

# NbTiN Hot Electron Bolometer Waveguide Mixers on Si<sub>3</sub>N<sub>4</sub> Membranes at THz Frequencies

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**Abstract**—We report on NbTiN hot electron bolometer (HEB) mixer design and fabrication for the 1.4, 1.9 and 2.5 THz frequency bands. The mixers under discussion are our contribution to the multi-band single-pixel receivers of the German Receiver for Astronomy at Terahertz Frequencies (GREAT), which is a first light instrument for the airborne Stratospheric Observatory for Infrared Astronomy (SOFIA), and the focal plane array receiver on the balloon-borne Stratospheric Terahertz Observatory (STO). We measure device noise vs. intermediate frequency (IF) and analyze the receiver system output power stability and IF band ripple with newly developed SiGe low-noise amplifiers from the S. Weinreb group (Caltech). The mixers use waveguide technology with the device coupled to the fundamental waveguide mode via an integrated probe antenna. The device is electrically connected through beam leads, which reliably suspend the 2 μm thin Si<sub>3</sub>N<sub>4</sub> membrane with micrometer mounting precision. Electron beam lithography defines the 400 nm long and 4 nm thick NbTiN microbridges and a novel deep reactive-ion etch is used for shaping of the substrates.

**Index Terms**—Allan variance, hot electron bolometer (HEB) mixer, radio astronomy, terahertz receiver.

## I. INTRODUCTION

EARLY in 2011 the German Receiver for Astronomy at Terahertz Frequencies (GREAT) is scheduled to begin its first science flights onboard the Stratospheric Observatory for Infrared Astronomy (SOFIA) [1]. GREAT is a modular receiver system that can operate two single-pixel receivers for different frequency bands simultaneously for very high-resolution spectroscopy ( $R > 10^6$ ) of interstellar line emission. GREAT will have the choice of four receivers covering the frequency bands around 1.4 THz, 1.9 THz, 2.5 THz and 4.7 THz. The receivers for 1.4 and 1.9 THz are fully operational for the science flights, and the 2.5 THz receiver components are currently being tested in the laboratory (see Section 6).

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The 4.7 THz channel is under development and will be introduced to GREAT once the technology is mature [2].

In addition to GREAT the long-duration balloon-borne instrument STO is scheduled for launch from Antarctica at the end of 2011 [3]. STO is a dedicated galactic mapping instrument for the astrophysically important spectral lines [N II] at 1461 GHz and [C II] at 1900 GHz and an ideal complement to the larger, individual target focused Herschel and SOFIA instruments. The 2x 4-pixel heterodyne receiver of STO will utilize a 1.4 THz band focal plane array from the Jet Propulsion Laboratory and one at 1.9 THz from the U. Köln.

We present the latest development state and performance test results for our superconducting hot electron bolometer (HEB) mixers employed by aforementioned receivers.

## II. WAVEGUIDE MIXER TECHNOLOGY FOR 2.5 THz

We are committed to push direct metal machining technology as far as possible because of the straight-forward and time efficient concept of a single metal block that can include the small waveguide and device structures as well as provide sufficient volume for mechanical and electrical attachments at the same time. The required machining technology for micrometer precise waveguides and profiled conical feedhorns is ambitious when compared to the usual approach at THz frequencies to use planar antennas and dielectric lenses to couple to the radiation. Machining difficulties are outweighed by the advantage of an easier alignment and match to Gaussian telescope optics, which is important for focal plane arrays of mixers.

