Development of Nb/Au bilayer HEB mixer for space applications

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Abstract

In this paper we propose to use a metal-superconductor bilayer as an RF detecting element for a diffusion-cooled hot electron bolometer mixer. The motivation is to engineer a superconducting material with a low transition temperature, T_c, (below T_c of commonly used Nb) and higher diffusion constant. With this it is expected to improve the overall HEB mixer performance, i.e. obtain lower noise and wider intermediate frequency bandwidth as well as reduce a local oscillator power requirement.

We report our initial experimental results. A couple of Nb/Au bilayer films with different thickness combinations have been fabricated on either glass or Si substrates. The measured sheet resistance and transition temperature of the bilayers are close to those desired for the fabrication of HEB mixers.

1. Introduction

Development of HEB mixers for space applications is now focused on both optimization of the current NbN (phonon cooled HEB) [1-6] and Nb (diffusion-cooled HEB) [7-10] technology, as well as on investigation of alternative superconducting materials, which may lead to an overall improvement of the HEB mixer performance [11-13]. The three basic parameters of HEB mixers are being addressed: sensitivity, IF bandwidth and local oscillator power requirement.

As it was shown in [11], for diffusion-cooled HEB (DHEB) improvement of the mixer performance is expected by implementation of a superconductor with lower critical temperature. First, the sensitivity is improved since the intrinsic mixer noise is proportional to the effective electron temperature, which is about the T_c. Secondly, for DHEB the LO power requirement has quadratic dependence on the superconducting temperature T_c. Finally, a larger diffusivity D can be expected in some of superconductors with lower T_c. This would lead to a shorter thermal time constant since it is inversely proportional to D and thus increase the intermediate frequency bandwidth of the mixer.

Originally considered Al has been shown to allow for very small LO power requirement of the HEB [14]. However, the mixers tested in a quasioptical setup exhibited very low gain of about –30 dB. This was explained by the saturation in the IF port due to the very small optimum bias range. The IF bandwidth was not improved with Al based HEBs compared to Nb HEB due to the limitation imposed on the bolometer length because of the proximity effect of the normal cooling pads. The influence of the normal cooling pads on the resistive transition of Al HEB has been modeled in the limit of a very short superconducting bridge (order of coherence length ξ or less) [15].

In this paper we propose using a superconductor-normal metal bilayer as a sensitive element of the HEB mixer. We show that it is possible to obtain desired parameters such as sheet resistance and transition temperature if we choose a bilayer of Nb and Au. The diffusivity is expected to be higher than that of the single layer of Nb due to the presence of Au. Ability to tune the individual layer thicknesses to meet the requirements for particular applications is considered to be a significant advantage of the bilayer based HEB mixer.

2. Material considerations for the bilayer

To make a decision on which materials to use for the bilayer, the following requirements have been considered:

a) T_c of the bilayer should in principle be easily tunable in a temperature range between 1-5 K;

b) the desired T_c of the bilayer for the first tests is around 3-4 K since this temperature is compatible with ^{4}He cryostats facilitating the lab tests. The LO power requirement of the DHEB mixer based on a superconductor with T_c of 3 K is expected to be ~ 20 nW. Further reduction of the T_c would lower this number and may cause saturation of the mixer by the 300 K background in the conventional lab tests;

c) the sheet resistance of the bilayer film should not be too small, order of 10 Ohm/□ or larger, to match the mixer with a planar antenna;

d) It is preferable to have a fabrication process being compatible with the existing clean-room technology and experience;

e) the larger diffusivity and shorter electron-electron interaction time constant of both superconductor and normal metal are desired. The large diffusivity will provide a wider IF bandwidth of the mixer for a given bolometer length and the fast electron-electron interaction favors the thermalization.

Different materials have been considered and finally the combination Nb/Au was chosen. We expected that the bilayer with film thicknesses: d_n~5 nm, d_s~5 nm may meet the requirements mentioned above. The main parameters of the Nb and Au we used are listed in the Table 1.

Table 1. Material parameters: v_f is the Fermi velocity, ρ is the resistivity, ξ is the coherence length, and l is the electron mean free path.

