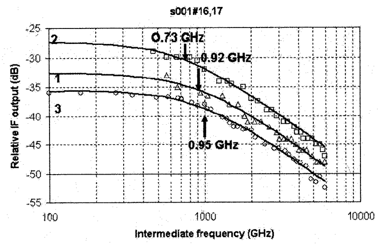

Fig. 2. IF bandwidth measurements of HEBs based on SiO_2/Si_3N_4 stress-less membrane.

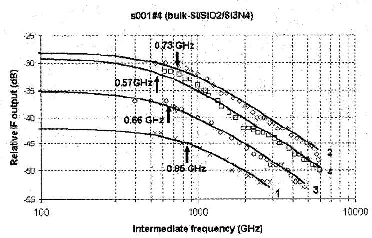

Fig. 3. The IF bandwidth measurements of bulk-$Si/SiO_2/Si_3N_4$ based HEB mixer (S001-4).

film on SiO_2/Si_3N_4 and bulk-$Si/SiO_2/Si_3N_4$ is lower. Other reason is: roughness of NbN film on SiO_2/Si_3N_4 is higher as compared with NbN on bare-Si [20] that increases the phonon escape time. Moreover, the gain bandwidth does not depend on whether Si is etched from under SiO_2/Si_3N_4 membrane or not, i.e. it is determined by the processes on the Si_3N_4/NbN interface.

One way of increasing of the gain bandwidth is the increase the critical temperature of the film, which can be done by deposition of a buffer layer. Hopefully, it also can improve an acoustical match on film/substrate interface. Our latest experiments have shown that application of MgO buffer layer on top of Si_3N_4 increases T_c from 7.5 K to 11.2 K for 3.5 nm NbN films. Measurements of these devices in progress. Other solutions can be fabrication of the devices on SOI substrates.

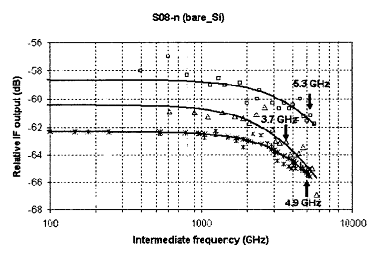

Fig. 4. IF bandwidth measurements of bare-Si based HEB mixer (S08-n).

REFERENCES

[1] H.W. Huebers, J. Schubert, A.D. Semenov, B. Voronov G. Gershenzon Gol'tsman, G., and G. Shwaab. A heterodyne receiver for terahertz frequencies for SOFIA. In *Proceeding of SPIE Conference on Airborne Astronomy Systems*, March 2000.

[2] G.L. Pilbratt, J. Cernicharo, A.M. Heras, T. Prusti, and R. Harris. The Herschel mission, scientific objectives. In *Proceeding of Symposium "The Promise of the Herschel Space Observatory", Toledo, Spain*, pages 13–20, December 2000.

[3] www.sofia.usra.edu.

[4] J. Baubert, M. Salez, H. Merkel, P. Pons, S. Cherednichenko, B. Lecomte, V. Drakinskiy, G. Gol'tsman, and B. Leone. IF gain bandwidth of membrane-based NbN Hot Electron Bolometers for SHAHIRA. *Applied Superconductivity, IEEE Transactions on*, 15(2):505–510.

[5] J. Baubert, M. Salez, H. Merkel, P. Pons, Y. Delomre, and B. Lecomte. IF gain bandwidth of membrane-based NbN Hot Electron Bolometers for SHAHIRA. *, in MM and subMM detectors for radioastronomy II, J.Zmuidzinas, W.S.Holland, S. Withington eds., 5498, p.667, Proc. SPIE Int. Soc. Opt. Eng., 2004.*

[6] D.F. Filipovic, W.Y. Ali-Ahmad, and G.M. Rebeiz. Millimeter-wave double-dipole antennas for high-gain integrated reflector illumination. *IEEE Transactions on Microwave Theory and Techniques*, 40(5):962–967, May 1992.

