Phonon-cooled hot electron bolometers on freestanding 2μm Si_3N_4 membranes for THz applications

Pedro Muñoz, Sven Bedorf, Michael Brandt, Thomas Tils, Martina Wiedner, Martin Brüll, Netty Honingh, Karl Jacobs

KOSMA, *I. Physikalisches Institut, Universität zu Köln, Zülpicher Str. 77, 50937 Köln, Germany*

ABSTRACT

KOSMA is working on the development of a heterodyne receiver channel (1.7 to 1.9 THz) for the GREAT instrument on SOFIA. We report on recent progress in fabricating and characterizing prototype mixers at 800 GHz on 2μm thick SiN membranes. The HEB is fabricated from a 5-6 nm thin NbTiN film with T_c= 8 K which was sputtered on a 20 nm thick AlN buffer layer at 400° C substrate temperature. An individual membrane device is then "flip-chip" bonded to a separately fabricated silicon frame. The frame assembly is mounted into the waveguide mixer such that the membrane is suspended in a substrate channel crossing the waveguide. All device fabrication including the thin NbTiN films is done at KOSMA. Heterodyne measurements with receiver noise temperatures of 1000 K at 1 GHz IF and 4.2 K bath temperature at first go are very promising for phonon-cooled HEBs on thin membranes as THz mixers.

1. INTRODUCTION

At KOSMA, we develop waveguide HEB mixers for SOFIA at 1.9 THz and APEX at 1.4 THz. Fabrication of mixer blocks at 1.9 THz with waveguide dimensions of 130 μm * 60 μm is complicated, but not impossible. The device substrate thickness must be thin enough to inhibit wave propagation in the substrate channel instead of coupling into the waveguide probes. At 1.9 THz, a substrate thickness less than 15 μm is the upper limit for a dielectric constant of 3.8 (crystalline quartz). Grinding and polishing crystalline quartz down to 25 μm has been realised elewhere [Loudkov]. Unfortunately quartz is very brittle at this thickness and it seems that the polishing and subsequent handling limits are around 20 μm. We have therefore concentrated on the development of a fabrication process on 2 μm thin Si_3N_4 layers. A successful attempt to fabricate devices on 3 μm thin Si-layers has been presented at the conference [Bass].

2. PHONON COOLED HOT ELECTRON BOLOMETER FABRICATION

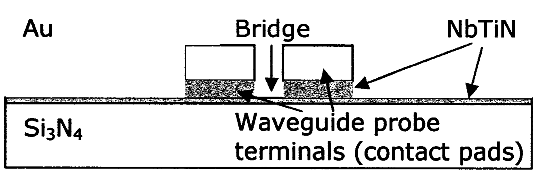


Fig. 1 simplified cross section of our HEB device

Phonon cooled NbTiN-HEBs on Si_3N_4 membranes were fabricated at KOSMA with exception of the Si_3N_4 layer, which was fabricated at Berkeley Microfabrication Lab. The 5-6 nm ultrathin NbTiN film was deposited by DC reactive magnetron sputtering at a substrate temperature of 400 °C on a 20 nm AlN buffer layer. Next the contact pads were patterned using a 210 nm single-layer PMMA mask with E-Beam lithography and liftoff. Before sputtering the 50 nm Au-contact pads, we applied an O_2 and Ar in-situ sputter clean and deposited a 20nm thick NbTiN layer [Baselmans]. The distance between the Au-contact pads determines the length of the HEB bridge. The RF-Filter structures are then patterned with UV lithography and liftoff. A bilayer of 80 nm low-stress Nb and 300nm Au are sputtered for the RF-filters. The last step of the device fabrication ist the patterning of the bolometer bridge itself with E-beam lithography and liftoff of an 30nm Al etch mask. A RIE etch process with NF_3 defines the width of the bridge.