Material	v_f, *10^8cm/s	ρ, μOhm cm	ξ, nm	l, nm
Au	1.4	8-10	50	5
Nb	0.27	20-25	10	3

Here we estimate T_c and the sheet resistance of such a Nb(5 nm)/Au(5 nm) bilayer. The T_c of a bilayer can be predicted using a Golubov model [16] if the T_c of the superconducting layer is known. It is however known from experience that a layer of 5 nm thick Nb can have a varying T_c, depending strongly on the sputtering condition. At the same time it is also not possible to determine T_c experimentally due to fast film oxidation (which proximitizes the superconductor as well). For our estimates we use T_c of 5 nm Nb being about 5-7 K. The model [16] is valid for arbitrary film thicknesses and interface transparencies. Initially the interface resistance was estimated as being simply a mismatch between the Fermi velocities v_f of the normal (N) and superconducting (S) layers. A calculation shows that the T_c of such a Au/Nb bilayer will be about 60 % of the T_c of the Nb, in the range 3-4 K.

To estimate the sheet resistance we have considered the N and S layers as two resistors connected in parallel:

$$R_{sq} = \left(\frac{d_n}{\rho_n} + \frac{d_s}{\rho_s} \right)^{-1} .$$

One should note, however, that the resistivity of very thin films is not equal to the bulk resistivity, but includes a "size" contribution due to the scattering of the electrons at the film surfaces. This causes the electron mean free path to be limited by the film thickness.

For a rough estimate of the Nb resistivity we took the measured value of 15 μOhm cm for the 10nm Nb film, and estimated it to increase to about 20-25 μOhm for the 5 nm film. To our knowledge there is no experimental data on so thin Au films resistivity. The estimate in the Drude model gives a value of 2 μOhm cm with the mean free path 40 nm. The thickness of our Au is smaller than that value so the “size” contribution to the resistivity may be large. Moreover, Au may not grow very uniformly likely having “island” structure in such thin films, so that the resistivity may increase due to this effect even further. For a crude estimate we took the resistivity of Au to be of the order of 8-10 μOhm cm for thickness 5 nm. With these numbers on resistivity of Nb and Au we expect a sheet resistance of the bilayer to be about 10-15 Ohm/□.

3. Films fabrication and dc characterization

Based on these considerations, the test samples on glass substrate with different film thickness combinations have been produced: “6/6”, “5/5”, “5/4”. The first number corresponds to the thickness of Nb, the second one to the thickness of Au in nm; for instance “6/6” means a bilayer made from 6 nm Nb and 6 nm Au. The layers were sputtered *in situ* to avoid oxidation of Nb. The samples were cut into 4 mm long and 2 mm wide pieces. Critical temperature of the bilayers was measured by a four-probe method. The temperature is controlled by an electrical heater and measured by a calibrated germanium resistor with an accuracy of 10 mK.

The results of the critical temperature measurements are presented in Figure 1. The critical temperatures of the samples made in different runs are consistent, correlating with the thickness combinations and lie within 3.5-4.2 K, close to the designed values and have a very sharp transition of about 50 mK. The sheet resistance of the films of about 15 Ohm/□ is also in a good agreement with the predictions and large enough to match the bolometer to the receiver antenna.

Table 2. dc parameters of the non-patterned Nb/Au bilayer films on glass substrate.

Nb / Au thicknesses, nm	T_c	Sheet resistance at 300 K, Ohm	Sheet resistance at 10 K, Ohm
6/6	4.25	18	13
5/5	3.5	20	16
5/4	3.7	21	16

As it was mentioned in the introduction, one of the very important material parameter to be considered for the DHEB mixer fabrication is the diffusion constant D, since it plays a crucial role in determining an intermediate frequency bandwidth of the device. In case of bilayer we expect the diffusivity to be largely influenced (however not necessarily determined) by the diffusivity of the cleaner material, which is Au. If we use the Drude model to predict diffusion constant of Au, we get a number of 40 cm^2/s. However, it is necessary to verify the diffusivity of a bilayer experimentally.

