Superconducting contacts and NbN HEB mixer performance

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***Abstract*— We demonstrate that the performance of phonon cooled NbN hot electron bolometer mixers depends on the superconducting interlayer between the NbN bridge and the Au antenna. This interlayer is either a superconducting Nb layer or a NbTiN layer. We find that, for given interface cleaning conditions, the mixers with a Nb interlayer show a similar or even a slightly better noise temperature in comparison with the mixers with a NbTiN interlayer. The best receiver noise temperature is 1230 K at 2.5 THz and becomes 980 K corrected for reflection loss due to the use of a Si lens. An important outcome of this study is that the Nb interlayer can lead to excellent performance of HEB mixers. Unlike NbTiN, a Nb sputtering process is widely available and easy to use. In addition, we also inspect the interfaces of the contact structures using HRTEM and find that the interfaces of NbN/Nb and NbN/NbTiN after Ar$^+$ cleaning are excellent.**

I. INTRODUCTION

Phonon-cooled superconducting NbN hot electron bolometer (HEB) mixers are so far the only sensitive detector at high frequencies beyond 1.5 THz [1], [2]. It is known that under operating conditions the parabolic electron temperature profile due to the absorbed LO power and DC power depends on the boundary conditions, related to the interface between antenna and bridge (contact pads) [3]. Earlier we have reported that the sensitivity and reproducibility of such a mixer depend on the contact pads. The best sensitivity has been obtained using a NbTiN superconductor interlayer between NbN and Au in the contacts [4]. In this work we revisit the issue of the contact structure for NbN HEB mixers and explore the use of Nb as an interlayer instead of NbTiN. The motivations are: a) gaining new insight into the role of the contacts and hence the device physics; b) Nb process is more widely available and easy to use; c) establish a more reliable fabrication process.

The performance and reproducibility of a HEB mixer are mostly limited by the contact resistance caused by the poor interface between NbN and Au layer. It has been reported [5] that NbN can form a protective layer on its surface which causes a contact resistance. This contact resistance can be as high as a few kΩ. That is why in our earlier study [4] we have introduced an Ar$^+$ sputter cleaning to remove this layer. We study the contact structures by measuring DC characteristics and RF performance. In particular, we have examined the interfaces of different contacts by using high resolution transmission electron microscopy (HRTEM).

II. DEVICE FABRICATION

The HEB devices are fabricated using sputtered ultrathin NbN films (the film thickness is around 5.5 nm) on highly resistive, silicon substrates, with a native oxide, prepared at Moscow State Pedagogical University, Moscow, Russia. Figure 1 shows a SEM photo of a NbN HEB mixer with a spiral antenna. The size of the bridge is 2 µm (width) x 0.2 µm (length) and hence requires the use of electron beam lithography. In the first lithography step we realise the

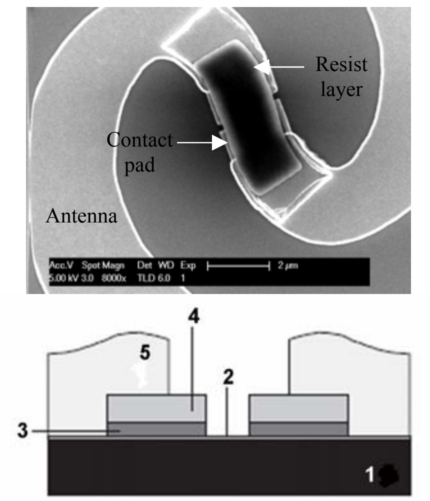

Figure 1: An SEM of spiral antenna coupled HEB mixer (Upper panel), and the lower panel shows the detailed layer structure of device: 1. Silicon wafer, 2. NbN film, 3. Superconducting layer (Nb or NbTiN), 4. Au of contact pad, 5. Au of antenna.

contact pads which also define the length of a bridge. Figure 1 also shows the layered structure of the device and emphasizes the contact pad between antenna and bridge. After e-beam writing and the development of contact pad patterns, short oxygen plasma cleaning (20 W RF, 20 sccm

O_2 and 20 μbar pressure for 5 seconds) is performed to remove the residual resist. After this step we perform an Ar^+ sputter cleaning for 32 sec using the same condition as in Ref. [6] to clean the surface of NbN and then sputter in situ a Nb or NbTiN superconducting interlayer and a gold layer on top of it. For a comparative study we prepare devices which have two different types of interlayer in the same batch. After the contact pad step we have a second lithography step for the antenna. The antenna is made of an evaporated gold layer of 150 nm thick. In the final lithography step a resist mask is patterned which defines the width of the bridge. We use this mask to selectively etch away NbN everywhere else.

