NbZr films for THz phonon-cooled HEB mixers

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Abstract— **This work is devoted to the investigation of the applicability of NbZr as a new material for wideband hot-electron bolometer (HEB) mixer, which is a device of choice for most of low noise heterodyne receivers operating above 1 THz in astronomy applications. Although currently 10-nm NbZr films offer a maximum gain bandwidth of only 450 MHz at T_c on sapphire substrates, there is every reason to believe that the above result can be improved by decreasing the film thickness and using other substrate material which will provide better acoustic match with NbZr.**

I. Introduction

Superconducting hot-electron bolometer (HEB) mixers have been under intensive research since the 1990s [1]. They use the effect of electron heating by incoming terahertz radiation. Currently such devices based on ultrathin NbN films are most sensitive detectors for heterodyne spectrometers between 1 and 6 THz. Their noise temperatures are about 450 K at 600 GHz, 700 K at 1.5 THz, and 900 K at 2.5 THz (see e.g. [2], [3], [4], [5], [6]). One more important parameter of such a mixer is IF bandwidth, which currently achieves the value of about 5 GHz [7]. Obviously a larger IF bandwidth allows simultaneous observation of several lines or instantaneous measurement of a single broad line. There are several possible solutions to expand the IF bandwidth hinted at by the physics of the hot electron effect. The first one is to use buffer layers between the film and the substrate; second, a novel substrate offering better acoustic match with the film; third, the use of new superconducting materials with shorter relaxation time i.e. with a shorter electron-phonon interaction time $\tau_{e\text{-}ph}$ and a shorter non-equilibrium phonons escape time τ_{esc} [8]. It is believed that strong electron-phonon coupling and as a result a short relaxation time - is associated with high superconductor critical temperatures T_c. Indeed, such materials as NbN and NbTiN, where T_c of ultrathin films exceeds 7-10K, have shown the best gain bandwidth results for HEB's so far ([7], [9]). We chose NbZr because it has a high $T_c \approx 11$K in bulk; this material is widely used and may be implemented as ultrathin film.

The simplest and most informative method of investigation of energy relaxation times in HEB is the study of the bolometer behavior under uniform electron heating. In the case of the uniform electron temperature distribution along the bridge, the physics of the device operation can be described by relatively simple equations for the heat balance, and the mixer's roll-off frequency is completely determined by several time constants of the film material ([10],[11]). The values of these characteristic times can be obtained from the dependence of the gain bandwidth on temperature and film thickness. For the electron temperature to be uniform throughout the bridge it is necessary that either the LO frequency be greater than the superconductor gap frequency, or that the ambient temperature be about T_c (in the latter case the LO frequency need not exceed the gap frequency of the unheated superconductor). Also the bolometer bias should be small and the power levels of the oscillators should not influence the operating point of the bolometer. In this paper we study deposition process of ultrathin NbZr films on sapphire substrates, gain bandwidth of NbZr bolometers and the possibly of using this material as a new material for HEB mixers.

II. Device fabrication

This work was aimed at development of a fabrication process of high-quality ultrathin NbZr films having the possibly highest superconducting transition temperature and the critical current density. The film quality depends on various deposition process parameters such as substrate temperature, pressure etc. To choose the optimal deposition regime, we performed a series of experiments changing both the substrate temperature and deposition rate. Deposited films were tested for such parameters as their sheet resistance (R_s), superconducting transition temperature (T_c), superconducting transition width (ΔT_c), ratio of a room temperature resistivity to a resistivity at 20 K ($R=\rho_{300}/\rho_{20,)}$ and critical current density (j_c) at 4.2 K.

NbZr films were deposited on sapphire substrates by DC magnetron sputtering of the Nb_{50}/Zr_{50} alloy target in the argon (Ar) atmosphere. We used R- and M-cut sapphire wafers. The R -plane substrates were 0.39 mm thick, the M –plane were 0.33 mm thick. All sapphire substrates were epi-polished on the front side and optically polished on the back side. Before deposition, the chamber was pumped down to a background pressure of $3\cdot10^{-6}$Torr. During the deposition process, the Ar pressure was of $3\cdot10^{-3}$ Torr, while the substrate was heated to a temperature in the range from 150 to 400°C.

For the deposited NbZr films, a sheet resistance R_{sq} was measured by the standard four-point method. The room temperature resistivity (ρ) of deposited NbZr films, defined as the film sheet resistance multiplied by the film thickness (d), was found to be from 60 to 100 μΩ×cm in the thickness range from 50 to 8 nm. The deposition process was investigated for the films 8, 10 and 15 nm thick. We researched into the dependence of the transition temperature on the substrate temperature during the deposition.
The results are presented in Table I.