[7] C.K. Walker, C.E. Groppiu, C.D. d'Aubigny, C. Kulesa, A. Hedden, D. Prober, I. Siddiqi, J. Kooi, G. Chen, and A.W. Lichtenberger. Millimeter-wave and terahertz integrated circuit antenna. In *Proc. SPIE, vol. 4855*, pages 349–354, 2003.

[8] E.M. Gershenzon, G.N. Gol'tsman, I.G. Gogidze, Y.P. Gusev, A.I. Elant'ev, B.S. Karasik, and A.D. Semenov. Millimeter and submillimeter range mixer based on electronic heating of superconducting films in the resistive state. *Sov. Phys. Superconductivity*, 3(10):1582, 1990.

[9] D. Meledin, P.-Y.E. Tong, R. Blundell, N. Kaurova, K. Smirnov, B. Voronov, and G. Gol'tsman. Study of the IF Bandwidth of the NbN HEB mixers based on crystalline quartz substrate with an MgO buffer layer. *Applied Superconductivity, IEEE Transactions on*, 13(2):164–167.

[10] M. Kroug, S. Cherednichenko, M. Choumas, H. Merkel, E. Kollberg, H.-W. Huebers, H. Richter, D. Loudkov, B. Voronov, and G. Gol'tsman. HEB quasi-optical heterodyne receiver for THz frequencies. In *Proceeding of 12th International Symposium on Space Terahertz Technology*, pages 244–252, 2001.

[11] H. Ekstrom, E. Kollberg, P. Yagoubov, G. Gol'tsman, E. Gershenzon, and K.S. Yngvesson. Gain and noise bandwidth of nbn hot-electron bolometric mixers. *J. Appl. Phys. Lett.*, 70(24):3296–3298, June,1997.

[12] S. Cherednichenko, P. Yagoubov, K. Il'in, G. Goltsman, and E. Gershenzon. Large basndwidtth of NbN phonon-cooled hot-electron bolometer mixers on sapphire substrate. In *Proceeding of 8th International Symposium on Space Terahertz Technology*, pages 245–257, 1997.

[13] Yu.B. Vachtomin, M.I. Finkel, S.V. Antipov, B.M. Voronov, K.V. Smirnov, N.S. Kaurova, V.N. Drakinskiy, and G. Goltsman. Gain Bandwidth of phonon-cooled HEB mixer made of NbN thin film mith MgO buffer layer on Si. In *Proceeding of 13th International Symposium on Space Terahertz Technology*, pages 259–270, 2002.

[14] NbN films are provided by Moscow State Pedadodical Univ. (Russia).

[15] Robert Bosch Gmbh, US.Pat.4855017, and 4784720, German Pat. 4241045c1.

[16] Yu. Gousev, G. Gol'tsman, A. Semenov, and E. Gershenzon. Broadband ultrafast superconducting NbN detector for electromagnetic radiation. *J. Appl. Phys.*, 75(7):3695–3697, Apr.1994.

[17] A.V. Sergeev and M.YU. Reizer. Photoresponce mechanisms of thin superconducting films and superconducting detectors. *International Journal of Modern Physics B*, 10(6):635–667, 1996.

[18] P. Yagoubov, M. Kroug, H. Merkel, E.Kollberg, J. Schubert, H.-W. Huebers, S.Svechnikov, B. Voronov, G. Goltsman, and Z. Wang. Hot electron bolometric mixers based on NbN films deposited on MgO substrates. In *Proc. Europ. Conf. on Appl. Superconductivity (EUCAS'99)*, 1999.

[19] J. Kawamura, R. Blundell, C.E. Tong, G. Goltsman, E. Gershenzon, B. Voronov, and S. Cherednichenko. Low noise NbN lattice-cooled superconducting hot-electron bolometric mixers at submillimeter wavelengths. *J. Appl. Phys. Lett.*, 70(12):1619–1621, March.1997.

[20] J. Baubert. Submillimiter heterodyne array for high-speed ratio astronomy. *Thesis for the degree of licentiate of engineering*, 2005. Chalmers University of Technology.