3. Si_3N_4 MEMBRANES

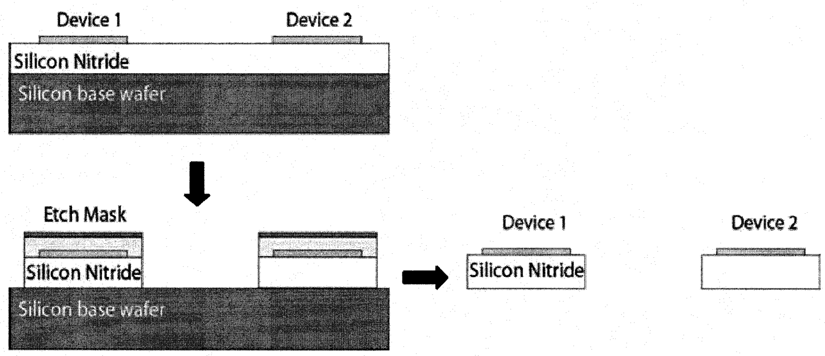


Fig. 2 Schematic description of the patterning and exposure of the Si_3N_4 membranes

The first step in fabricating the free-standing membranes is to define the boundaries of each device by patterning the Si_3N_4 layer in a grid as shown in picture 2, using a bilayer UV-Resist/Cu mask for increased etch resistance for the 2μm Si_3N_4 etch. After NF_3 RIE etch the devices are still connected, but the Si_3N_4 is removed between the individual devices. Before removing the etch mask, 500nm Au is sputtered onto the exposed Si surface, which helps to protect the devices during the wet etching step described below. After liftoff, we dice the devices to isolate them electrically in order to perform DC-characterization. After device characterization the wafer pieces are glued face down with w-wax. on a glass carrier wafer. The back side of the Si-wafer is polished to 80 μm thickness. This step eases the consequent wet etching with a solution of HNO_3 and HF dissolved in acetic acid. This is a standard isotropic Si-etching recipe and takes around two minutes to completely dissolve the Si on the back side of the membranes. As the acid solution is very abrasive, it is important to protect the devices well enough. Gold between the membranes has shown to be a resistant etch-stopper. The gold between the devices is now wet etched with an iodine based solution. Finally, the comb-like membrane structures with 14-33 devices are freed from the w-wax. Due to residual film stress, the membranes are slightly convex. As it turns out, this does not pose a mounting problem. More details on fabrication can be consulted in [Brandt].

4. SI-FRAMES

On one batch we produce a maximum of about 200 devices, which can be quite identical if so designed, assuming a realistic production yield of 80%. This rather large number of devices per batch is only possible because the frames to which the membranes are mountd in the mixer block are fabricated separately, so they do not occupy space on the membrane wafer. This also prevents device damage during frame fabrication.

The Si frames are fabricated from of a Si wafer with a top layer of Si_3N_4. 300nm gold films are patterned as bond contact pads for the membrane devices on opposite sides of the frames. The Si_3N_4 layer is patterned to frames similar to the device membranes. The Si_3N_4 is used as a mask for the Si wet etch in TMAH at 90 °C. The etch is stopped at the required depth and the wafer is polished from the backside precisely to the desired frame thickness.

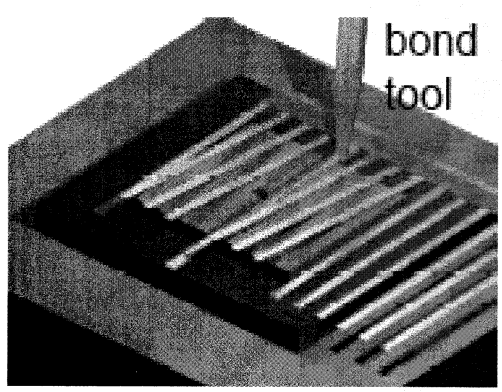


Fig. 3 Schematic description of bonding individual HEB device into the mixer block.

5. Mounting into The Mixer Block

The Cu mixer blocks including the waveguide and substrate channel are made at KOSMA. The Si-frame is glued with w-wax into a pocket surrounding the waveguide area. The comb-like membrane structure is placed on the mixer block. The membrane structure is shifted until the selected device falls into the substrate channel with the metallization facing down. A bond tool is used to attach the membrane device to the frame contact pads. An ultrasonic pulse on the back side of the membrane (now facing the bond tool) bonds the metallized side of the membrane to the gold contact pad of the Si frame (see fig. 3). The individual device can be easily broken off and the remaining devices of the comb structure are untouched. Details can be looked up in [Brandt]

