SUPERCONDUCTING HOT ELECTRON BOLOMETERS ON FREESTANDING SILICON NITRIDE MEMBRANE STRIPS USING FLIP-CHIP MOUNTING

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ABSTRACT

We report on a novel fabrication scheme for 1.9 THz waveguide mixers for SOFIA, where Hot Electron Bolometer mixers (HEB) or SIS mixers are fabricated on 2 μm thick Si_3N_4 membrane strips. The strips are robust enough to be mounted on a separately fabricated Si support frame using an adapted flip-chip technology. Mounted onto the frame, the devices can be easily positioned and glued into a copper fixed tuned waveguide mount. Fabricating the large frames and the small Si_3N_4-strips separately requires significantly less space on the device wafer, allowing many more devices per wafer.

This concept is currently being tested in an 800 GHz prototype mixer with a HEB device. We have demonstrated that the cooling of the device via membrane and RF filter metallization is sufficient by comparing the resistance versus temperature measurements in Helium atmosphere and in vacuum. Heterodyne and Fourier transform spectroscopy measurements are currently being set up.

I. INTRODUCTION

Within the scope of the GREAT (4 Pixel, 1.6 – 2.0 THz) and STAR (4x4 Array, 1.9 THz) receivers for SOFIA we need low noise mixers with good coupling to the telescope. Waveguide mixers at THz frequencies demand considerably more technical effort than quasi-optical mixers, but they provide a set of advantages as :

- single mode Gaussian beam shape for optimum coupling to the telescope
- compact design for array and satellite applications
- intrinsic band pass filtering avoiding saturation

Scaling the fixed backshort mixer design that we have successfully used in submillimeter mixers to Terahertz frequencies is possible but obviously requires scaling of the substrate thickness. At 2 THz, a quartz substrate would be too thin to fabricate and handle. This paper describes our efforts to develop an alternative solution.

II. MIXER DEVICES ON MEMBRANES WITH SUPPORT FRAMES

The RF signal is coupled from waveguide to the device via the waveguide antenna probe. The substrate with antenna probe, HEB detector and IF filter has to be thin and narrow enough to prevent RF loss through the substrate channel. For 800 GHz mixers the standard procedure is to grind a quartz wafer down to 25 μm, which is almost the limit in quartz thickness that can be reliably fabricated and handled. To realize considerably thinner substrate the general idea is to fabricate the mixer device on a thin (~2 μm) membrane layer deposited or grown on a bulk wafer. The membrane is then structured into the thin strips which are used as the substrates for the devices. By backside etching, the support wafer is taken away, leaving only the membrane strips and their frames of bulk material for support [1]. Materials tested were GaAs membranes on GaAs wafers with an AlGaAs etch-stop and Low Stress Silicon-Nitride on Silicon wafers. With both material combinations, frames with membrane strips have successfully been produced.

III. SEPARATE FABRICATION OF DEVICES AND SUPPORT FRAMES

One disadvantage of the frame/membrane concept is the relatively large wafer real estate occupied by the support frames. As the process for the THz mixer devices has only limited yield, the chances of producing a sufficient number of good and - important for array receivers- identical devices are comparably poor. This and some other points of concern led to a further optimization of the concept.

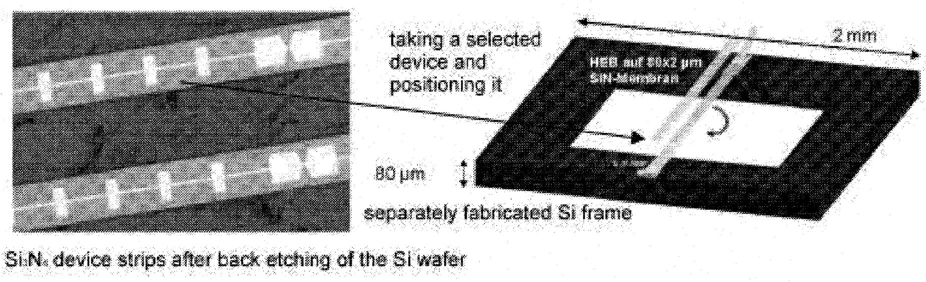

Fig. 1: "Flip-chip" concept

The mixers are fabricated on wafers with a membrane layer, and the support frames are produced on similar, but separate wafer. The finished devices on their thin membrane strip substrates then have to be mounted individually onto the frames, where they are electrically connected [2]. Of course, the mounting process is delicate and requires a special process. We therefore developed an adapted "flip-chip" process, taking advantage of an advanced microgripping station. With this process about 400 devices fit easily on a 1" wafer, about 20 times as many as with the conventional concept with typical quasioptical antenna circuits.