TABLE I

Substrate temperature, C	170	280	350
Film Tc, K	5.1	7.3	4.5

The best of the obtained 10-50nm thick NbZr films reveal good superconducting properties as shown in Table II. The films demonstrate a sharp superconducting transition and a high critical current density.

TABLE II

Film thickness, d (nm)	8	10	20	50
Critical temperature, T_c (K)	4.3	7.3	7.5	9.1
Transition width, ΔT_c (K)	0.2	0.09	0.06	0.02
Critical current density at 4.2 K, jc×10^6 (A/cm^2)	-	1.1	1.5	4
Sheet resistance, R_s (Ω/sq)	130-140	85- 99	35- 38	11- 12

We studied bridges 10μm long and 1 μm wide patterned in NbZr films of 20nm and 10nm thickness on 390μm R-plane cut sapphire substrate. Figure 1 shows a SEM photo of our bridge. The NbZr films deposited on M-cut sapphire have shown much worse DC characteristics and parameters of the films. This is probably through bad acoustic match between the film and the substrate, which is why we did not, studied them further.

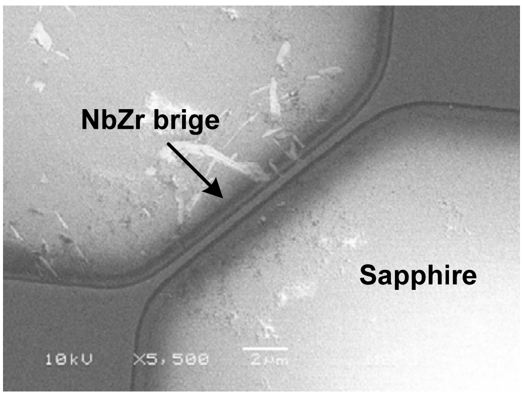

Fig. 1 A SEM photo of NbZr bridge the size of 10×1μm^2 supported by sapphire substrate.

III. MEASUREMENT SETUP AND TECHNIQUE

The gain bandwidth of NbZr bridges was measured by detection of the intermediate frequency (IF) signal power as a function of IF. As tunable sources above 120 GHz it is convenient to use backward wave oscillators (BWO's), which have a wide frequency tuning range and sufficient output power. In our experiments, BWO with a 126.5-146 GHz range, were used. This type of local oscillator made it possible to sample the IF band with a resolution of 5MHz.

The LO and the signal beams were combined with a beam splitter, focused with a Teflon lens and fed into a liquid-helium-cooled vacuum cryostat (see Fig. 2). The temperature of the device block was raised to the critical temperature of the device which varied for different devices between 4.5 -10K.

The IF chain consisted of a bias-Tee, one room-temperature wide band amplifier (0.06-12 GHz), and power-

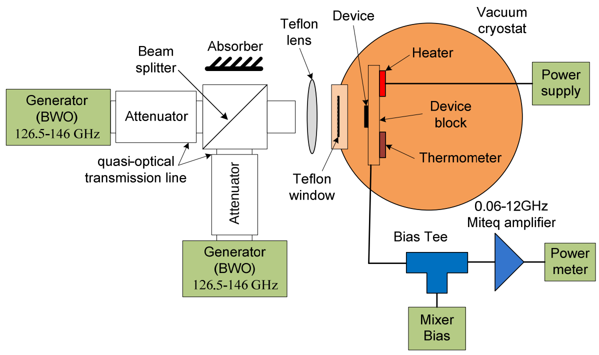

Fig. 2 The intermediate frequency gain bandwidth measurement setup

meter. The frequency of the signal BWO was kept constant, while the LO BWO frequency was swept. The IF bandwidth was measured at a fixed operating point. The value of bias current was used to monitor the absorbed LO power. Figure 3 shows IV curves taken at a few temperatures of the device block.

