Development of membrane based NbN-HEBs for submillimeter astrophysical applications

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***Abstract* — We are developing membrane based Nb N hot electron bolometer (HEB) arrays for sub-millimeter astrophysical applications. Here we report in detail on the device fabrication process using a silicon oxide based resist (HSQ). The e-beam patterned HSQ is used as a mask in reactive ion etching for HEB definition and then remains on top of the HEB providing protection against contamination. This process is relatively simple since it requires less steps than previously reported and therefore reduces the risk of degradation of the ultra thin NbN film. To get good quality membranes for THz-HEB applications, different membrane process have been investigated. Electrical characterisations have been performed at room and cryogenic temperatures to compare the quality of the devices with membranes made up of Si/SiO$_2$ or Si$_3$N$_4$/SiO$_2$ and processed with either dry or wet etching methods.**

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. OH (2.5 THz), the hydroxyl radical 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 prototype of a 4 pixels camera using NbN Hot Electron Bolometer (HEB) mixers with a membrane based quasi-optical design in the frame of the balloon project CIDRE (Campagne d'Identification du Deutérium par Réception hÉterodyne), proposed to the CNES (Centre National d'Études Spatiales).

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II. MEMBRANE-BASED QUASI-OPTICAL STRUCTURE

The proposed quasi-optical structure[1,2] for each pixel of the camera is illustrate in the Fig. 1. A parabolic mirror collects and focuses the incoming signal on the membrane where is placed an integrated planar antenna connected to the HEB. A metallic back reflector on the second membrane allows to increase the gain of the antenna. This design, in comparison with the conventional coupling structure employing lens and thick substrates, will provide particular features such as larger antenna size, absence of the substrate mode and lower request for P_{LO} and then will help to achieve higher coupling efficiency.

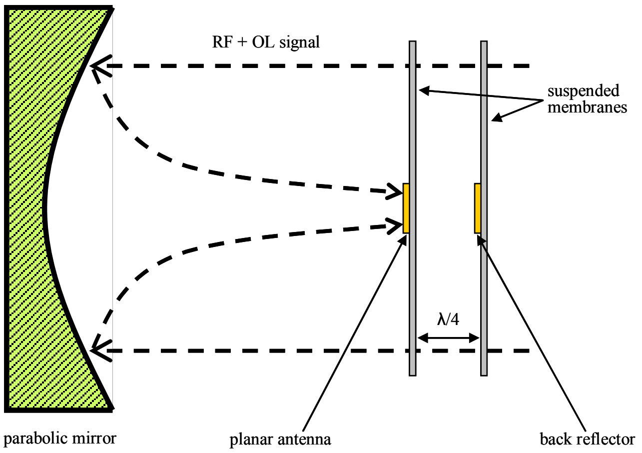

Fig. 1 Schematic view of the quasi-optical structure for one pixel of the camera.

III. FABRICATION PROCESS

We have selected two kinds of membrane for this study: 1.4 µm thick Si$_3$N$_4$/SiO$_2$ membrane and 3.5 µm thick SOI membrane. Both membranes are deposited on Si substrates with a thickness around 500 µm.

The fabrication process concerns first the HEB and all circuits on the membrane side of the substrate and second the suspended membrane formation through the backside of the substrate. We'll illustrate (Fig. 2) and describe step by step the whole fabrication process developed in our lab.

(a) Deposition (realized by Moscow State Pedagogical University) by sputtering of an ultra thin superconducting film of NbN (3.5 nm expected, while 5 – 10 nm measured[3]) with or without a buffered layer of MgO (200 nm) underneath.

(b) One step e-beam lithography to pattern the whole circuits: the antenna, the electrodes as well as the length of the HEB, the RF choke filter, the CPW and the bonding pads. By this way, we avoid additional lithography steps (e-beam or optical) and then limit the risk of layer degradation.

(c) Use of FOx, an inorganic negative resist, to define by e-beam lithography the width of the HEB and the passivation area above the HEB. FOx, based on hydrogensilesquioxane (HSQ), contains atoms of H, Si and O and will form during lithography a kind of SiO mask. This mask is used for next etching and is left on the substrate to protect the bolometer from aging. In addition, the FOx mask is compatible with organic solvents, so we can clean the chip before bonding using many standard solvents like acetone for example.

(d) Etching of NbN film by RIE with SF_6 and O_2. This step defines the HEB. Fig. 3 shows images of the HEB taken by SEM and AFM.

(e) Pattern of the etching mask on the backside of the substrate. It can be a thick organic resist, a thin Au layer or a Si_3N_4/SiO_2 bilayer.

(f) Making of the suspended membrane by etching the Si substrate through the backside mask, which is removed at the end.

