Terahertz NbN hot electron bolometer fabrication process with a reduced number of steps

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***Abstract*—We have developed a superconducting hot electron bolometer fabrication process which requires fewer steps than conventional process. NbN phonon-cooled hot electron bolometers have been fabricated without any additional superconducting interlayer to NbN/Au contact, using a single layer of Au and a single step of passivation. This process has been proved efficient, reliable and reproducible. Excellent receiver noise temperature of 800 K at 2.5 THz has been obtained with a quasi optical HEB mixer developed for a stratospheric balloon experiment. In this paper, we will present in detail the fabrication process which has been performed with different substrates including silicon, sapphire and 1.4 µm thick SiO_2/Si_3N_4 membrane.**

***Index Terms*—e-beam lithography, hot electron bolometer, heterodyne receiver, noise temperature, terahertz.**

I. Introduction

THERE are many astrophysical relevant molecular transitions in the frequency window between 2.3-2.8 THz. Observations of the rotational transition of the deuterated hydrogen molecule, HD, at 2.7 THz, will provide critical information on the star formation history across the Galactic disk and nearby galaxies. The hydroxyl radical, OH (2.5 THz), is one of the most important molecules in interstellar chemistry. It is vital for understanding the water chemistry, and its observations will be used to derive information about shocked molecular gas and will allow to discriminate between different shock models.

Our laboratory is developing a heterodyne receiver with a multipixel camera for a balloon project called CIDRE (Campagne d'Identification du Deutérium par Réception hÉterodyne). This project is supported by the French Space Agency (CNES). The heterodyne instrument on board a stratospheric balloon at an altitude of 40 km will be able to observe OH and HD with a very low atmospheric absorption. The first flight of CIDRE is expected in 2015. In this framework we have developed an efficient, reliable and reproducible fabrication process for the mixer element based on NbN hot electron bolometer (HEB). Our main motivations in this process development were to minimize the number of fabrication steps to perform the process more easily and to get a device yield as high as possible.

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II. Fabrication Process

In standard, the devices were manufactured starting from 400 µm thick Si substrate. The planar dimensions of the substrate were 10 mm x 15 mm. Fig. 1 shows a scheme of the main steps of the HEB fabrication process. This process was the same for devices on sapphire substrate and on SiO_2/Si_3N_4 membrane. After the complete process the average yield was about 90 %.

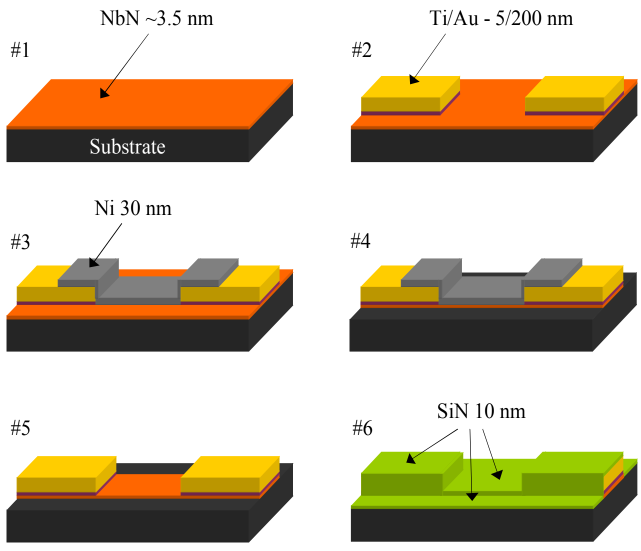

Fig. 1. Scheme of the main steps of the HEB fabrication process. #1 deposition of an ultrathin NbN film by reactive sputtering. #2 realization of the HEB electrodes; the gap between them defines the length of the bolometer. #3 protection of the bolometer with a Ni mask. #4 etching of the unprotected NbN; this defines the width of the bolometer. #5 removal of the Ni mask. #6 passivation of the whole sample with SiN.

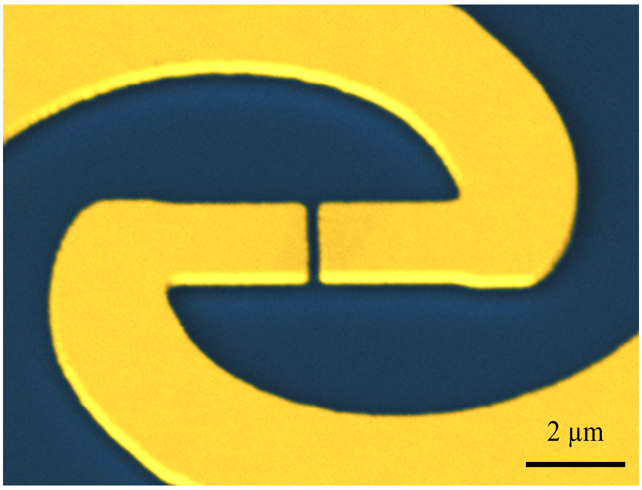

Fig. 2. SEM image (colorized and tilted view) showing the inner part of a log-spiral antenna and the gap between electrodes where the HEB is located.