TABLE I
KEY PARAMETERS OF THE CONTACT PAD STRUCTURE TYPE I & II FOR THE HEB MIXERS AND TYPE III ONLY FOR HRTEM STUDY.

Parameters	Type of contacts		
	Type I	Type II	Type III
Ar^+ etch clean	32 Sec.	32 sec.	No clean
Interlayer	Nb (6-7 nm) $T_C = 6.45K^*$	NbTiN (6-7 nm), $T_C = 8.8K^*$	NA
Gold	50-60 nm	50-60 nm	50-60 nm

* The T_C values are for the single layer Nb and NbTiN films grown on Si substrate and the thickness of these films indicated here is extracted from HRTEM pictures. From an α-step and AFM measurement the thickness is 10 nm for both films.

For HRTEM study we fabricate structures containing three different types of contact pads: Nb/Au with a 32 sec Ar^+ cleaning, the NbTiN/Au with 32 sec Ar^+ cleaning, and only Au layer without Ar^+ cleaning. It is important to note that the first two were the same as used for HEB devices.

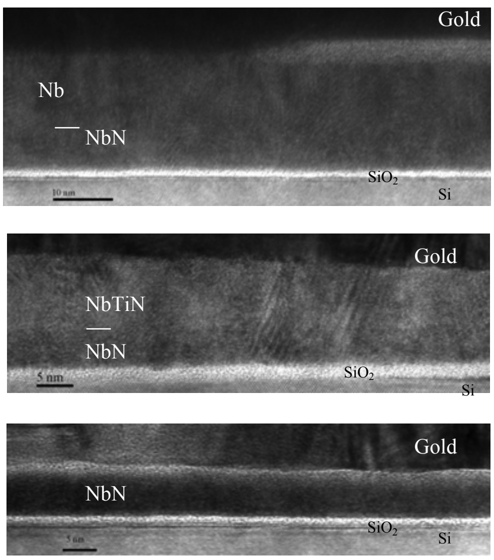

Figure 2: TEM pictures of three types of contact pads all on Si with a native oxide: a) Au/Nb contact to NbN with Ar etch, b) Au/NbTiN contact to NbN with Ar etch, and c) Au contact to NbN without Ar etch clean.

Table 1 indicates all key parameters used for the contact pads. Figure 2 shows HRTEM pictures of all three types of contact pads. Figures 2a and 2b show that after cleaning the growth of NbTiN and Nb follows the lattice structure of the NbN layer and both interfaces look excellent. In contrast, as shown in figure 2c there is always a white amorphous layer on top of NbN without Ar^+ cleaning. Very likely the reported poor reproducibility and high contact resistance for HEB mixer without Ar^+ cleaning is caused by the presence of this additional interfacial layer. We also find that without Ar^+ cleaning, the adhesion of the gold layer to NbN is poor.

III. MEASUREMENTS AND RESULTS

We measured several devices with both type of contact pads and also test structures to know the T_C of individual layers [7]. Test structures are fabricated in the same batch and simulate the real devices. Both DC and RF analysis of devices have been done.

