Development of NbN-based Hot Electron Bolometer Mixers fabricated by standard UV lithography

C. Chaumont*, F. Boussaha, R. Lefèvre, G. Gay, T. Vacelet, F. Reix
Observatoire de Paris, 77 avenue Denfert-Rochereau, 75014 Paris
*Contact: christine.chaumont@obspm.fr, phone +33 1 40 51 22 59

Abstract— **We present the fabrication of NbN-based hot electron bolometer mixers for THz spectral line astronomy applications. Superconducting HEB nanobridges are defined from ultrathin NbN layers sputtered on Si substrates. The thin films of 3-5 nm exhibit critical temperatures (T_c) of ~ 8-10K so far. We propose to define the whole HEB mixer structures, including nanobridges, by the conventional UV lithography technique with a limited number of steps.**

I. Introduction

Nowadays, to detect and resolve atomic and molecular transitions in THz frequency range, typically beyond 1 THz, the hot electron bolometer (HEB) mixer is the key element to build ultrasensitive heterodyne receivers [1]. The HEB device which features a nanoscale superconducting strip on the order of few hundred nm, typically 100-300nm, is usually defined by the e-beam writing technique [2]. However, this may not be available and usually requires high-cost machines.

In this paper, we present the current development of HEB devices from ultrathin superconducting NbN films deposited by means of a new sputtering machine at Paris Observatory. In order to fabricate HEB mixers, these films are patterned using the standard 320nm UV lithography technique to realize HEB nanobridges.

II. Optimisation of Ultrathin NBN deposition

The NbN layers are deposited using the new sputtering machine Plassys MP700S which works at a base pressure of 3×10^{-8} mbar. It is equipped with a 6-inch diameter Nb target and 3-inch silicon carbide substrate heater designed to go up to 1000 °C. The distance between the target and the substrate is 8 cm. In order to find out the reasonable starting range for NbN deposition parameters, we first recorded the complete current-voltage characteristics of the Nb dc magnetron cathode using current stabilization in pure argon Ar gas then in a N_2/Ar mixture. Fig. 1 shows the cathode I-V characteristics obtained with a N_2/Ar flow ratio and Ar flow rate set at, respectively, 0.12 and 50sccm. Depending on the current between electrodes, the curve shows three slopes corresponding to three states of the system during the sputtering when the N_2 gas is injected along with Ar gas into the chamber. At low currents, a small amount of nitrided Nb atoms are sputtered from the target. The increase of the current leads to enhancing the reaction between N_2 and Nb atoms. This leads to the decrease of N_2 partial pressure in the chamber causing a drop in the discharge voltage resulting in a negative resistance region observed in the I-V curve [3]. Thus, the best conditions for deposition of NbN thin films should be found in this region. At high currents, the curves with and without N_2 are joined indicating likely the vanishing of the N_2 amount as it reacts with Nb atoms. The quality of the NbN films can be assessed by measuring the difference discharge voltage ΔV between the discharge voltage with Ar gas only and its value when N_2 is injected into the deposition chamber [3].

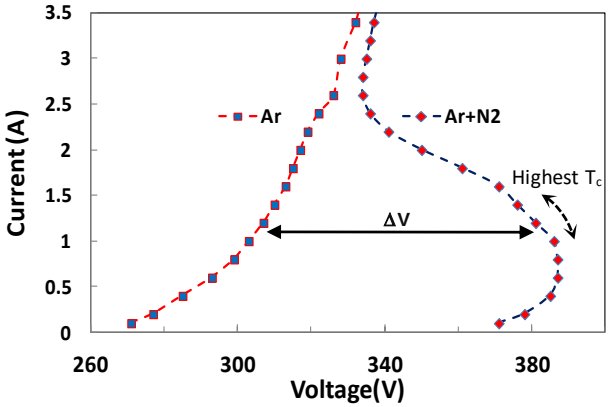

Fig. 1. Current-voltage characteristic of the Nb magnetron sputtering cathode using current stabilization in Ar/N_2 and in pure argon gas mixture.

Ultrathin NbN Film deposition

As it is not possible to efficiently measure a thickness below 10nm using the existing contact profilometry technique, the targeted thickness of 4-5nm would be achieved by adjusting the sputtering time. This is deduced from the thickness versus sputtering time curve which was recorded for measurable thicknesses, above 20nm. NbN films are deposited on 3-inch Si substrates which are heated between 600 and 700°C during the deposition. Using the atomic force microscopy (AFM) technique as well as RIE end-point detection compared to a known sample, the thickness of NbN films is estimated to be 3-7nm thick.