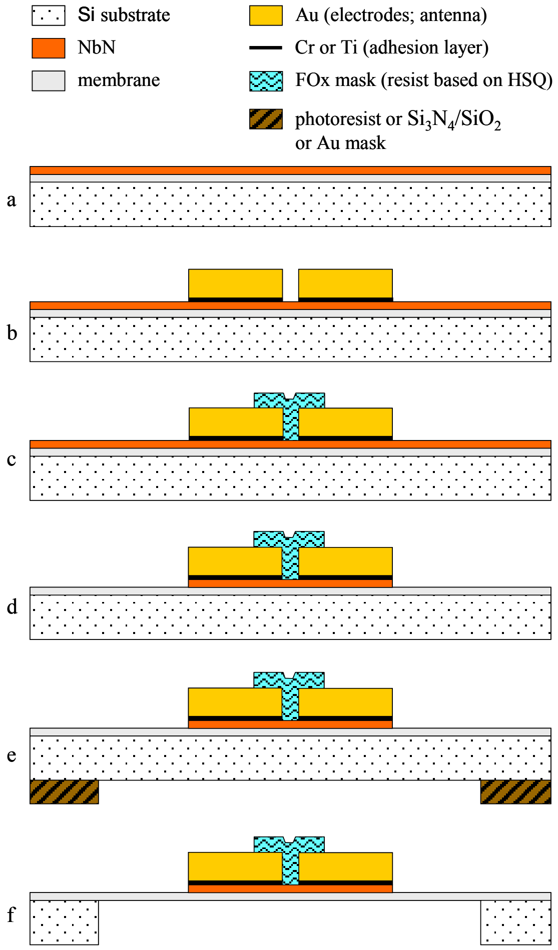

Fig. 2 Fabrication steps of a HEB on suspended membrane with a FOx mask.

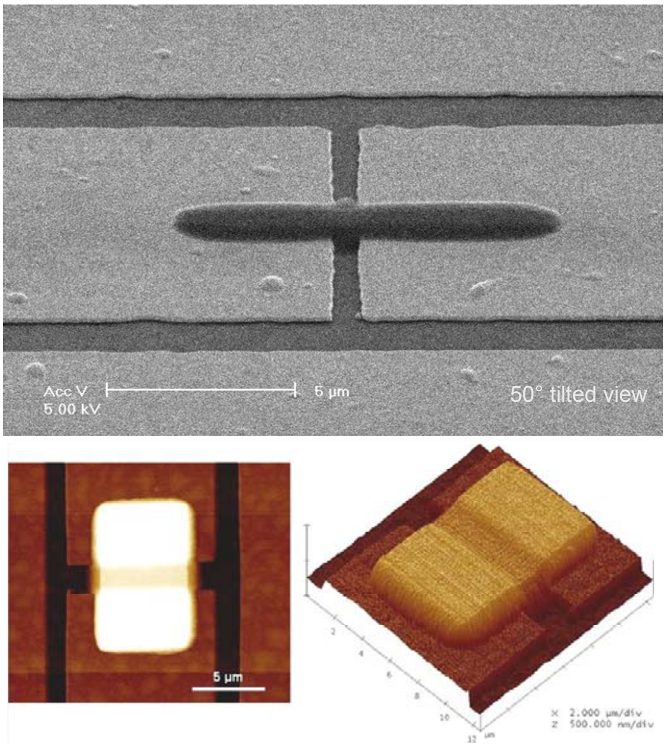

Fig. 3 Top: SEM image of a ‘standard dimensions’ NbN HEB. The dark pattern is a FOx resist mask. Dimensions of the HEB: L = 680 nm and W = 2.7 µm. Bottom: AFM images of a ‘large’ NbN HEB. The clear pattern is a FOx resist mask. Dimensions of the HEB: L = 2 µm and W = 8 µm.

IV. PROCESS FOR SUBSTRATE ETCHING

Different wet and dry etching methods have been explored (KOH, standard DRIE and cryo-DRIE) to make suspended membranes (either Si_3N_4/SiO_2 or SOI) through backside masks made of different materials. Conditions and results are presented in the Table 1.

TABLE II
CONDITIONS AND RESULTS OF ETCHING METHODS

wet	**etching**	**DRIE Bosch process**	**cryo-DRIE**
membrane material	Si_3N_4/SiO_2	SOI	SOI
temperature	90°C	10°C	- 85°C
etchant	KOH (aq) 20 wt.%	$SF_6 + 0_2$ (g)	$SF_6 + 0_2$ (g)
passivation	n.a.	C_4F_8 (g)	autopassivated
frontside protection	resist + special chuck	resist + cool grease	resist + grease
rate	1.5 µm/min	7 µm/min	10 µm/min
membrane shape	square	all shape	all shape
compatible mask	Si_3N_4/SiO_2; Au	resist	Si_3N_4/SiO_2; Au
sidewall	angular	vertical	random
protection stripping	easy	difficult	easy

Fig. 4 shows a chip with 4 pixels on suspended membrane obtained by wet etching. At the moment we process with all these three methods since a large number of samples is necessary to determine which method will be the most suitable for our applications.