Fabrication of THz waveguides with novel micro fabrication technology is currently only being pursued by a few groups, e.g. [4], and potentially could enable waveguide mixer technology up to 5 THz or even higher. Currently we have gained expertise in reproducibly machining waveguide sizes down to 96 μm x 48 μm, which provide the basis of our new 2.5 THz mixers and will be discussed in the following. We use backshort blocks for our THz mixer thus avoiding possibly lossy E-plane splits and their alignment issues. The feedhorn with its clamp structure is orientated perpendicular to the device, which is placed in a channel parallel with the front surface. The metal base of the feedhorn, which is a custom spline-profiled conical feed that is fabricated at Radiometer Physics GmbH, acts as a lid for the channel [5], [6]. Machining of the waveguide features utilizes individually

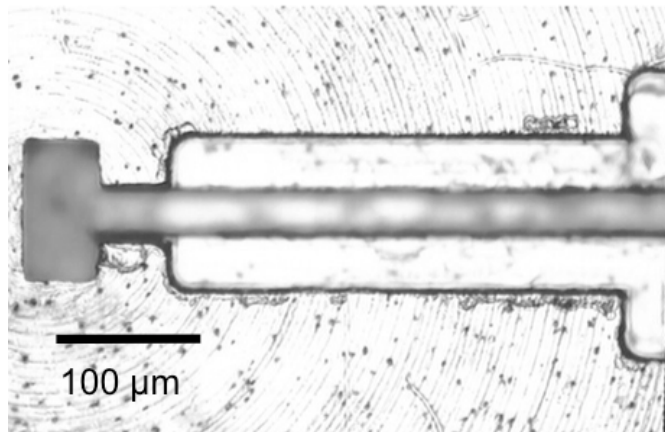


Fig. 1. Optical microscope image of a direct metal machined 2.5 THz waveguide environment, looking down on the front face of the mixer block. The input waveguide, measuring  $96\ \mu\text{m} \times 48\ \mu\text{m}$ , is to the left. A short channel section widens to the shallow beam lead cavities. Features sizes are precise to a couple of micrometers.

optimized techniques: The waveguide backshort cavity is stamped with a precisely milled and polished spring steel tool. The channel and beam lead features are milled using a  $25\ \mu\text{m}$  diameter tool and an electropolishing step for local de-burring of the milled features edges is employed. Finally, the whole front face of the mixer block is plasma-cleaned and sputter-coated with  $200\ \text{nm}$  of gold. Fig. 1 shows an optical microscope image of the waveguide environment of one of our new 2.5 THz mixer blocks after completion of the fabrication sequence.

### I. NEW BEAM LEAD DEVICE DESIGN

Our development goal for 2.5 THz HEB mixers for GREAT was the decisive factor to perform a complete redesign of our previous 1.4 and 1.9 THz mixers, which relied on a design adapted from our HIFI Band 2 SIS mixers [7]. These mixers use a substrate across the waveguide with a probe that provides coupling to the HEB microbridge. RF rejection and IF output are realized in suspended microstrip, which also provides the DC biasing connections. The thin membrane substrate required at THz frequencies is suspended by a deep reactive-ion etched (DRIE) silicon frame, which also provides bond pads for ultrasonic flip-chip tab bonding of the device as well as for the wire bonds to the IF output connector and mixer ground. This layout has proven itself in terms of performance and flight worthiness and is the current hardware in the 1.4 and 1.9 THz channels of GREAT.

Alignment of the device's antenna with respect to the waveguide is critical and relies on moving the frame with attached device with a micromanipulator under a microscope with large magnification. The visual alignment procedure is only accurate to  $5\ \mu\text{m}$  and therefore not sufficient for a tolerant 2.5 THz design. As a consequence we selected beam lead structures for the new design as this provides several advantages with respect to device performance, mounting tolerances, device performance, cryogenic cycling, and electrical connections [8]–[10]. The beam leads are used for electrical contacting the device through ultrasonic tab bonds, and they suspend the thin membrane substrate, making the additional silicon frame obsolete, and they are used for precise