Step #1: The fabrication started with the deposition of the superconducting NbN film. This was done by Scontel or Inac by reactive sputtering [1], [2]. Since it is the active layer of the HEB mixer, it will play a key role in the performances of the receiver. We need an ultra-thin film, around 3.5 nm of thickness, with a high critical temperature T_c and a narrow transition width ΔT in order to get a wide bandwidth and a good sensitivity. The NbN films that we obtained exhibited a T_c about 11-12 K.

Step #2: The HEB electrodes, the antenna and the bonding pads were patterned at the same time by electron beam (e-beam) lithography, deposition of metals, and lift-off. For the lithography we used the e-beam writer JEOL JBX 5DIIU at 50 kV and the PMMA A7 resist. The resist, 400 nm thick, was spin-coated on the sample at 4000 RPM and baked at 170 °C for 15 min in an oven. Fine structures, like HEB electrodes, were exposed with a beam current of 200 pA and a dose of 500 µC/cm². Larger structures were exposed at 20 nA and 600 µC/cm². All the structures were exposed in the same run and aligned better than 50 nm (we used alignment marks fabricated before, not shown in Fig. 1). The resist was developed with MIBK:IPA (1:3) for 60 s. For the deposition of metals, we used the electron beam evaporator Plassys MEB 550 SL. First, the sample was cleaned *in situ* by ion beam etching with argon for 45 s. The gas pressure and flow rate were 1 x 10^{-4} mbar and 5 sccm. The current density and the acceleration voltage of the ion beam were 7 mA/cm² and 500 V. Second, we deposited 5 nm of Ti as adhesion layer followed by 200 nm of Au, with a residual pressure below 2 x 10^{-7} mbar. Afterwards, we removed the resist with trichloroethylene at 90 °C and rinsed the sample in two baths of acetone and isopropanol and dried it with nitrogen. In this step the length of the HEB was defined by the gap between its electrodes ranging from 100 to 200 nm, as shown in Fig. 2 and Fig. 3(a).

Step #3: We patterned a rectangle mask of Ni 30 nm thick across the two HEB electrodes. At this stage the width of the bolometer (usually 2 µm) was defined. As in the previous step, we used e-beam lithography (alignment precision was better than 50 nm), metal deposition by electron beam evaporation, and lift-off.

Step #4: The unprotected NbN film, either by gold metal or Ni mask, was removed by reactive ion etching with SF_6 plasma for 90 s. The RF power was 10 W, the flow rate and gaz pressure were 10 sccm and 10 mTorr, and the self-bias was - 85 V. An optical system with a laser ($\lambda = 635$ nm) focused on the sample allowed us to monitor and to detect the end of etching. We have done an over-etching to be sure that the unprotected NbN was completely removed, as illustrated in Fig. 3(b).

Step#5: Because the Ni mask short-circuits the HEB electrodes, we needed to remove it. This was done by wet etching with nitric acid at 69 % for 6 min. Then the sample was rinsed with deionized water.

Step #6: Finally, to protect the devices from the ambient atmosphere, we covered the sample with a 10 nm thick SiN passivation layer. This was performed by plasma enhanced chemical vapor deposition at 280 °C.

Finally the sample was diced into 6 chips of size 3 mm x 3 mm. Then, the chips are mounted either on a chip-carrier for DC measurements with a dipstick or into a mixer block for RF measurements with a cryostat, at the liquid helium temperature. Typically bolometers with a size of 0.15 µm x 2.0 µm (length x width) have a resistance of 75 Ω, and a critical temperature of 9-10 K.