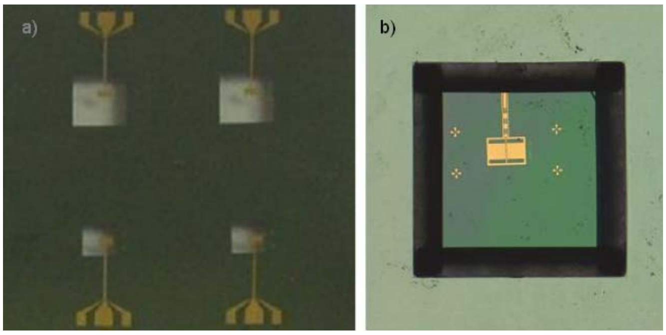

Fig. 4 a) Top view of a chip (10 x 10 mm²) with 4 pixels on suspended membranes obtained by wet etching of the Si substrate (400 µm thick). b) Back view of one pixel with the antenna, the RF choke filter and the CPW seen through the Si_3N_4/SiO_2 membrane.

V. DC MEASUREMENTS

DC measurements have been performed on several devices with thick substrates (i.e. without suspended membrane) in a cryostat at the liquid He temperature (Fig. 5). The critical temperature T_c was about 10 K. From the IV characteristics (shown in Fig. 6), the critical current I_c was around 300 µA for 'normal' and 600 µA for 'large' HEBs. The sheet resistances of different devices at 300 K range from 1000 to 5000 Ω/□, quite scattered and higher than expected values. Investigations are underway in order to find out the reasons which could affect the measured resistances.

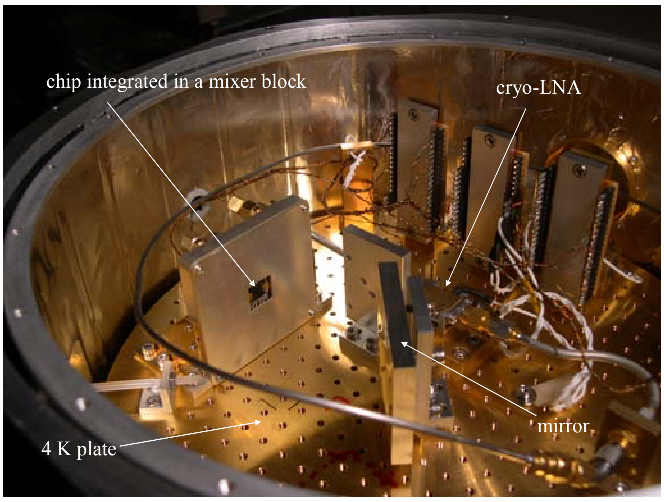

Fig. 5 Inner view of the cryostats used for DC measurements.

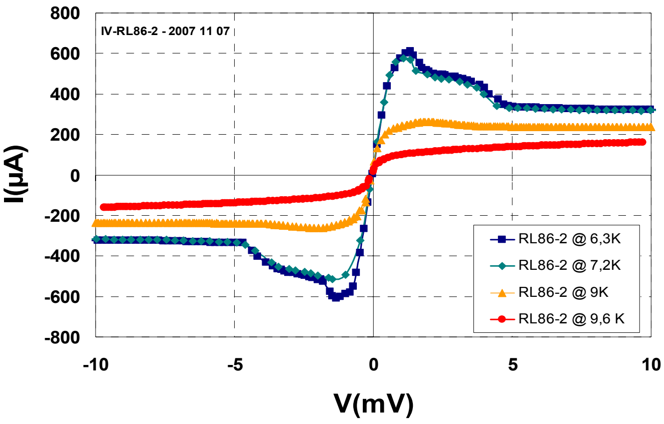

Fig. 6 Measured I-V curves of a 'large' HEB (on thick substrate).

CONCLUSION & PERSPECTIVES

We've developed a relatively simple fabrication process for a membrane based NbN Hot Electron Bolometer array. By using the Fox resist as etching mask and passivation layer, we reduce the number of process steps and then the risk of layer degradation. Different wet and dry etching ways have been explored to get suspended membranes by Si substrate etching. The fabrication process is being enhanced; efforts will be made to improve the quality of suspended membranes and the quality of substrate cleaning during the process.

First DC measurements of HEBs before membrane process have shown normal IV characteristics. We are planning to perform both DC and RF characterizations of HEBs on suspended membranes and make comparison with those on thick substrates.

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