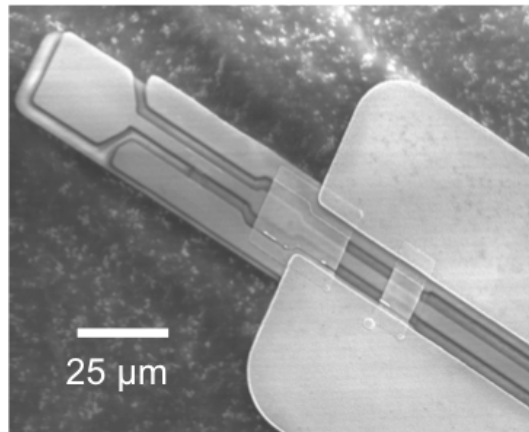


Fig. 2. Electron microscope image of a single fully processed 2.5 THz device at 326x magnification. The view depicts the front part of the device with the RF circuitry, the beam leads and the part of the IF output cpw. The HEB microbridge and contact structures are approximately at the center of the first cpw transmission line after the waveguide antenna.

and reproducible alignment of the device within the metal waveguide environment. In addition, they provide a much larger cooling cross-section. From the fabrication viewpoint beam leads are easily incorporated into a fabrication scheme, which uses DRIE for substrate shaping and can be aligned to the device structure with sub-micrometer precision.

A suitable transmission line circuit in combination with beam leads is the coplanar waveguide (CPW) type, and we therefore incorporated this into our new design. Beam leads connected to the mixer block provide the CPW ground plane. Since CPW provides uniplanar circuitry, this essentially decouples the circuitry from the ground planes at the bottom or top of the substrate channel and therefore increases the vertical mounting tolerance of the design as well as the machining tolerance of the channel height. We use a modified rectangular shaped one-sided waveguide probe antenna, which provides a very broadband match to the transmission line that feeds the HEB microbridge [11]. The 2.5 THz waveguide environment including device circuit was completely designed in CST Microwave Studio™ and was optimized with a thorough tolerance analysis including thin film losses [12]. For the other important frequency bands 1.4 and 1.9 THz we adapted a similar design. The front beam lead section of each device (see Fig. 1) is  $450\ \mu\text{m}$  and the beam lead for contacting to the IF connector is  $1.8\ \text{mm}$  long. In each frequency band we optimized for several HEB impedances ranging from  $20$  to  $120\ \text{Ohm}$ , with emphasis on higher impedances at the higher frequency bands in order to accommodate the lower available local oscillator (LO) power.

### II. DEVICE FABRICATION

Fabrication of our HEB devices utilizes frontside and backside processing steps in a similar manner to the SOI wafer processes published in [9], [10]. At first the front side steps define the device structures on a  $30\ \text{mm} \times 30\ \text{mm}$  wafer of  $2\ \mu\text{m}$  thickness low-stress silicon nitride (LSN) backed by a  $520\ \mu\text{m}$  silicon handle layer [13]. The thin  $4\ \text{nm}$  NbTiN microbridge layer is reactive DC magnetron sputtered at  $800\ ^\circ\text{C}$  substrate temperature. Then the global and local device alignment marks are defined with photolithography and

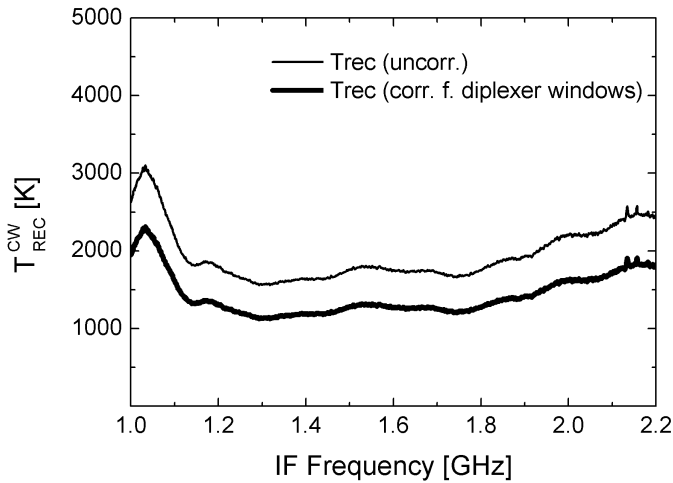


Fig. 3.  $T_{\text{rec}}(\text{IF})$  for a mixer measured with a 1.5 GHz bandwidth digital Fourier transform spectrometer at a LO frequency of 1899 GHz. Note that the feature at 1.05 GHz is an artifact of the Martin-Puplett diplexer used for these test measurements.