Measurement of critical temperatures

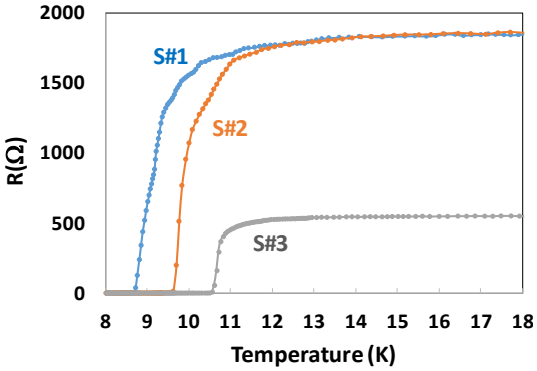

Fig. 2. Resistance versus temperature curves of ultrathin NbN films deposited on 3-inch Si substrates for a substrate temperature of 700°C during deposition. Critical temperatures are measured at the mid temperature transition. Using AFM technique and RIE end-point detection, the thickness is estimated to be 4-5 nm for films 1 and 2 and 6-7 nm for films 3.

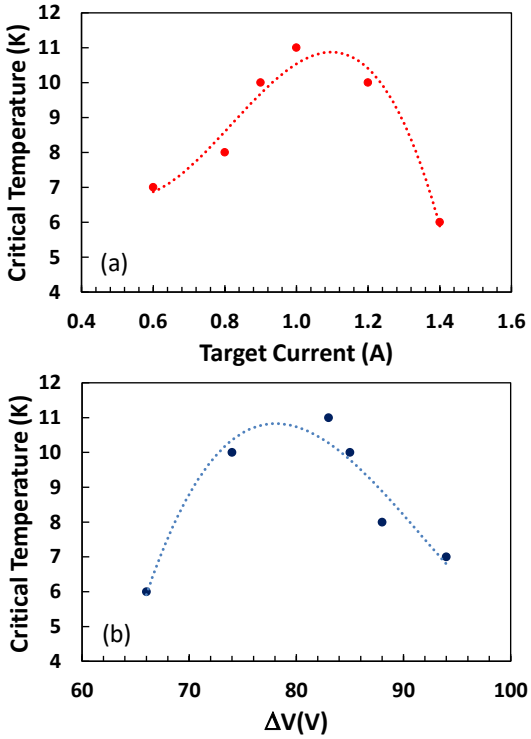

Fig. 3. (a) Critical temperature versus cathode current. (b) Critical temperature versus ΔV.

Rectangular samples are cut off and mounted on a dipstick which is dipped into liquid helium to measure the critical temperature (T_c). Fig. 2 shows typical measured resistances as a function of temperature R(T) curves we performed. In Figs. 3a and 3b, we show curves of respectively the cathode current and ΔV as a function of measured T_c. The highest critical temperatures varies between 9 and 10.7 ± 1K and are obtained with a cathode current in 0.9-1.2A range and ΔV at around 80V. As expected, the currents belong to the negative resistance region with the largest value of ΔV as shown in Fig. 1. These critical temperatures would allow to achieve high quality HEB mixers. Furthermore, even a higher T_c is expected as it is possible to heat the substrate temperature up to 1000°C. As depicted in [3], the optimal reaction between Nb atoms and N_2 gas takes place within this negative resistance region.

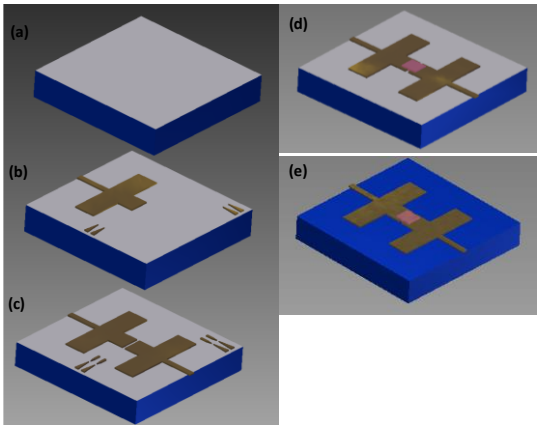

Fig. 4 Fabrication process sequence using standard 320nm UV lithography.