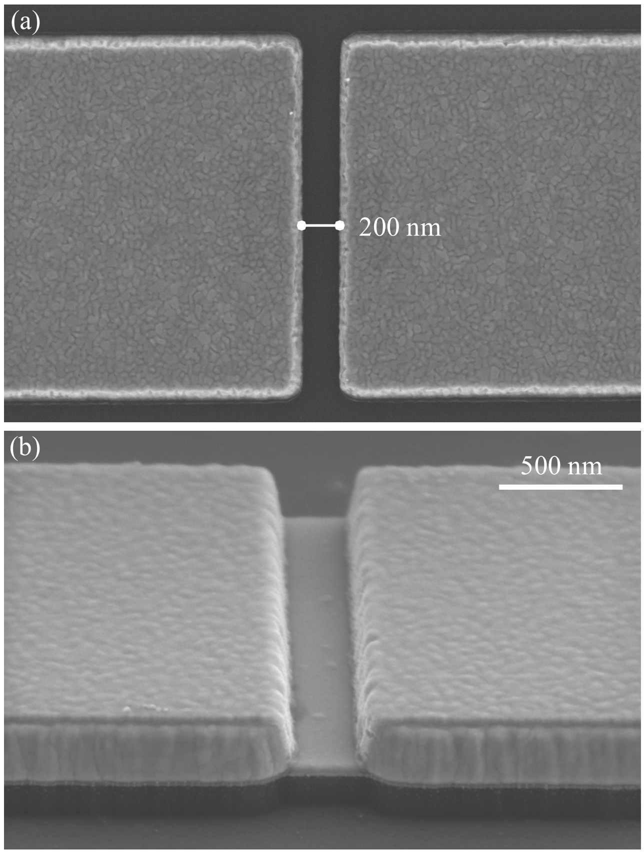

Fig. 3. SEM images of a device at different steps of fabrication. (a) HEB electrodes after lift-off; the gap between them defines the length of the bolometer. (b) Stacking of layers: the Ni on the top protects the bolometer during the NbN etching; Si substrate is partially etched due to an intentional over-etching.

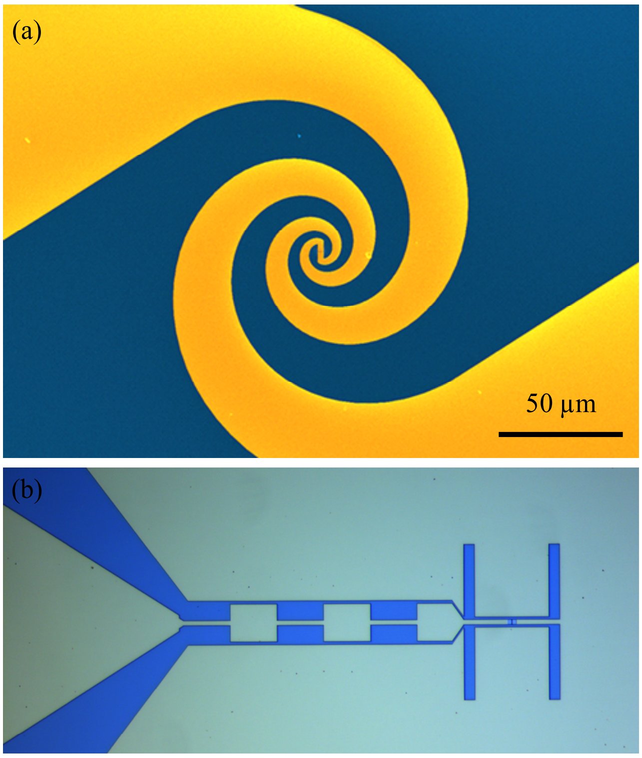

Fig. 4. (a) SEM image (colorized) of a log-spiral antenna designed for 1.3-1.6 THz. (b) Optical image of a double-slot antenna designed at 1.25 THz with a RF choke filter.

A particular case was that of the Si substrate with a SiO_2/Si_3N_4 membrane on both sides. At the end of the steps described before, we etched the Si substrate to get a suspended membrane. This was used to develop a new membrane based quasi-optical design. Details are reported elsewhere [3]-[5].

III. Process Key Points and Mixer Performances

Here, we highlight some key points, original features, and advantages of our process described above compared to conventional HEB fabrication processes found in the literature [6]–[13].

First, our process has a reduced number of steps (at least less lithography steps than conventional ones) and only e-beam lithography is required. This all e-beam process gives us a high flexibility to test in a short time different designs of antenna (shape, size, and operating frequencies ranging from 600 GHz to 2.5 THz in this work) as illustrated in Fig. 4 and reported in [14]-[16]. Typically, for a new design, it takes about one week to get the devices ready to be tested.

Second, a “direct” contact of gold on the NbN film is established without any additional superconducting layer (only the Ti adhesion layer beneath Au). In addition, there is no interface between HEB electrodes and antenna (as shown in Fig. 2) since they were processed with a single deposition of Ti/Au. By this way we hope to reduce the contact resistances close to the bolometer, which can be a source of undesired heating.

Third, the SiN passivation layer, deposited on the whole sample, did not require any lithography, lift-off or etching steps. This layer was thin enough to preserve the performance of the devices. Moreover, it is possible to wirebond the device directly through the 10 nm thick SiN (with Al wires at room temperature). The bondings we performed have withstood numerous thermal-cycles between 4 K and 300 K.

One of the quasi-optical HEB mixers, developed in the framework of the balloon project CIDRE, has been tested during a joint experimental campaign at SRON under the European research program Radionet-AMSTAR+. The lowest measured DSB receiver noise temperature at 2.5 THz without any correction was as low as 790 K and presented a relatively broad region in its voltage dependence. The LO power absorbed by the HEB was about 280 nW. The details of this experiment have been reported in [14].

IV. Conclusion

We have processed NbN hot electron bolometer on Si, sapphire and SiO_2/Si_3N_4 membrane substrates with a recently developed process requiring a reduced number of steps. This process has been proved to be reliable and high yielding. It also provides additional flexibility to validate new mixer designs in a relatively short time.

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