sputter deposition. The latter serve as registration reference for the subsequent electron beam lithography (EBL) step, which defines the HEB contact pad areas using a bilayer co-MMA/MAA-PMMA resist scheme. With the spacing of the contacts we conservatively set the microbridge length to 400 nm for all devices, which guarantees not too critical lift-off behavior of the sputtered contact pad metallization and therewith sufficiently reproducible device lengths. We follow the proven concept of [14] using a carefully adjusted low power two-step  $\text{O}_2$  and Ar reactive-ion etch clean of the contact areas with subsequent room temperature sputter deposition of an additional 10 nm layer of NbTiN before sputtering the 50 nm Au contact layer. Next comes the 200 nm Au metallization for the CPW structures including waveguide probe and seed layer for the beam leads. The microbridge itself is defined via EBL of negative resist and plasma etch using the already defined metal structures as additional etch mask for the NbTiN. Subsequently we use photolithography and deposition steps for defining the 50 nm Ge passivation layer, 400 nm  $\text{SiO}_2$  dielectric for the capacitive filter elements and 200 nm Au ground strap metallization. Finally, the beam leads are electroplated into a photoresist pattern to 2  $\mu\text{m}$  thickness and conclude the front side processing.

At this stage the device circuits including leads to bond pads are completed and the wafer is diced into segments of approx. 30 devices each for measurement of the direct current-voltage and resistance-temperature characteristics.

After these measurements backside processing then is performed with one wafer segment glued facedown onto a sapphire carrier wafer. The bulk Si is removed through a high-power deep reactive-ion etch process with cooling breaks every 10 min. The etch rate is approx. 4  $\mu\text{m}/\text{min}$  but increases towards the end of the process and visual endpoint confirmation of successful removal of the Si is performed.

Thick photoresist (AZ9260) is used for photolithographic definition of the membranes, with the backside alignment being performed on the front side registration marks visible through the optically transparent membrane. The membranes then are cut with the second high power DRIE process. This

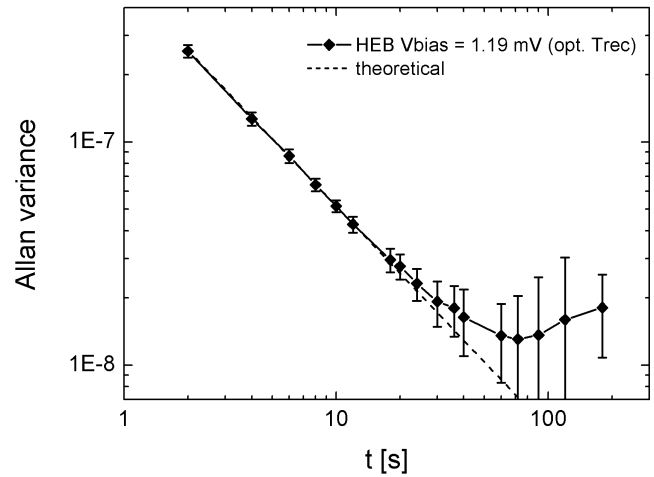


Fig. 4. Total power (0.6 GHz bandwidth, centered on 1.45 GHz) Allan stability plot for an 800 GHz HEB test receiver with input-matched cryogenic low-noise amplifier (S. Weinreb, Caltech) without the usually required RF isolator between mixer and amplifier.

completes fabrication and the now separated devices are easily removed from the sapphire carrier using an organic solvent.

Fig. 2 shows an electron beam image of a single 2.5 THz device after processing. Our initial look at the fabrication yield and direct current characteristics indicate that the additional processing steps do not show an impact when compared to the previous design.