A second problem of producing the frames together with the devices is solved with this approach at the same time. Anisotropic etching of the frames from the back side is necessary to achieve a reproducible mechanical interface to the mixer mount. Most reasonably anisotropic etch processes with high etch rates only work well at temperatures above 80°C. At this process stage, the wafer already carries the delicate and temperature sensitive bolometer devices on the front side, so that etch protection is of utmost importance. We have not found a reliable way of protection for small wafers.

IV. FABRICATION PROCESS

The HEB devices are fabricated on a 2 μm thick, low stress Silicon Nitride (Si_3N_4) film deposited on a silicon wafer [3]. The process is the same as described in [4] with only minor changes. The IF bond pads, which are later used for the "flip-chip" bonding, consist of 300 nm Au for good electrical and thermal contact.

The HEBs are passivated with SiO_2 which also serves as an additional protection against the Silicon back etch solution. In the last step the Si_3N_4 membrane is cut into 80 µm strips with Reactive Ion Etching. For 1.9 THz these strips are scaled down to a width of 40 µm. During RIE, the HEBs are protected by a trilayer of resist/Cu/resist which can withstand the 12 minute silicon nitride etch. After RIE, a gold layer is deposited to cover the silicon area between the strips using the same photoresist for liftoff. This gold film protects the strips from being attacked by the etch solution when it breaks through from the backside. The wafer is diced into smaller pieces and the ground connections are cut to allow DC-testing of the devices while they are still supported by the bulk wafer.

The most critical part of the process is the final back-etching of the supporting Silicon wafer, leaving the devices on free standing silicon nitride strips. Obviously, this etch process does not have to be anisotropic. Still, all isotropic recipes with reasonable etch rates either use HF or need about 80°C process temperature. Long exposure to elevated temperatures deteriorates the bolometer characteristics. HF on the other hand attacks nearly any material or peels it off, making it difficult to find masking materials. We are now working with a room temperature solution using $Cu(NO_3)_2$ and NH_4F. In contrast to the standard HF/HNO_3 process, it is selective to SiO_2, so that SiO_2 can be used as an etch stop and passivation for the HEBs. The wafer is glued face down onto a subwafer with wax [5]. The reduced Cu precipitates on the Si surface and has to be removed with a polishing step. When the bulk Si is completely etched away, the gold between the strips is removed. Dissolving the wax results single devices on 80 µm x 1600 µm x 2 µm substrates.

V. "FLIP-CHIP" ASSEMBLY

For the support frames Si wafers are thinned down to 80 µm by lapping. After depositing Nb/Au bonding pads, the frames are etched with TMAH at 80°C using SiO_2 for masking. The anisotropic TMAH etch produces 70° side walls in <110> Si. The metallization on the frames could also be used to incorporate IF matching circuits.

For mounting on the frame, a selected device is removed from the storage box with the help of the KOSMA Micro Assembly Station (MAS) and is positioned onto the bond pads of the frame. The bond pads and IF filter metallization of the device are facing downwards. The device is ultrasonically bonded to the Au/Nb pad of the frame with a modified bond tool. When bonding the opposite substrate end, substrate strips that are slightly bent due to residual film stress can be straightened out. The resulting device/frame assembly can be easily handled and put into position by the micro-assembly station and electrically connected via the bond pads of the frame. Fig. 2 shows a finished device mounted into a 800 GHz copper waveguide block.

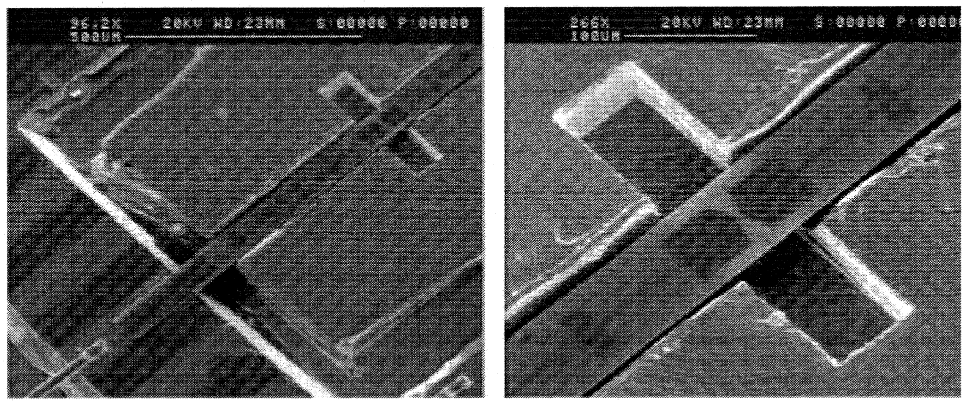

Fig. 2 SEM photo of "flip-chip" mounted HEB device. The left photo shows one part of the frame with the IF bond wire connection, the right photo shows a close-up of the RF waveguide and the freestanding device substrate. The substrate channel is 40 μm deep.