In case of a single superconductor the diffusion constant can be estimated from the residual resistivity and the density of states at the Fermi level. There is also a straightforward experimental way to determine this parameter, namely by measuring a temperature dependence of the perpendicular critical magnetic field H_{c2}. However, in the case of thin films bilayer the situation is more complicated and the above mentioned method are not applicable *a priory*. We used the formalism of Fominov and Feigel'man [18] to model the system but came to the conclusion that in our particular case magnetic field measurements can not be used directly for the predictions of the diffusion constant of the bilayer system [19]. Instead, the microwave measurements of the impedance or direct measurements of the HEB IF bandwidth have to be performed.

4. HEB mixer fabrication and dc test results

Figure 2 shows an SEM micrograph of a Nb/Au bilayer HEB mixer using a spiral antenna. In this device the Nb/Au bridge with a length of 250 nm and a width of 190 nm is in the middle, between the antenna arms. Pads directly contacting to the bridge are thick Au, functioning as cooling pads for hot electrons. The structures above the cooling pads are the thick Nb layer as a part of spiral antenna. Due to misalignment in the lithographical process, the thick Nb structure locates not symmetrically with respect to the cooling pads.

The fabrication process of the bilayer mixers is as following. The substrate is a highly resistive Si (111) wafer. The Nb/Au bilayer is sputtered on the whole wafer. Au cooling pads (80 nm) are formed by evaporation in combination with e-beam lithography and lift-off. Then, the antenna structure is realized by sputtering thick Nb (80 nm) followed by a layer of Au and by lift-off. The last step is to etch the Nb/Au bilayer to form a superconducting bridge. The etch mask used is a thin, narrow strip of Al.

The resistance of this device is measured as a function of temperature, shown in Figure 3. The observed R-T characteristic resembles very much those obtained in Nb HEB mixers [20], characterized by two T_c's, one corresponding to the T_c of the bridge (~3.5 K) and the other to the bilayer under the cooling pads (~2 K). The normal state resistance is 13 Ω. The current-voltage characteristic is measured at 1.4 K, which is also included in Figure 3. We observe a critical current of 100 μA and also hysteresis in the IV curve. However, the hysteretic effect is so small that it is hard to be seen in the plotted IV curve. Although no detailed analysis for the R-T and I-V data is done, they can be further evaluated at high frequency, judging from the understanding of Nb HEB mixers.

5. Summary

We present a new approach for diffusion-cooled HEB mixers by using Nb/Au bilayer as a superconducting bridge instead of Nb or Al. We have fabricated Nb/Au bilayer films with different thickness combinations on glass substrate. The dc parameters of the films are close to the designed values. HEB mixers based on 5 nm Nb + 5 nm Au bilayer films on Si substrate have been fabricated and the first dc results are obtained. The next step is rf characterization of the mixer.

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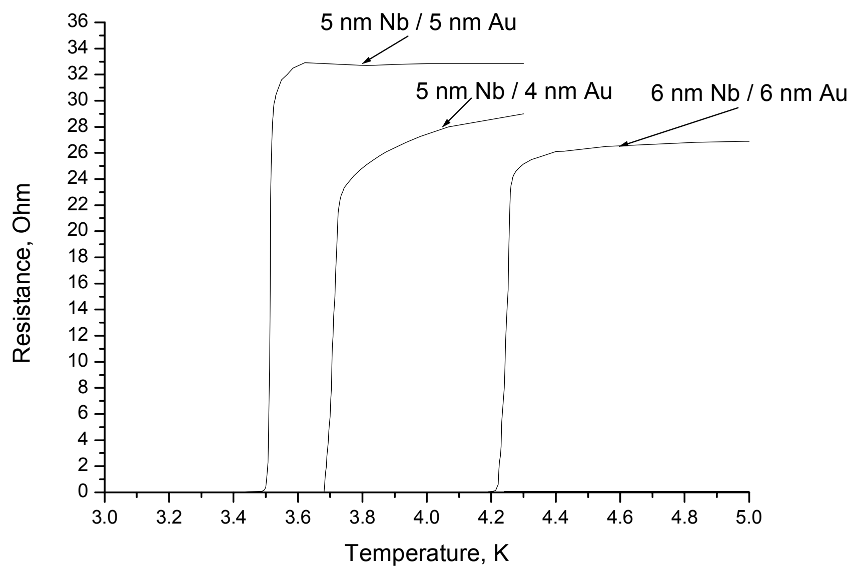

Figure 1. Critical temperatures of Nb/Au bilayer films with different thicknesses combinations. The films are fabricated on a glass substrate and are non-patterned.