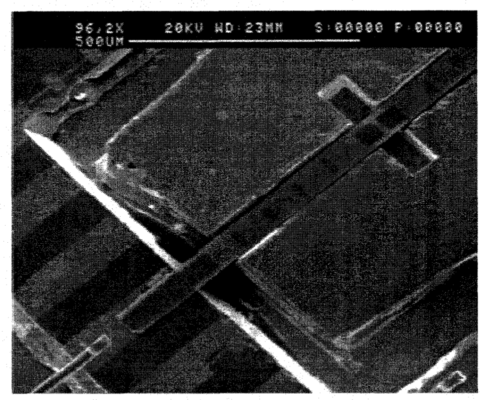
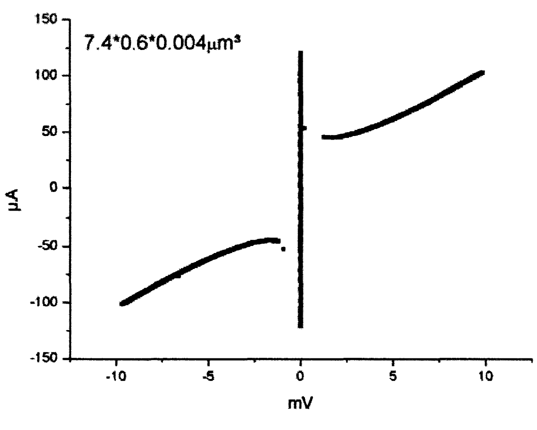


Fig 4. SEM-Picture of suspended membrane into the waveguide

6. DC-Measurements



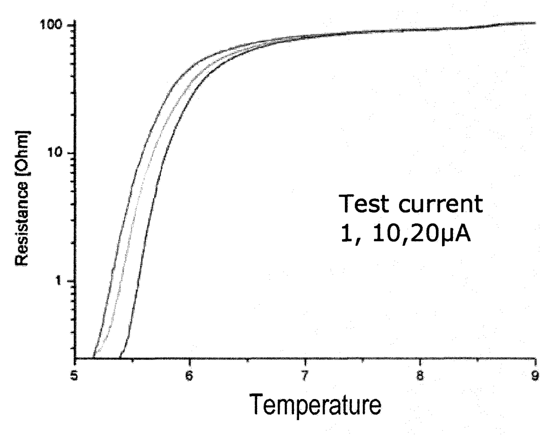


Fig. 5 Left: IV-Curve of the measured device. Right: RT-curve with three different test currents(20, 10 and 1µA, left to right)

In Fig. 5 an I-V characteristic of the selected HEB device is shown at 4.2 THz. This curve was measured during the initial DC tests of the device, using a dipstick setup. The nominal device dimensions are LxWxH=0.6x7.4x0.006 μm^3. The critical current of 125µA implies that the critical current density of this device is 282 kA/cm^2. The normal state resistance is 70 Ω. The device dc parameters (resistance and critical current) scale very well with the geometry of the device. This fact points to the spatial uniformity of the film and the reproducibility of the fabrication process. The bridge becomes superconducting at a critical temperature of about 6 K.

7. RF-Measurements

Prior to characterizing HEB mixer performance the RF spectral response has been checked using a Bruker IFS66v/s Fourier-transform spectrometer. The center frequency (800GHz) and bandwidths (=20%) in general agreed with that expected for our computer simulations. The HEB was used as a direct detector for the spectral response measurements. In order to increase the HEB voltage responsivity, the device was operated at 9K.

The receiver noise temperature was

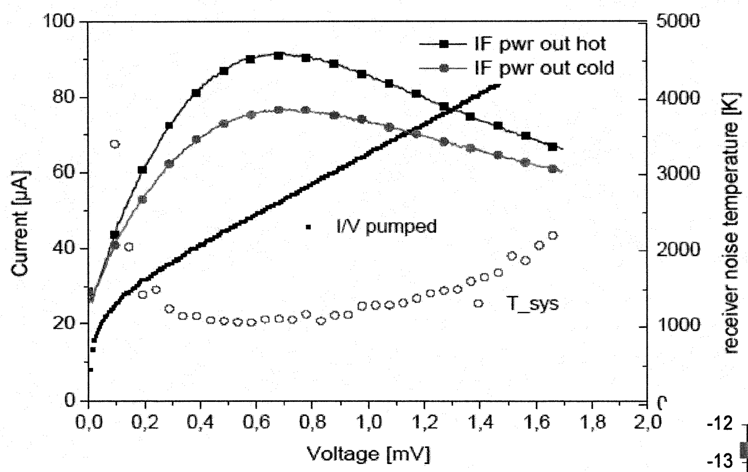


Fig. 6 Pumped IV curve (solid line). Hot and cold output (dots + line). Receiver temperature (dots).