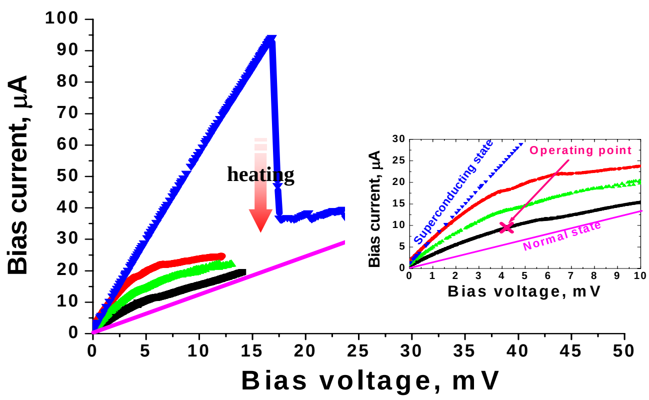

Fig. 3 Set of dc voltage bias characteristics (increasing from top to bottom) levels of the LO power. The upper curve was taken without LO power.

IV. Measurement Results and Analysis

In our experiments the bolometer is heated close to T_c, and the power levels of the oscillators are so low that they do not appreciably affect operating point (see Fig.3).We chose an operating point with the a good signal-to- noise ratio but with DC current low enough to keep U_{bias}/I_{bias} close to device resistant at zero I_{bias}. In this case the electron heating is uniform and we can use the classical model of uniform heating, which was presented in (e.g. [11], [12], [13], [14]).

In the frame work of this model the device output signal $P(f_{IF})$ depends on the intermediate frequency f_{IF} as

$$P(f_{IF})=P(0)[1+(f_{IF}/f_0)^2]^{-1}, \quad (1)$$

where $P(0)$ is the output signal at zero IF, and f_0 is the 3 dB roll-off frequency.

Figure 4 shows the output power vs IF for NbZr bolometers with thicknesses of 10nm and 20nm. The data were fitted with the use of (1).

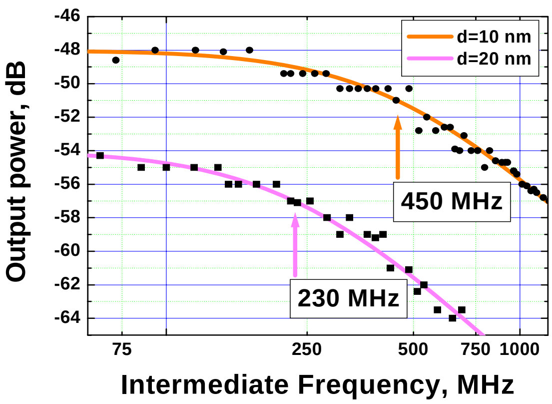

Fig. 4 The output signal vs IF bandwidth for NbZr bridges 10nm and 20nm thick. The 3 dB roll-off frequency is marketed for all curves. The fitting lines are obtained from (1).

The energy relaxation time for a bolometer τ_{bol} is determined from the 3 dB roll-off frequency as

$$\tau_{bol} = 1/(2\pi f_0) \quad (2)$$

Whence we can calculate two different 350ps (10nm) and 690ps (20nm) energy relaxation times which depend on the film thickness. It is evident that for NbZr bolometers

$$\tau_{bol} \sim d, \quad (3)$$

where d is the film thickness. Heat transfer from the film into the substrate is determined by the non-equilibrium phonons-escape time τ_{esc}, which is a function of the film thickness, sound velocity U and the transparency factor α [15]

$$\tau_{esc}=4d/(\alpha U) \quad (4)$$

In terms of (3) and (4) we have found that the IF bandwidth of the NbZr bolometers is limited by the non-equilibrium phonon escape time, which is supported by the dependence of the IF bandwidth on the film thickness. Our result shows that the energy relaxation time in NbZr films are 2.5 times as long as that in NbN films of the same thickness (e.g. [16], [17]). In perspective we believe that our result can be improved by further decreasing the film thickness and using other substrate material which will provide better acoustic match between NbZr film and a substrate. The latter allows reducing the escape time τ_{esc} of non-equilibrium phonons and consequently time constant of the bolometer. Further increase of the IF bandwidth will be limited by the electron-phonon interaction time $\tau_{e\text{-}ph}$.

Conclusion

We have fabricated and tested NbZr ultrathin films at 2 millimeter wavelength. The best bolometers (thickness 10nm) showed following results: critical temperature about 7.5 K, critical current density at 4.2 K about 1×10^6 A/sm^2 and IF bandwidth 450MHz.

The obtained results show that the IF bandwidth of NbZr bolometers is currently limited by the non-equilibrium phonons-escape time τ_{esc} and in perspective we believe that our result can be improved by further decreasing the film thickness and using other substrate material.

Acknowledgment

The authors wish to thank Sergey Ryabchun for help and prompting.

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