A. DC characterization and analysis

Here we discuss the DC property of devices. The resistance versus temperature (RT) curve is shown in Fig. 3. The HEB device has three resistive transitions with respect to temperature because of the proximity effect at different multilayers [7]. T_{C1} is the transition temperature for the Nb contact pads, T_{C2} is for the antenna layer and T_{C3} for the bridge. The bridge has a T_c which is equal to that of the NbN film. Contact pads involve an Ar cleaning step and in situ

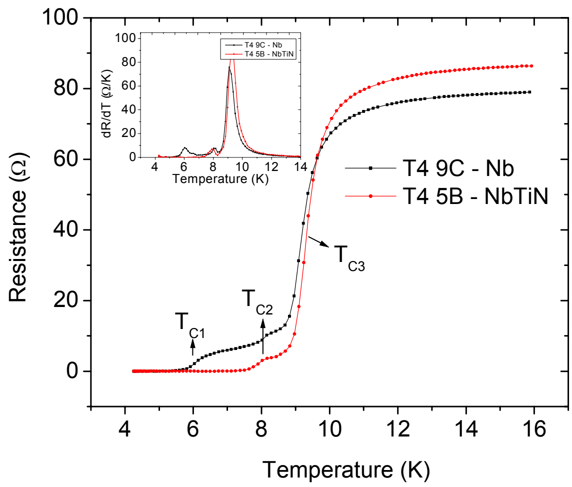

Figure 3 Resistance versus temperature curve of two HEBs with either Nb or NbTiN interlayer in the contacts. Inset shows corresponding differential resistances in log-scale.

sputtering of Nb or NbTiN and a gold layer on top of it. Hence, we expect a different transition temperature for the contact pads than for the bridge. The antenna layer has the thin NbN under the 150 nm gold layer. Since no Ar^+ cleaning is applied before the gold layer, we expect the interface to be poor and thus a weak proximity effect.

As we see clearly from the inset of figure 3, a transition at 8 K is common for both type of devices (Nb and NbTiN interlayers), and in the case of Nb device T4-9C we see a transition at 6 K. This gives us the first indication that T_{C1} is the transition temperature for the contact pads and T_{C2} is for the antenna layer which is the same for both types of devices. To confirm this we study the RT of a test structure, containing the same individual multilayers as the contact pads and antenna, which are also fabricated in the same batch. Fig. 4

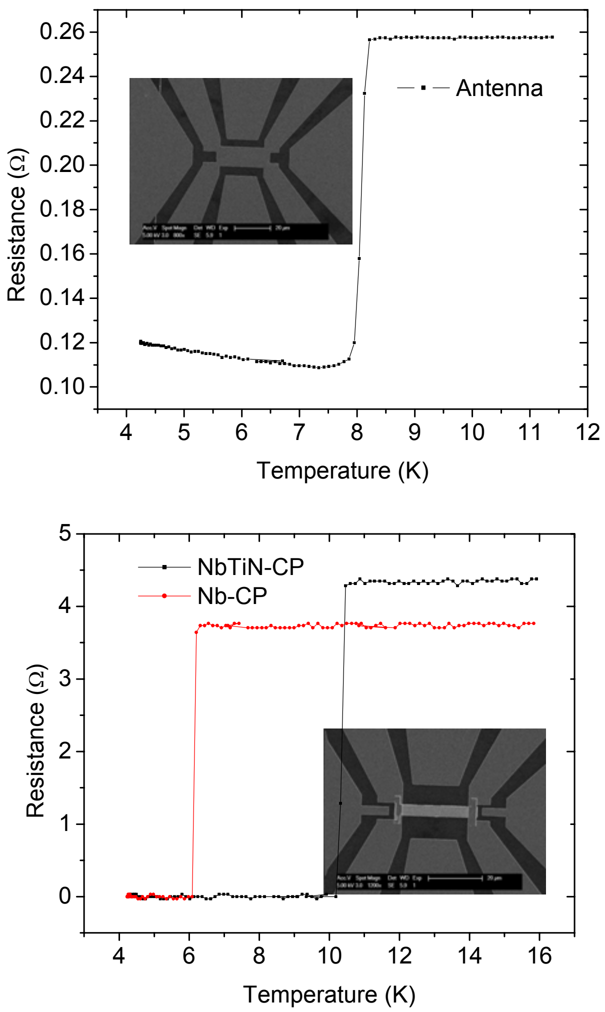

Figure 4. RT curve of the antenna test structure (upper panel) and the RT curves of Au/Nb/NbN and Au/NbTiN/NbN multilayers from the test structures (lower panel). Insets show the corresponding SEM pictures of the test structures

shows RT curves of the test structure while the insets show the corresponding SEM pictures of the test structure. The results indicate that the Nb contact pads have a T_C of 6 K, and the NbTiN contact pads have a T_C of 10.3 K. The latter explains why we do not see the transition T_{C1} in the case of NbTiN HEB devices, as it is merged with T_{C3}. We note that the present results do not agree with our previous analysis in [7] about the differences in T_C.