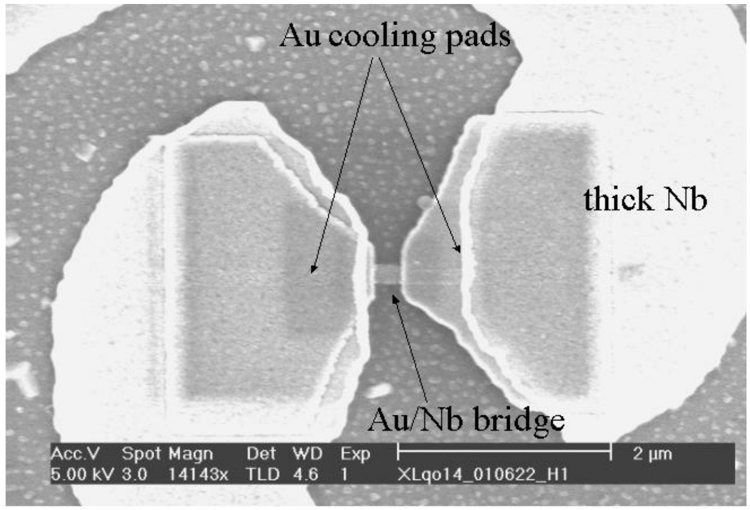

Figure 2. SEM micrograph of a part of Nb/Au bilayer HEB mixer using spiral antenna, fabricated on Si substrate. In the center is the Nb/Au bridge. Two sides of the bridge are contacted to thick Au cooling pads. Above the cooling pads is the antenna structure with thick Nb(80 nm)/Au layer. The bar in the photo is 2 µm.

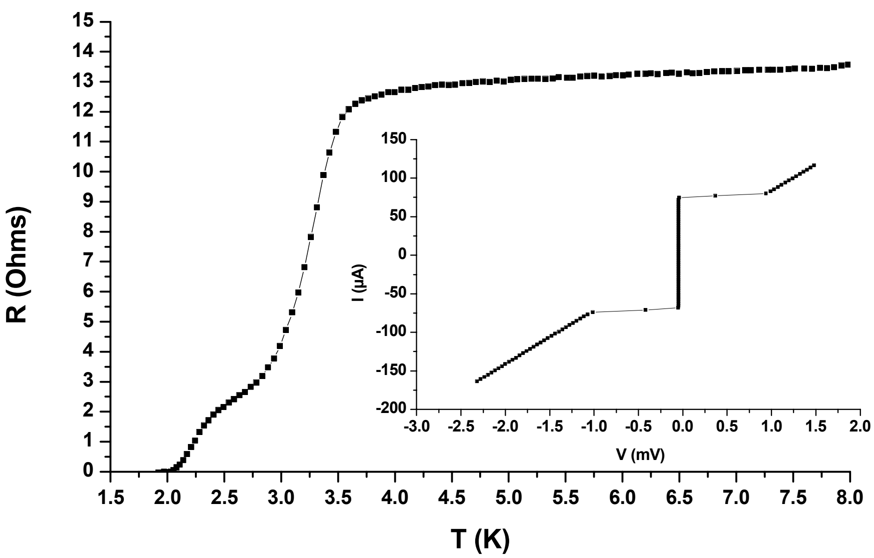

Figure 3. The resistance of the Nb/Au HEB mixer (shown in Fig. 2) as a function of temperature. The current-voltage characteristic at ambient temperature 1.4 K is shown in the inset.