VI. DC RESULTS

A point of concern for HEB devices on freestanding thin membrane substrates could be the cooling of the devices in vacuum. Fig. 3b shows a comparison of resistance versus temperature measurements in liquid Helium and in a vacuum dewar. The results show that there is no visible difference and that cooling via the gold wiring seems to be sufficient. The R/T and I/V characteristics are also very similar to devices fabricated on crystalline quartz.

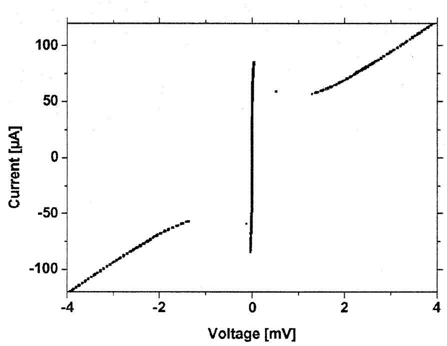

Fig. 3a I/V curve of HEB on freestanding membrane

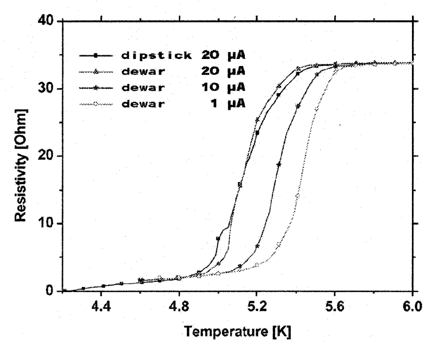

Fig. 3b R/T curves in liquid He (dipstick) and vacuum (dewar)

VII. RF CIRCUIT SIMULATIONS

Compared to the standard designs, where the devices are on top of a 25 μm thick crystalline quartz substrate and face the horn antenna, the "flip-chip" devices are on the backside of a 2 μm membrane with a dielectric constant of 7.5 and face the backshort section of the waveguide. Simulations with CST MicroWaveStudio [6] show that sufficiently good coupling to the waveguide is still achievable (Fig. 4). Further optimization to reduce the inductive component and increasing the bandwidth appears to be feasible.

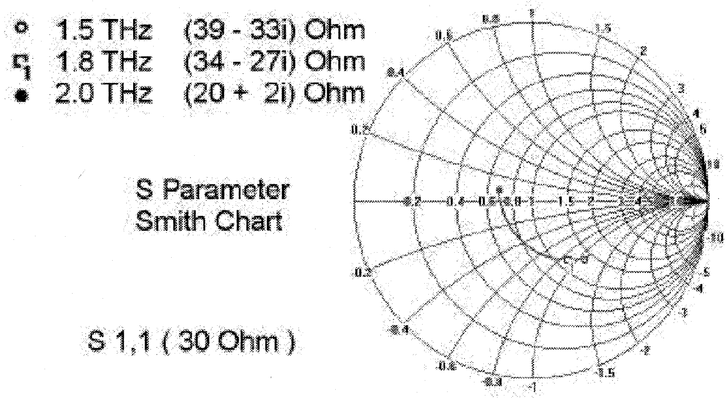

Fig. 4 S11 Smith Chart simulating the bolometer source impedance of a waveguide mixer for the 1.5 THz to 2.0 THz GREAT band.

VIII. Conclusions

Hot Electron Bolometers have been fabricated on freestanding silicon nitride membrane strips with DC device characteristics very similar to bolometers fabricated on quartz substrates. A modified flip-chip process is used to bond the devices to a separately fabricated silicon frame. The Si_3N_4 membranes with a thickness of 2 µm can be safely gripped and positioned with the KOSMA Micro Assembly Station. The "flip-chip" process shows a similar yield as our standard wire bonding and none of the "flip-chip" bonded devices lost its contact at 4.2 K.

IX. Outlook

The 800 GHz design is a proof of concept for the mixers at 1.5 to 2.0 THz we are developing for SOFIA. Although the conventional copper "stamped backshort" waveguide mixer can still be fabricated at least at low Terahertz frequencies, we are working on novel methods to fabricate the waveguide mounts and the horn antennas with the help of micro-stereo lithography [7] and electroforming. These methods would allow scaling of the mixer designs to several Terahertz.

X. References

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