B. RF characterization and analysis

We study the RF property, primarily the receiver noise temperature, of the HEB devices with both contact structures at 2.5 THz. We use a standard lens–antenna quasi-optical coupling method to couple THz radiation to a HEB. We stress that all the measurements were done with a Si lens without antireflection coating. As local oscillator, we employ a far-infrared gas laser. We use the Y-factor method and the Callen-Welton definition to obtain the DSB receiver noise temperature ($T_{N,rec}$). Furthermore, we apply a new characterization method to obtain a noise temperature as discussed by Khosropanah et al in Ref. [8]. This method gives

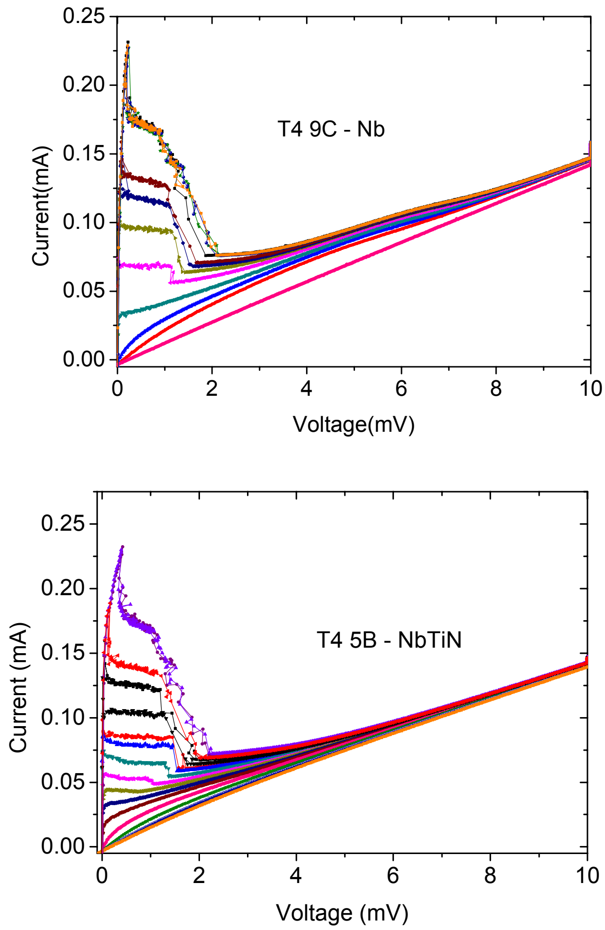

Figure 5. Pumped IV curves of a NbN HEB mixer with NbTiN/Au contacts (upper panel). Pumped IV curves of a NbN HEB mixer with Nb/Au contacts. The LO is operated at 2.5 THz.

us a Y-factor and hence the noise temperature which is not influenced by the direct detection effect and not affected by the instability of local oscillator power. Thus, the data obtained in this way are more accurate. Fig. 5 shows pumped IV curves of two HEBs with either Nb or NbTiN contacts. We find an optimum operating bias point for devices T4-9C and T4-5B around 0.8 mV and 0.6 mV respectively.

We obtain a minimum receiver noise temperature of 1230 K at optimal operating conditions for device T4 9C (Nb contacts) and 1300 K for device T4 5B (NbTiN contacts). These noise temperatures were obtained at an IF frequency of 1.4 GHz and at 4.2 K. We notice that the noise temperature of the HEB with Nb contacts seems slightly better than the HEB with NbTiN contacts. Since the difference is only 6 %, we consider both devices having equal performance. This result suggests that HEBs with Nb contacts are not necessarily worse than HEBs with NbTiN contacts, as reported earlier [7]. The lowest value of 1230 K from the HEB with Nb contact pads can be reduced to 980 K if we would apply a lens with anti-reflection coating layer (20% reflection loss is assumed). This value is essentially the same as the best performance reported in a HEB with NbTiN contacts at the same frequency [4].