measured with a solid state LO (Gunn diode with 2x and 3x multipliers) with an optimal output power of 40 µW. The Y-factor was measured by inserting a liquid nitrogen cooled absorber by hand into the path of the beam using a 35µm Mylar beam splitter (5% LO power reflection). The LO had to be manually detuned from optimal performance in order not to overpump the HEB.

To determine the noise bandwidth a tuneable band pass filter (Bandwidth 50MHz) was used to measure the noise temperature at different IFs. At fig. 7 this results are shown. The noise of the IF chain was previously determined in the same experiment through heating the HEB and using it as a Johnson noise source. Independently the IF chain was also calibrated using a SIS junction as a shot noise source. Both calibrations were in good agreement. The IF chain accounts for 6-10K over the IF-bandwidth. We measured a minimum receiver noise temperature 1000K at 0.4 mV voltage bias. At 1.0 GHz IF the calculated mixer gain is –13dB, whereas at 1.3-1.4 GHz IF it is –16db. Measurements of similar devices on bulk Si (measured using a quasioptical design at 800GHz) and devices from other groups using still thinner NbTiN HEB bridge films (4nm) [Loudkov] do not show significantly higher bandwidths. This points out the fact that the bandwidth, which is expected to increase reciprocally with the film thickness, may be limited by other factors, such as the escape time of the phonons into the substrate, which is in this case given by the phonon transparency and coupling of the NbTiN and AlN layers.

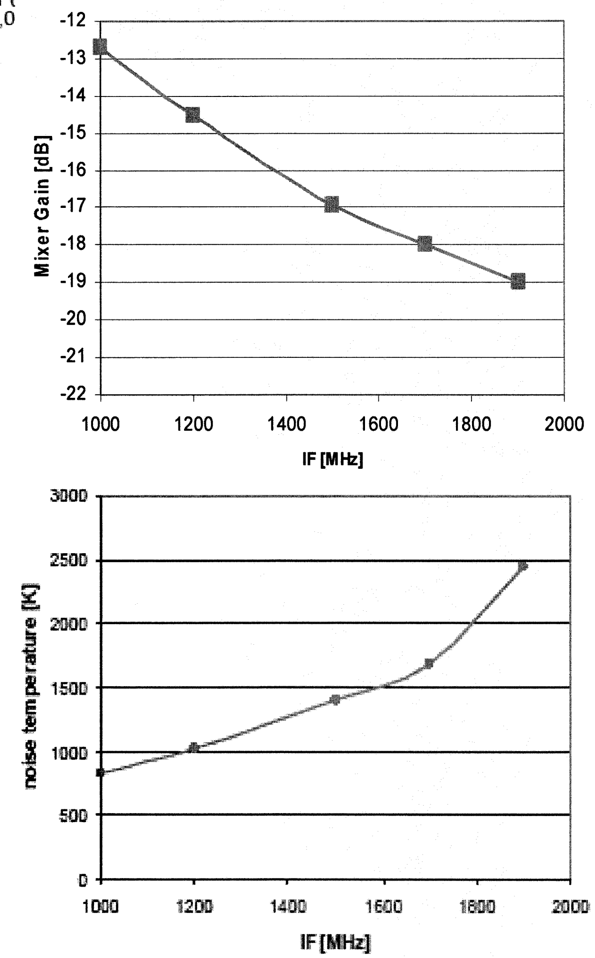


Fig. 7 Calculated mixer gain (upper diagramm) and measured noise temperature (lower diagramm) over the IF.