### III. RECEIVER IF OPTIMIZATION

In parallel to mixer design we continue our work on the optimization of the receiver IF in terms of output power stability and ripple. In agreement with [15], [16] we can confirm that using the latest SiGe HBT input-matched cryogenic low noise amplifiers [17] in combination with a dedicated low input reflection and short electrical length bias-tee yields stable and low ripple receiver IF performance. This makes the previously used L-band RF isolator with its < 0.6 GHz bandwidth obsolete, and therefore results in a broader IF passband that uses the whole IF range of our HEB mixers. For our previous design with the 2  $\mu\text{m}$  thick LSN membranes held and suspended by the silicon frame we measure relatively large 3-dB gain roll-offs > 3 GHz for our 4 nm thin NbTiN microbridges at optimum  $T_{\text{rec}}$  bias voltages. This indicates a sufficiently fast phonon-cooling channel through the 2  $\mu\text{m}$  LSN membrane [18], [19]. For the new devices we expect an improved heat sinking of the microbridge through the beam leads and to measure a positive influence on the mixer performance shortly.

Fig. 3 demonstrates the measured  $T_{\text{rec}}(\text{IF})$  for one of our 1.9 THz flight mixers for GREAT as measured with our test setup.  $T_{\text{rec}}$  is calculated with the well-known Y-factor method using the Callen & Welton equivalent load temperatures [20]. An evacuated Martin-Puplett diplexer was used for LO/signal multiplexing. The lower curve shows  $T_{\text{rec}}(\text{IF})$  corrected for the measured reflection losses at the two high-density polyethylene vacuum windows of the diplexer in the optical path to the loads. Fig. 4 shows the excellent total power stability expressed as Allan variance over a 0.6 GHz band using the optimized IF [21]. Here we choose to measure at

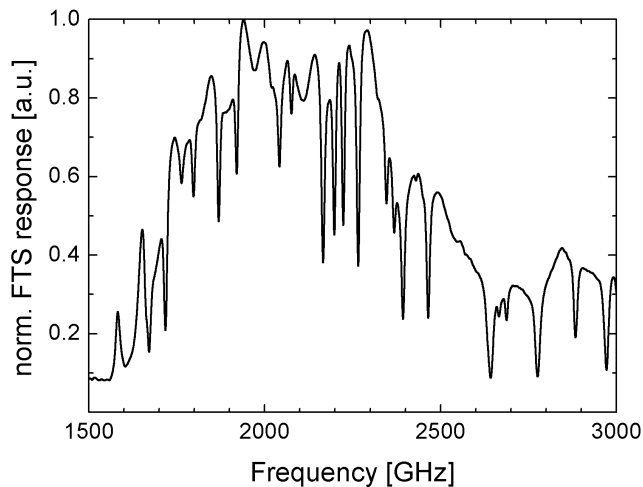


Fig. 5. Measured FTS response of a 2.5 THz HEB waveguide mixer. All sharp dips are a result from water absorption lines. The FTS was evacuated to 5 mbar with approx. 2 cm optical path remaining not evacuated.

810 GHz where instabilities arising from the lab surrounding (atmosphere, acoustics, pressure gradients) have significantly less influence. An excellent Allan stability time in excess of 20 s is measured under optimum Trec voltage bias and is comparable with good SIS receivers.

#### IV. FIRST RF RESULTS AT 2.5 THZ

We conclude with the first RF results of the new 2.5 THz design. To-date we have fully assembled mixer hardware. An initial direct-detection measurement using our commercial Fourier transform spectrometer (FTS) system is shown in Fig. 5. The measured response looks promising for this very first device mounted, and the shift of maximum response to lower frequencies is under investigation. The heterodyne response measurements for GREAT will be done in collaboration with I. Cámara Mayorga and T. Klein, from the photomixer LO group at the Max-Planck-Institut für Radioastronomie, Bonn, who have developed a dedicated 2.5 THz source for this purpose.

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