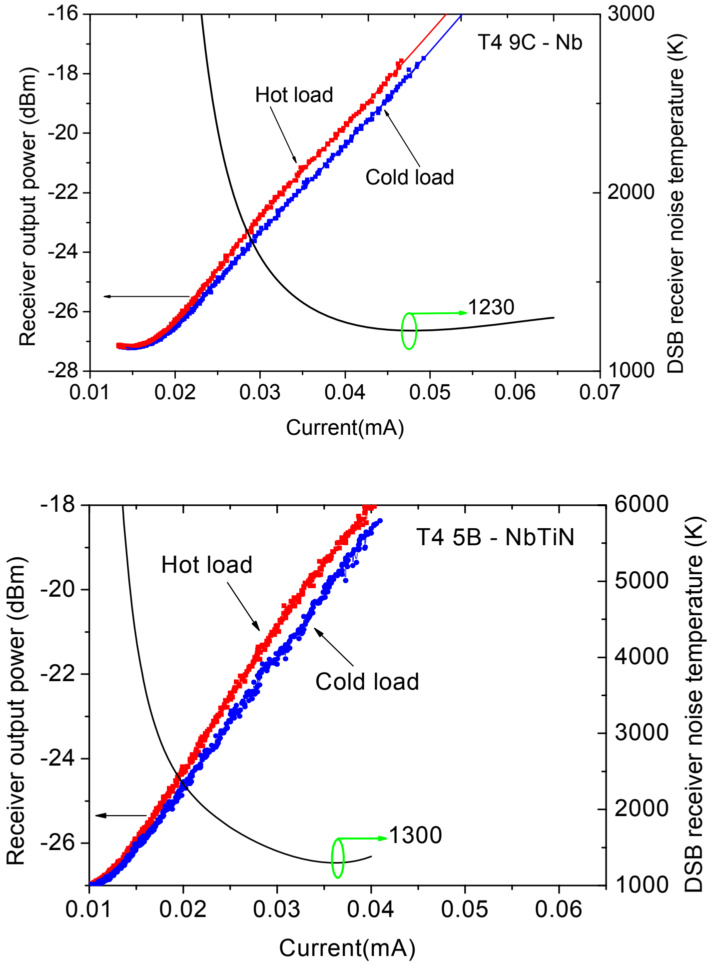

Figure. 6 Receiver output power (left axis) to hot/cold loads and resulting noise temperature versus current at an optimum bias voltage for a HEB mixer with Nb contacts (upper panel) and for a HEB mixer with NbTiN contacts (lower panel). The lowest noise temperature is indicated

CONCLUSIONS

We successfully demonstrated that NbN HEB mixers using a superconducting Nb interlayer for the contacts show a comparable or even slightly better sensitivity than with the HEBs with an NbTiN interlayer. The lowest receiver noise temperature at 2.5 THz for the HEB with Nb contact pads is 1230 K, which becomes 980 K if we would apply a lens with an anti-reflection coating. This value is the same as the best performance reported in a HEB with NbTiN contacts at the same frequency [4]. Since Nb is easier to sputter, high performance HEB mixers can be realized in different labs, which usually do not have a NbTiN process.

We have performed HRTEM inspections of various types of contact pads. We find that the interface between NbN and an interlayer of either a Nb or NbTiN after Ar^+ sputter cleaning is nearly perfect, implying no contact resistance. We also confirmed that there is an interfacial layer on the top of NbN if we do not perform Ar^+ sputter cleaning, which is the origin of the high contact resistance.

We have also identified the different transition temperatures in HEB devices. This helps to understand the physics of HEB devices as this affects the boundary conditions for the cooling mechanism. Thus we expect that IF bandwidth in HEBs with Nb contacts might be larger than those using NbTiN contacts.

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