8. ASTRONOMICAL OBSERVATIONS AND ALLAN VARIANCE

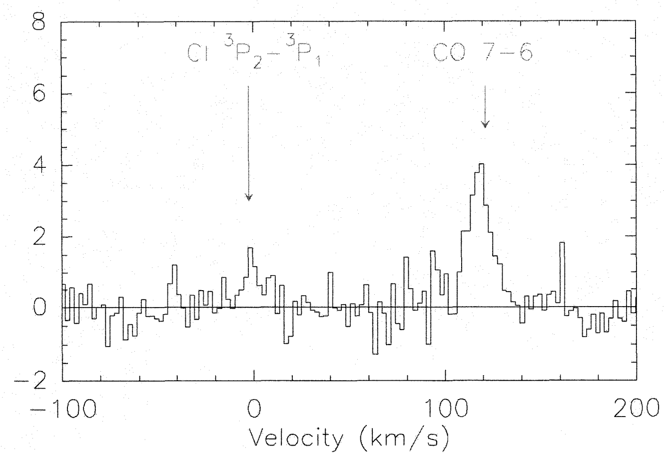


Fig. 8 Observation of DR21 with HEB mixer. The CO 7-6 line (right) lays in the lower band.

We mounted the HEB mixer discussed above in the SubMillimeter Array Receiver for Two frequencies (SMART) [Graf] at the Koeln Observatory for SubMillimeter Astronomy (KOSMA) on the Gornergrat in Switzerland. SMART is a dual frequency array receiver currently containing four 490 GHz SIS mixers and three 810 GHz SIS mixers and the 800 GHz HEB. The mixers are pumped by two Local Oscillator at 490 and 810 GHz respectively and cooled by a Gifford-McMahon closed cycle refrigerator. Unfortunately, a low quality diagonal feed horn had to be used to direct the signal to the HEB as the Potter horn was needed for further laboratory measurements. This is the main reason that the noise temperature of the HEB at the telescope was 4000K.

With this set-up Allan variance measurements were performed looking at a liquid nitrogen load and using the read out of the Acousto-optical Spectrometers (AOS) with a resolution of 1MHz and over a band width of 735 MHz. From the data a spectral Allan variance similar to the one described in [Schieder] was calculated, resulting in a minimum time of around 7 sec, see Fig. 9. The SIS mixers in the same set-up are slightly more stable with a minimum time around 10s. The spectral Allan variance is sensitive to variations in the spectral response of the device over time and thus is a significant quantity for spectral line observations. It is a different quantity than the total power Allan variance which traces gain variations averaged over the whole band.

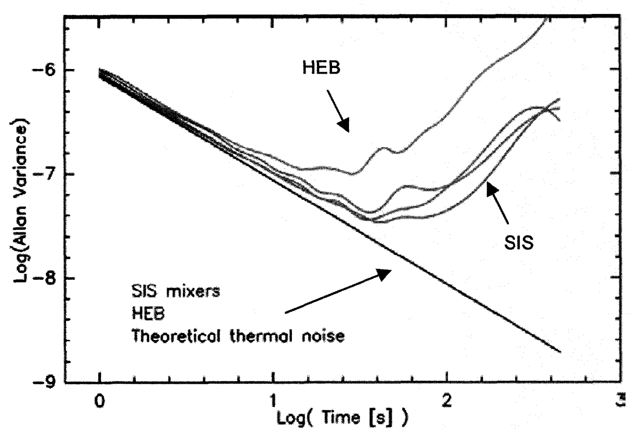


Fig. 9 Spectral allan variance of the HEB and SIS versus the theoretical thermal noise (straight line)

We also performed the first astronomical observations with a HEB in a closed cycle system, as far as we know. The atmospheric tau was between 1 and 2. We successfully detected DR21 (Fig. 8) in the CO 7-6 rotational transition. There is also a hint of the C0 3P2-3P1 (809 GHz) line, which was in the other (upper) side band.

9. Conclusions and Outlook

We have demonstrated receiver noise temperature of 1000K at 800GHz for a NbTiN HEB waveguide mixer on suspended 3µm Si_3N_4 membrane. The measured IF noise bandwidth was 1.3 GHz. We did not observe a limitation of the IF bandwidth caused by the use of Si_3N_4 membranes instead of bulk substrate materials. The device was also used for astronomical observations at the KOSMA telescope at Gornergrat, Switzerland, showing sufficient stability operated in a closed cycle refrigerator. At KOSMA we are optimizing the NbTiN film characteristics as well as device fabrication in order to improve the IF bandwidth and reduce noise temperature, moving up to 1.2, 1.4 and 1.9 THz RF frequencies.

Acknowledgment

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