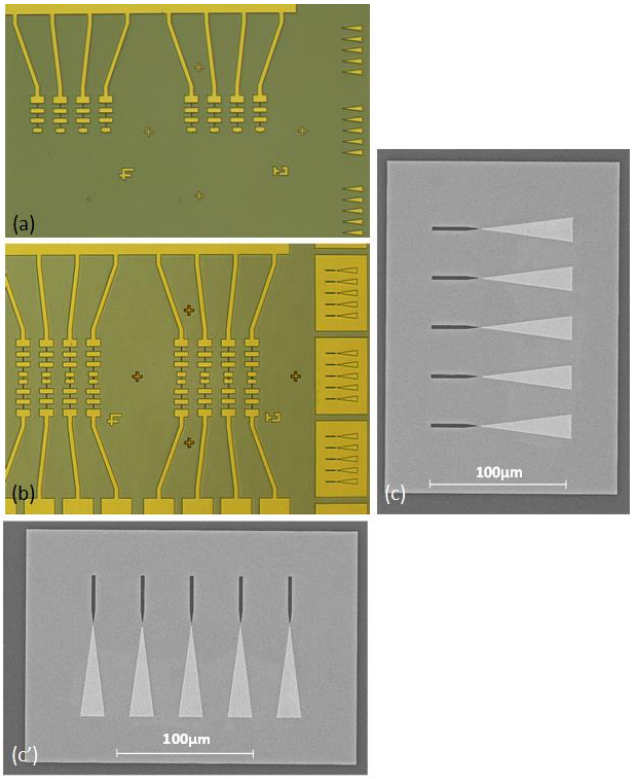

Fig. 5 Fabrication process sequence using standard 320nm UV lithography. (a) Definition of the first Au electrode, (b) definition of the second Au electrode which is closely and precisely aligned to the first one using horizontal and vertical arrow mark alignment.

III. Definition of HEB Nanobridges by UV Lithography

To quickly assess whether we can fabricate HEB mixers using the deposited ultrathin NbN films, we are developing a straight fabrication process based on the use of the standard low-cost UV 320nm lithography technique. Because of UV light limits, it is obvious that the optical lithography cannot pattern the superconducting HEB nanobridge whose length should be ideally in 100-200nm range. To overcome the UV photolithography limits, the HEB is viewed as being made up

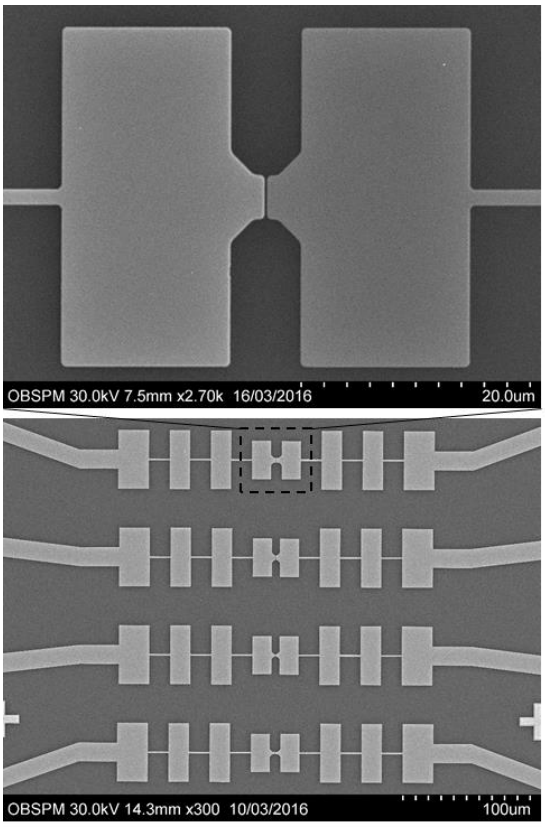

Fig. 6 Electron microscope picture of four HEB devices featuring two Au electrodes defined by UV photolithography. The zoom in picture shows the

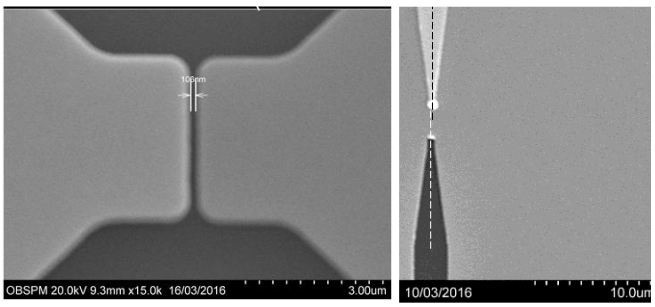

Fig. 7 Electron microscope picture of electrodes separated by a gap of ~100nm patterned by UV lithography. This is achieved when the arrows are misaligned by Δw (right picture).

of two microscale electrodes which can be separately defined in two successive UV lithographic steps. In this case, the issue is no longer the UV light limits but the positioning accuracy of one electrode to the other. This can be addressed by designing proper alignment marks on the mask. For example, we can use a set of arrows whose points must align to ensure an accurate alignment of electrodes with the desired gap between electrodes (i.e., length of the nanobridge) as shown in Figs. 4 and 5. As electrodes must be both horizontally and vertically well aligned, we define arrows along horizontal and vertical axes. In Fig. 4, we summarize the fabrication process sequence using the standard 320nm UV lithography. This is done thanks to the widely used MGB 4 aligner mask of SUSS Micro Tech. After the deposition of the ultrathin NbN layer on 3-inch Si substrate,

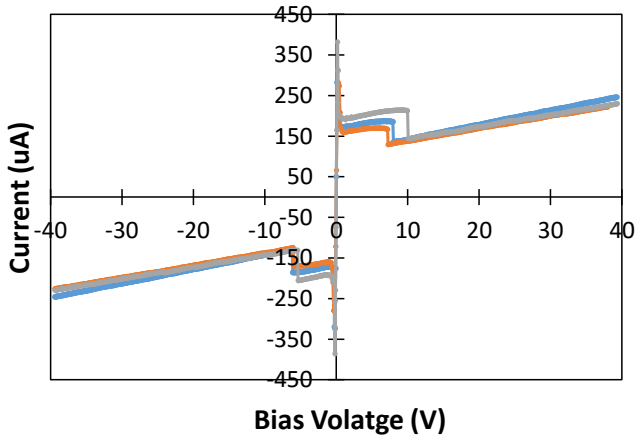

Fig. 8. First I-V curves of HEBs fabricated by UV lithography process using NbN layer with R□≈550Ω/□ and nanobridges of L×w≈0.25×2, 0.3×2 and 0.4×2 μm.

we first define one of electrodes as well as the first set of arrows by UV lithography using SPR700 positive photoresist. The deposition followed up by the lift-off of Au 150 nm-thick allowing the realisation of the first Au electrode as shown in Figs.4b and 5a. Using again the SPR700 photoresist, the second step consists in pattering the second electrode which must be precisely and closely aligned to the first Au electrode. This is done when the points of the second set of arrows align with those of the first set as shown in Fig. 5. The width of the nanobridge is defined using 2μm-width rectangular photoresist or insulator (SiO) layer which must be well aligned in the center of electrodes. Finally, the uncoated NbN layer is removed by reactive ion etching. Thus, this process requires a limited number of steps. Fig. 6 shows the electron picture of four HEB devices. On the zoom-in picture, the gap between electrodes is around 250nm while the targeted one is 200nm. This difference is not due to the alignment process but to the used mask which features a deviation of patterns in XY plane. It is possible to recover this by adjusting the position of arrows as illustrated in Fig. 7 (right picture).

To assess the capability of this technique to achieve a smaller HEB nanobridge length, we could further reduce the gap between the electrodes by shifting and misaligning the arrows as shown in Fig. 7. This shows a gap of ~100nm obtained when the arrow marks are shiftted by around Δw≈150nm.

Fig. 8 shows first I-V curves of HEB featuring nanobridges of L×w≈0.25×2, 0.3×2 and 0.4×2 μm.

CONCLUSION

NbN films of 3-5 nm thick deposited on Si substrate exhibiting critical temperatures of 9-10K have been achieved using a new sputtering machine at Paris Observatory. These films are deposited on 3-inch Si substrates heated up to 700°C. However, we expect to achieve higher T_c with a temperature substrate of 1000°C. In order to fabricate HEB mixers, nanobridges of typically 100-400 nm length have been patterned using the standard low-cost 320 nm UV lithography. The UV light limits were overcome by pattering the HEB

electrodes in two separated UV lithographic steps. HEB devices with lengths up to ~200nm were achieved.

ACKNOWLEDGMENT

This work has been carried out at Centrale Technologique de l'Observatoire de Paris (CTOP)-GEPI and LERMA and is partly supported by Région Ile-de-France.

REFERENCES

[1] F.Boussaha, J.Kawamura, J.Stern, A.Skalare,and V.White,"Alownoise2.7 THz waveguide based superconductingmixer," IEEETrans. THzSci.Technol., vol. 2, no. 3, pp. 284–289, May 2012.

[2] R. Lefèvre et al., "Terahertz NbN hot electron bolometer fabrication process with a reduced number of steps", 23rd International Symposium on Space Terahertz Technology, Japan, 2012.

[3] S. Miki, Y. Uzawa, A Kawakami, and Zhen Wang, "Fabrication and Bandwidth Measurements of NbN Hot-Electron Bolometers," Electronics and Communications in Japan, Part 2, Vol. 85, No. 7, 2002.